The question of combating the problem of lodging has long been a sustaining major objective of the overall national tef improvement program. But the lodging resistant tef varieties have remained elusive.

Kebebew Assefa (PhD)
National Tef Research Coordinator

Similar to other worldwide popular cereals, it is possible to develop high yielding tef varieties with good grain quality and other desired traits—variety 'Quncho' is a testimony of what can be done in tef improvement.

Hailu Tefera (PhD)
Breeder/Consultant, IITA
National Tef Research Coordinator (1998-2006)

Development of rapid and cheap screening techniques to identify various stress-tolerant cultivars and utilize efficient techniques for developing superior cultivars are essential for overcoming present constraints.

Seyfu Ketema (PhD)
Executive Director, ASARECA
National Tef Research Coordinator (-1995)

The world has seen significant increases in the productivity major cereal crops such as wheat and rice. As a member of this family of Grasses, tef is no exception, and therefore has a similar potential for improvement.

Tareke Berhe (PhD)
Tef Value Chain Adviser
Ethiopian Agriculture Transformation Agency (ATA)

The recent progress in tef improvement is encouraging. We need to implement useful techniques developed for major crops to further increase the productivity of this staple food crop of Ethiopia.

Zerihun Tadele (PhD)
Project Leader, University of Bern, Switzerland
National Tef Research Coordinator (1995-1996)

ISBN: 978-3-033-03818-9

9 783033 038189 >

Kebebew A., Solomon C., Zerihun T. (Eds.)

Tef Improvement

Achievements and Prospects of Tef Improvement

Edited by

Kebebew Assefa
Solomon Chanyalew
Zerihun Tadele

UNIVERSITÄT BERN

January 2013

Achievements and Prospects of
Tef Improvement

Proceedings of the Second International Workshop, November 7-9, 2011, Debre Zeit, Ethiopia

Edited by

Kebebew Assefa, Solomon Chanyalew
Ethiopian Institute of Agric. Research, Debre Zeit Center
&
Zerihun Tadele
University of Bern, Institute of Plant Sciences, Switzerland

January 2013

Correct citation: Kebebew Assefa, Solomon Chanyalew and Zerihun Tadele (eds.) 2013. Achievements and Prospects of Tef Improvement; Proceedings of the Second International Workshop, November 7-9, 2011, Debre Zeit, Ethiopia. Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; Institute of Plant Sciences, University of Bern, Switzerland. Printed at Stämpfli AG, 3001 Bern, Switzerland. ISBN: 978-3-033-03818-9.

Cover picture: Stacks of tef harvest at the threshing ground near Melka Kunture, Central Ethiopia. Photo: Sonia Plaza-Wüthrich, Novemeber 2011.

Dedication

This Proceedings is dedicated to the late ***Dr. Melak Hail Mengesha*** (1935-2009), the first tef researcher in Ethiopia

Foreword

This proceedings on 'Achievements and Prospects of tef Improvement' is the outcome of the Second International Tef Workshop held at Debre Zeit (Ethiopia), the location which represents the major tef growing areas in the country as well as the oldest and biggest center on tef research. As an indigenous crop, the bulk of tef research is carried out in the country by scientists based at various higher-learning and research institutions. Hence, unlike major crops of the world such as wheat and rice, research on tef benefited little from modern improvement techniques. However, in the recent years, there is an increasing interest by several researchers and funding organizations in developed nations to promote tef research and development through implementation of modern genetic and genomic tools. The recent efforts and progresses made on tef research and development were presented and discussed in detail at the workshop.

The tef research and development in Ethiopia has recently shown tremendous improvement. This is witnessed by the decision of the Ethiopian government to award a Gold Medal in November 2012 to our Institute for the discovery and promotion of a very popular *Quncho* variety. At this juncture, I would like to congratulate all involved in research and development of tef as the achievement was obtained due to concerted efforts of the tef community.

The editors of the proceedings did a wonderful job of undertaking the painstaking task of editing all 23 manuscripts presented at the workshop. In addition, the proceedings include a 44-point roadmap for future tef research and development which can be used as a guideline for researchers, development workers and policy makers.

I would like to extend my thanks to sponsors of the workshop and the publication of the proceedings.

Adefris Teklewold (PhD)
Director, Crop Research Process
Ethiopian Institute of Agricultural Research

Preface

Tef [*Eragrostistef* (Zucc.) Trotter] is a cereal crop extensively cultivated in Ethiopia with annual coverage of about 2.8 million hectares. The crop harbors several useful traits both for farmers and consumers. Some of these beneficial traits are: i) the plant is tolerant to extreme environmental conditions; ii) the seeds are not attacked by storage pests; and iii) the seeds are gluten-free, and hence considered as a healthy food. Despite all these advantages, scientific improvement on the crop has lagged far behindthe level made for the major cereals such as wheat and rice. Consequently, tef is considered as an orphan (or under-studied) crop, and its yield is one of the lowest compared to other major world cereals.

In order to increase tef productivity, various attempts were made using both conventional and modern breeding techniques. Using the conventional breeding techniques, about 32 improved cultivars have been released to the farming community. The modern techniques so far include marker development towards marker-assisted breeding and TILLING (Targeting Induced Local Lesions IN Genomes). The tef genomics research has also developed PCR-based markers in attempts towards utilizing them in marker-assisted selection (MAS). The Tef Genome Sequencing Project has also been initiated in order to obtain substantial genomic and transcriptome sequences. In general, these biotechnological and genomic tools would play key role in designing tef for the future challenging environments. Cropping systems and agronomic studies have also been done at many locations representing different agro-ecological zones. Moreover, extensive studies have been made on the utilization of tef both for human food and livestock feed. Mechanization especially the harvesting process is the outstanding problem in tef cultivation as tef is severely affected by lodging. Significant progresses have also been made in socio-economic studies and dissemination of tef technologies to farming communities.

Hence, this international workshop on tef research and development was held i) to review previous studies and achievements made on tef research and development, and ii) to set strategies for future research. At this juncture, we would like to express our sincere gratitude to the Syngenta Foundation for Sustainable Agriculture, the Ministry of Science and Technology, Sasakawa Global 2000, the Ethiopian Institute of Agricultural Research, and the University of Bern for sponsoring the workshop, and the Syngenta Foundation for Sustainable Agriculture for covering the entire cost of printing the proceedings.

Editors, December 2012

Table of Contents

Opening Session

Welcome Address

Kebebew Assefa

National Coordinator of the Tef Research Project, Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O. Box 32, Debre Zeit, Ethiopia

Dear Dr. Solomon Assefa,
Director General, Ethiopian Institute of Agricultural Research

Distinguished Guests from Abroad,
Dear Workshop Participants and Colleagues,
Ladies and Gentlemen,

On behalf of the Ethiopian Institute of Agricultural Research and the Organizing Committee of this workshop, and on my own, I would be glad to warmly welcome you, all our participants, to the Second International Workshop on Tef Improvement: Achievements and Prospects.

We thank the international participants for accepting our invitation; for traveling several thousand kilometers and spending their valuable time with us to participate on this workshop. Furthermore, I know that most of you, the local participants, are currently busy with field research activities, and we greatly appreciate your cooperation in preparing paper presentations and for your time to be here with us for the next three days.

It is to be recalled that the first-ever workshop in tef in its history of over half a century of research was carried out from 16-19 October 2000, almost exactly before 11 years. Ever since, and particularly as a decade went on after that, we were not certain of having a second one. Nevertheless, thanks to our sponsors, it so happened that we have been able to organize this Second international Workshop. And, as such not only are we proud of it, but we also feel that it is organized at a very good time of the year.

Dear Participants,

This workshop is organized with the following quadruple objectives:

i) To review tef research undertakings (both conventional and biotechnological) over the past decade with a focus on the major achievements and progress made;
ii) Based on the review, to discuss and design strategies and a roadmap for future tef research directions;
iii) To create awareness on tef and promote research linkage with the international scientific community; and
iv) To produce an updated comprehensive reference material on tef on top of that produced through the first workshop.

As part of the efforts to meet these objectives, the Organizing Committee has worked hard to identify and select topics for presentations. The Committee has also ensured that this workshop offers you a blend of brainstorming sessions and field visit to see tef research activities. For some of you, this may be the first opportunity to see this unique cereal crop, and appreciate its roles towards the food security of Ethiopia, which has about 80 million people.

Dear Participants,

In this workshop a total of 23 papers will be presented. The subjects covered are from conventional to modern biotechnological approaches of tef improvement. This workshop is special not only in the sense that we will be hearing about the advances in genomics and other areas of research on tef, but also we are expected to work out the road map strategies for the future improvement of the crop.

We sincerely hope that at the end of this workshop you will leave the venue of the workshop, Debre Zeit, with a sense of satisfaction over what you have accomplished.

Having said so much by way of brief remarks, allow me to conclude by respectfully calling upon Dr. Solomon Assefa, Director General of the Ethiopian Institute of Agricultural Research, to deliver the opening remarks and officially open the Second International Workshop on Tef Improvement: Achievements and Prospects.
Welcome again to our Workshop!

Thank you!

Opening Address

Solomon Assefa

Director General, Ethiopian Institute of Agricultural Research, P.O. Box 2003, Addis Ababa, Ethiopia

Distinguished speakers from abroad,
Dear local speakers and participants,
Ladies and Gentlemen,

On behalf of the Ethiopian Institute of Agricultural Research and myself, I once again welcome you to the International Workshop on Tef Improvement: Achievements and Prospects. This workshop is organized at a wonderful time of the year in Ethiopia, and I hope that you will enjoy being here. The crops in the field are at the grain filling stage and approaching maturity, and I hope you will be able to see tef in the field during this workshop.

Tef is a major staple cereal crop of Ethiopia. Ethiopia is the center of both origin and diversity for tef. Tef is annually cultivated on about 2.8 million hectares of land, thereby covering about 28% (largest) of the total acreage of cereals, and accounting for about 23% of the total area of all grain crops, and about 22% of the whole area cultivated to annual field crops. Its area is expanding from time to time. For example, a 15% increase was noted in 2009/10 as compared to that in 2005/06. The expansion of the tef acreage is continuing without any promotion of tef culture, and amidst several cereal crops that are also being cultivated. With an average of 3.18 million tons of grain per year, tef constitutes about 21% of the gross yearly grain production of cereals, about 18% of all grain crops, and 17% of the gross production of all annual field crops grown in the country.

Dear Workshop Participants,

Because tef is endemic to Ethiopia, it is hardly known or grown anywhere else as a food crop. It has been bypassed by the international scientific community and funding agencies for a long time. In order to meet the food requirement of the ever-increasing population of Ethiopia, the current level of tef production should be increased. At this juncture, it may be in order to quote what His Excellency PM Meles Zenawi has once said: *"Unless a miracle happens, tef will cease to be the* *staple food for many Ethiopians"*. The needed increase in tef productivity and production can be achieved through genetic improvement and optimization of the crop management practices. Efforts have been made locally to address these issues during the past fifty years. However, progress is sl ow because of lack of basic knowledge on tef biology, and shortage of trained manpower and facilities. We can witness that the remarkable progresses made in the other major world cereal crops such as wheat, rice and maize is as a result of prior acquisition of basic knowledge and its application towards the development of high yielding varieties in the midst of adequate funding and trained scientists. To a great extent, tef has remained excluded from plant science advances, thus being categorized as "orphan", "neglected" or "underutilized" crop. However, beginning in the middle of the 1990's interest in tef increased and through the help of the McKnight Foundation and the International Atomic Energy Agency (IAEA) current advances in biotechnology have begun to be applied to tef research. This has been pursued not only through the McKnight Foundation but also through the support of a tef improvement project in the University of Bern through Syngenta Foundation for Sustainable Agriculture.

The McKnight Foundation's Collaborative Crop Research Program supported Tef Research project which has still being going-on since the mid-1950s, and has helped us to acquire knowledge on tef at the molecular level, to train Ethiopian researchers and to improve our research facilities. The Tef Improvement Project at the University of Bern has further inculcated the TILLING approach to solving the problem of lodging in tef and also for the first time to sequencing the whole genome of tef. The Syngenta Foundation for Sustainable Agriculture, apart from funding the Tef improvement Project in the University of Bern, has also made this workshop possible along with other sponsors. On behalf of EIAR, I extend my sincere appreciation for the help of both the McKnight Foundation and Syngenta Foundation for Sustainable Agriculture. For those of you who are not familiar with the McKnight Foundation, it is a private philanthropic organization established in 1953 by William L. McKnight and his wife Maude L. McKnight in Minneapolis, Minnesota, USA. The Foundation established the Collaborative Crop Research Program in 1993 to support research and training devoted to improving food security and human nutrition in the developing countries of Asia, Africa, and Latin America. Through the support of the McKnight Foundation the tef improvement project were able to develop PCR based markers, and tef linkage and QTL maps.

It is also worth mentioning that the International Atomic Energy Agency (IAEA) has supported the tef research under the technical cooperation project entitled

'Improvement of Tef through Mutation Breeding and *In Vitro* Techniques' through the then Ethiopian Science and Technology Commission, and now the Ministry of Science and Technology. Through this project, the Tef Research Program at Debre Zeit has acquired an irradiation facility and a small and modest tissue culture laboratory and has trained researchers; although retaining trained personnel is an on-going problem in our country.

Dear Workshop Participants,

It is to be noted, at this juncture, that the Ethiopian government has in recent years given due emphasis to the development and transformation of the Ethiopian Agriculture in general and that of tef crop in particular. The emphasis given to tef research and development has been obvious as tef is one of the domain crops of transformational undertakings under the recently established Agricultural Transformation Agency. Concurrent to the emphasis given by the government, the role of the national agricultural research system in the agricultural transformation is unequivocally recognized. To this effect, EIAR has been strategizing and doing its level best towards accomplishing its expected national mandates and responsibilities towards the required development of the agriculture sector.

The TILLING and Eco-TILLING work being undertaken at the University of Bern through the support of the Syngenta Foundation for Sustainable Agriculture and other genomics research activities being undertaken through various collaborative projects are, needless to say, of high importance to tef for transferring knowledge from other highly studied crops to tef and thereby allowing tef to benefit from the current advances of molecular biology in resolving its major agronomic constraints such as in tackling the lodging syndrome.

I believe that this workshop is another means that will help us to further strengthen our research strategy for the coming five to ten years. As its very title itself implies, this workshop is organized with the following objectives:

i) To review past and current tef research undertakings (both conventional and biotechnological) and outline future research directions;
ii) To create awareness on tef and promote research linkage with the international scientific community; and
iii) To produce an updated comprehensive reference material on tef on top of that produced through the first workshop.

I feel that this workshop will come up with appropriate research recommendations, research linkages and networks for tef that will allow us tackle its problems and increase its productivity, and thereby impart impacts that transcend beyond ensuring food security in Ethiopia.

I wish you all a successful workshop. I hope that those of you who came from abroad will enjoy your stay in Debre Zeit, and EIAR will do all it can to facilitate and make your stay enjoyable. I would like to ex tend my sincere thanks to t he Organizing Committee members for their time and energy to bring this workshop together as an event of the second in its kind in the whole history of tef research. Once again, I extend my appreciation to Syngenta Foundation for Sustainable Agriculture, SG2000, the Ministry of Science and Technology, and the University of Bern for sponsoring and making this workshop possible.

Dear Participants,

Last but not least, it is my great pleasure to declare the "Second International Workshop on Tef Improvement: Achievements and Prospects" open.

Thank you very much!

Keynote Address
Tef: the Ethiopian Miracle Crop
Past, Present and Future

Tareke Berhe
Tef Value Chain Adviser, Ethiopian Agriculture Transformation Agency, P.O.Box 708, Addis Ababa, Ethiopia

Ladies and Gentlemen,

It is a great honor and privilege for me to stand in front of this prestigious audience and deliver the keynote address. I began loving the tef crop back in 1969, when I did my senior research work on it at the then Alemaya College of Agriculture and Mechanical Arts. That love did not diminish since I continued my masters and PhD research works also. Conditions separated us during the 1982-2009 period (27 years) but now destiny has brought us back together again. I must be one of the few lucky ones to start my profession on tef and get a second chance so that I can end my career and life with the crop which is very close to my heart.

The year 2011 in the Gregorian (or 2003/2004 in the Ethiopian) Calendar can be remembered as the year for the re-birth or renaissance of tef. Equally important and memorable event to the decision of harnessing the Blue Nile River was the recognition of tef by the present Ethiopian Government as an important and priority crop worthy of focused research and development. That is one of the reasons why I chose the title “Tef is no more orphan” for my keynote address. The organization of this workshop is then very timely and critical for tef to hold its right place in the arena of important crops. My heart- felt gratitude and congratulations to the organizers.

Before elaborating on the current situation and future prospects of tef, it is befitting to touch on the past. I would like to underline and recognize individuals and institutions - both national and international- that kept the tef candle burning and protected it from being extinguished. I am sure that I will miss many names (my sincere apologies for that). But, if I may be allowed, let me mention some of the important contributors to t ef research and development. To start from national institutions, the Ministry of Agriculture, the Jimma and Haramaya Colleges of

Agriculture, Debre-Zeit Agricultural Experiment Station and the Institute for Biodiversity Conservation can be cited. Among the many Ethiopian individuals who contributed immensely to tef research and development can be mentioned: Dr. Melak Hail Mengesha, Dr. Tesfaye Tessema, Dr. Taddesse Ebba, Dr. Seyfu Ketema and Dr. Hailu Tefera. Among scientists currently working on tef can be listed as Dr. Zerihun Tadele, Dr. Kebebew Assefa, Dr. Solomon Chanyalew and Dr. Likyelesh Gugsa. At the International level, Dr. Mark Sorrells of Cornell University and Dr. A. Tavassoli and Dr. B.M.G. Jones of Royal Holloway College, University of London come to mind for their valuable contributions to tef chromosome mapping and tef cytology, respectively. Several international universities and institutions have also played a critical role in adding knowledge to tef science. Out of a host of others, the Rockefeller Foundation, the McKnight Foundation and the Syngenta Foundation for Sustainable Agriculture stand out as contributors to the education of tef scientists, to tef chromosome mapping and to TILLING and genome sequencing, respectively. The ODA (UK) and CADU also deserve recognition. Many US Universities – Cornell, Purdue, Oklahoma, Nebraska, the Royal Holloway and Wye Colleges of the University of London and others have also contributed by hosting and allowing Ethiopian students do their studies on tef. USAID, USDA, Joint FAO/IAEA Division, SIDA/SAREC and the Swedish University of Agricultural Sciences (SLU) have also played significant roles. Our heartfelt gratitude to all of them and also to those we have failed to mention.

Data from the Central Statistics Agency reports that tef area and production have been increasing at an average rate of >4% per annum in the last decade. There was a logical reason for this continuous increase. I am sure that many of the speakers in this workshop will elaborate on the importance of tef in the Ethiopian diet and economy and therefore, I will not dwell on that. It is worth mentioning, though, that at the moment tef demand must have surpassed its supply since its price has sky-rocketed and has become prohibitive to many. Here, allow me to quote Prime Minister Meles who rightly said, "*unless some sort of miracle is created, tef will cease to be the daily staple for the majority of Ethiopians*". It is my earnest wish and hope that this group and workshop will help in the making of the needed miracle.

I just want to state that "Tef is 100% Ethiopian". It is as Ethiopian and as indigenous as the Nile River, the Stele of Axum and the Hewn Churches of Lalibela. I also believe that tef will live as long as Ethiopians are present on this earth. This year, Ethiopians have tied their shoes, tightened their belts and searched their pockets for development. It is high time that tef also gets its chance to develop with its people.

The world has seen significant advances and productivity increases (known as the Green Revolution) in many of the staple cereal crops: wheat, maize, rice, sorghum, etc. As a member of this family of Gramineae, tef is no exception, and therefore has a similar potential for improvement. A huge natural variability exists in tef but this enormous wealth has yet to be tapped. There already are indications that the variability can be put to good use. The very popular varieties known as *Magna* (DZ-01-196), *Enatit* (DZ-01-354), *Dessie*, *Gea Lammie*, *Fesho* and a host of many others were mass selected from natural populations. Moreover, crossbreeding has produced the improved varieties such as *Quncho* (DZ-Cr-387) and *Tsedey* (DZ-Cr-37).

A modest breakthrough occurred in 1974 when this author discovered the opening and pollination period of tef florets that occurs early in the morning between 6:00 and 6:45 a.m. This discovery came as a result of suspecting that tef pollination may occur at a specific time period. A decision was made to pollinate specific emasculated florets repeatedly every hour or every two hours starting around 8:30 to 9:00 a.m. which led to the observation that fluffy and shiny stigmas full of pollen grains were observed only at that time. This led to the breeder checking half an hour and an hour earlier. It was then discovered that at 6:30 am, florets ready for pollination that day were found completely open. That permitted for the classical tef cross-breeding breeding program to begin. The current outstanding varieties in use *Tsedey* and *Quncho* which have enabled farmers to produce up to 3 tons ha^{-1} are products of the cross breeding program.

In the last two years, another breakthrough has occurred. This time it is in the agronomic management of the crop. The change involves in (i) reducing seed rate to one-tenth of that normally used, (ii) planting in rows rather than broadcasting, and (iii) using a more balanced plant nutrient (NPK + micro-nutrients) instead of just di-ammonium phosphate (DAP) and Urea as was the case for decades in Ethiopia. This type of management has shown a doubling and sometimes tripling of yields of both grain and straw. This will be explained further in one of the presentations in this workshop. But, it is worth mentioning that the above package is being tested this season on more than 1,500 farmers' fields in four regions with over 90% success. Yields of 5 tons/ha and above are expected in several cases. The country is posed to scale up this technology in the coming and following crop seasons with the objective of doubling production during the current five-year plan.

From what has transpired to date, it is quite evident that tef has a bright future. It is not a crop that can be considered “minor”, “forgotten” or “orphan” as many authors try to classify or depict it in cited literature. It is a crop with great importance to more than 60% of the over 80 million Ethiopian population and also one that has tremendous potential to become a world dietary/health crop. What it needs is a focused attention to be rendered to it as was done for other cereals in terms of intensive breeding—both conventional and non-conventional-and agronomic research.

This workshop is v ery appropriate and timely in that it will help to bring out the developments achieved to-date and point out the challenges that remain. There is no doubt that the Ethiopian Government is keen in pushing tef research and development to big heights. It is my hope that the international development community will also come aboard to render its usual support.

Ladies and Gentlemen,

Let me conclude by wishing all of us a very fruitful workshop - one that will concretely map out the way forward for an action-oriented tef research and development strategy recommendations that will guarantee all Ethiopians with ample supply of tef, their favorite crop, without forgetting that the crop has also a potential to develop as a world crop.

I thank you for your kind attention!

I. Germplasm, Breeding & Tissue Culture

1. Genetic Resources of Tef in Ethiopia

Alganesh Tesema
Institute of Biodiversity Conservation (IBC), P.O. Box 30726, Addis Ababa, Ethiopia.
Email: Adishihu@yahoo.com

The Ethiopian diversified agro-ecology and culture makes the country to be the center of origin and diversity for many economically important crops including tef [Eragrostis tef (Zucc.) Trotter*], which belongs to the Grass or Poacea family and the genus Eragrostis. This genus comprises about 350 species of which 54 are found in and 14 are endemic to Ethiopia. Tef is an allotetraploid and the sole cultivated species in the genus Eragrostis, and it is believed to be originated from Eragrostis pilosa (L.) Beauv and other species. The crop is widely cultivated in Ethiopia as a staple cereal crop. It adapts to diverse types of environmental stresses including drought and waterlogging. Large number of variants has been observed within the existing tef genetic resources. Amonf the traits depicting huge variability are days to maturity (60 to 120 days), number of grains/plant (9,000 to 90,000), plant height (31 to 155cm), tillering capacity (5 to 35 tillers/plant), panicle type (very loose open to very compact), and flag leaf area (2 to 26 cm^2), culm diameter (1.2 to 5 mm). The Institute of Biodiversity Conservation (IBC) of Ethiopia makes regular collection of tef accessions from diverse agro-ecological regions in the country in order to reduce genetic erosion and conserve the native genetic resources. So far, 5169 tef accessions and 10,000 tef genotypes are available at the institute. From these genotypes, 114 types of panicle forms were identified of which 94 were present in rare frequency (< 1%). Five variants contribute for lodging resistance. Since the tef landraces have particularly in recent years been under increasing threats of replacement by high-yielding and improved varieties, appropriate conservation measures should be taken in order to harness the valuable and unique characters of the landraces.*

Key words: *Eragrostis tef*, tef accessions, collection, conservation, maintenance, utilization

1.1. Introduction

Due mainly its diverse agro-ecologies and culture, Ethiopia is the center of origin and genetic diversity for many economically important crops including tef [*Eragrostis tef* (Zucc.) Trotter], noug [*Guizotia abyssinica* (L.f.) Cass.], enset [*Enset ventricosum* (Welw.) Cheeseman], coffee [*Coffea arabica* L.], khat [*Catha edulis* (Vahl.) Forssk. ex Endl.], and Ethiopian mustard or *gomenzer* [*Brassica carinata* A. Braun] (Vavilov, 1951). Like all other cereal crops, tef belongs to the Poacea or Grass family and believed to be first domesticated by pre–Semitic inhabitants in Ethiopia between 4000 and 1000 B.C. The crop species is an allotetraploid believed to have originated from *Eragrostis pilosa* (Endeshaw and Lester, 1981). It is also considered native to Northern Ethiopia, although so far only five wild types or accessions were collected from only the lowlands in the North East and South East Ethiopia (Tadesse, 1975).

Tef is widely cultivated throughout Ethiopia as a staple cereal crop. The tef collections of landraces maintained at the Institute of Biodiversity Conservation represent altitudes ranging from 800 to 3200 m. a.s.l. Tef adapts to extreme environmental conditions which include both drought and waterlogging. In the genus *Eragrostis*, there are about 350 species in the tropical and subtropical regions (Pankhurst, 1995). Among these, 54 species are found in Ethiopia from which 14 are endemic. However, attempts have not so far been to collect and conserve them. Tef is the only cultivated species in this genus *Eragrostis,* and together with finger millet *(Eleusine crocana* L.*),* they are the only two species in the sub-family Chloridoidae that are cultivated for human consumption of the grains.

1.2. Tef Germplasm Collection and Conservation

The available data to-date indicates that the world-wide collections of tef germplasm accessions amounts to about 5966 samples, and of this only about 13.4% (i.e. 797 accessions) are known to be present in institutions outside Ethiopia (Table 1).

In a review of the tef genetic resources of Ethiopia, Abebe (2001) reported the then total IBC holdings of tef germplasm accessions to be 4300. But since then the number has to-date rose to a total of 5169 accessions through the new collections made after the year 2000. Of the total of 5169 accessions under the holdings of the IBC, only 2533 accessions have got some necessary passport data, while the remaining 2636 accessions lack passport data as they were collected from various markets and/or obtained through repatriations of collections made by different individuals (Fig. 1.) Disaggregation of the 2533 collections having passport data based on altitudes of origin indicates that most (about 43%) of the collections were from regions with altitudes in the range of 2000-2500 meters above se level followed by collections (about 40%) from altitudes in the range of 1500-2000 meters above sea level (Fig. 1).

Table 1. Summary of world-wide tef germplasm collections [Source: adopted and updated from Seyfu (1997)].

Source /Institution	No. of samples or accessions
Ethiopia, Institute of Biodiversity Conservation (IBC), P.O.Box 30726, Addis Ababa, Ethiopia	5169
Germany, Institute of Crop Science, Federal Research Center for Agriculture (FAL), Bundesallee 50, 38116 Braunschwelg	30
Germany, Institute for Plant Genetics and Crop Plant Research, (IPK) - Genebank, Correnstr 3, 06466 Gatersleben	5
Japan, Department of Genetic Resources, I Nat. Inst. of Agrobio. Resources, Tsukuba-gun, Ibaraki-ken 305, 1-1 Kannondai, 3-Chone, Yatabe-Machi	30
Yemen, Agricultural Research and Extension Authority, P.O.Box 87148, Dhamar, Republic of Yemen	2
Russia, N.I. Vavilov All-Russian Research Institute of Plant Industry, Bolshaya, Morskaya Str. 44, St. Petersburg, 190000, Russian Federation	14
Slovak Republic, Botanical Garden of the University of Agriculture, Trieda A. Hlinku2, Nitra	1
South Africa, Division of Plant and Seed Control. Dept. of Agric. Tech. Service, Private Bag X179, Pretoria	3
UK, Welsh Plant Breeding Station, Inst. of Grassland and Environ. Res., Plas Gogerddan, Aberystwyth, Dyfed SY23 3EB	3
USA, National Seed Storage Laboratory, USDA-ARS, Colorado State University, Fort Collins, Colorado 80523	341
USA, Western Region Plant Introduction Station, USDA-ARS, Washington State University, 59 Johnson Hall, Pullman, WA 99164-6402	368
Total	5966

In general, the tef landrace collections of the IBC holdings were made from regions with altitudes ranging from 800 to 3200 m. a. s.l. Most Ethiopian farmers grow tef landraces. The selection criteria for the type of landrace vary from farmer to farmer. Although some landraces perform at only specific agro-ecologies, the majority of accessions are present in most regions. While early maturing landraces are commonly found in the lowland areas with moisture scarcity, late maturing landraces are prevalent in the highland areas with long growing period.

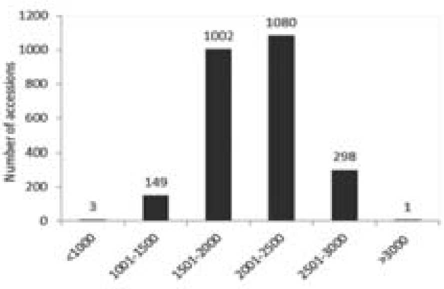

Figure 1. The number of IBC holding tef collections from diverse altitude ranges. Out of the total 5169 tef accessions currently available at the IBC, 2636 accessions were collected from markets in different parts of the country are excluded from this figure.

The main conservation strategy is *in-situ* conservation. However, the fate of this strategy has been managed/decided by the preference of traditional farmers. Therefore, to sustain the conservation, it is essential to complement with *ex-situ* conservation. Hence, the Ethiopian Institute of Biodiversity Conservation (IBC) made some efforts to explore and collect the tef germplasm. So far, 5164 accessions of tef landraces and 5 accessions of wild relatives are conserved in the national gene bank of Ethiopia. The accessions were collected from the former twelve administrative regions representing diverse agro-ecological zones. All accessions are stored at -10 ^{o}C under long-term storage.

1.3. Genetic Variability and Diversity in Tef Accessions

Tef is highly diverse and variable in terms of morphological and agronomic parameters (Melak Hail, 1965; Seyfu, 1993; Tiruneh et al., 2000; Kebebew *et al.*, 2001). The distribution of the crop in different agro-ecological zones coupled with the wise selection of farmers resulted in a number of variants with unique characters. Parameters or characters with huge variability include days to maturity (60 to 120 days), number of grains/plant (9,000 to 90,000 seeds), plant height (31 to 155 cm), number of tillers/plant (5 to 35), panicle type (from very loose open to very compact), flag leaf area (2 to 26 cm^2), culm diameter (1.2 to 5 mm) (Seyfu, 1993; Kebebew *et al.*, 2001). These accessions with substantial variability are currently being evaluated by breeders and other researchers in order to incorporate their useful traits into the improved tef varieties to be developed.

However, this genetic variability is rapidly declining as farmers are quickly adopting to grow improved cultivars instead of landraces. Hence, in order to reduce the expected genetic erosion, the Institute of Biodiversity Conservation made rescue collections from different agro-ecological zones. From 10,000 genotypes analyzed, 114 types of panicle forms were found of which 94 are rarely present. The same investigation also showed that five variants were obtained for resistance to lodging.

1.4. The Way Forward

The following five points are suggested regarding tef germplasm collection, conservation and utilization:

i) to collect and conserve genetically variable landraces from diverse localities in each agro- ecological zones;
ii) to perform detailed characterization and evaluation of the existing tef accessions;
iii) to implement molecular techniques in the characterization of the landraces already conserved at the IBC;
iv) to learn from farmers' indigenous knowledge, valuable information and/or practices useful in the selection and conservation of germplasm; and
v) to provide incentives to farmers in order to encourage them to grow landraces on their fields.

1.5. Abbreviations

IBC: Institute of Biodiversity Conservation; **IFPRI**: International Food Policy Research Institute; **m.a.s.l**: meter above sea level.

1.6. References

Abebe Demissie. 2001. Tef genetic Resources in Ethiopia. *In*: Hailu Tefera, Getachew Belay and Mark Sorrells (eds.). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia, 16-19 October 2000, p27-31.

Endeshaw Bekele and Lester RN. 1981. Biochemical assessment of the relationships of *Eragrostis tef* (Zucc.) Trotter with some wild *Eragrostis* species (gramineae). Ann. Bot. 48: 717 -725.

Kebebew Assefa, Seyfu Ketema, Hailu Tefera, Fufa Hundera, Tiruneh.Kefyalew. 2001. Genetic diversity for agronomic traits in tef. *In*: Hailu Tefera, Getachew Belay and Mark Sorrells (eds.). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia, 16-19 October 2000, p33-48.

Melak Hail Mengesha, Pickett RC, and Davis RL. 1965. Genetic variability and interrelationship of characters in Tef, *Eragrostis tef* (Zucc.) Trotter. Crop Sci. 5:155-157.

Pankhurst S. 1995. Flora of Ethiopia, volume 7, the National Herbarium, Biology Department, Science Faculty, Addis Ababa, University, Ethiopia and the Department of Systematic Botany, Uppsala University, Sweden, April 1995.

Seyfu Ketema. 1993. Tef, (*Eragrostis tef*): Breeding, genetic resources, agronomy, utilization and role in Ethiopian agriculture. Institute of Agricultural Research, Addis Ababa, Ethiopia.

Seyfu Ketema. 1997. Tef (*Eragrostis tef* (Zucc)Trotter). Promoting the conservation and use of under utilised and neglected crops. 12. The Institute of Plant Genetics and Crop Plant Research. Gatersleben/International Plant Genetic Resources Institute). Rome, Italy.

Tadesse Ebba. 1975. Tef (*Eragrostis tef*) cultivars; Morphology and classification. Part II. Expt.Sta. Bull. No. 66. Addis Ababa University, College of Agriculture. Dire Dawa, Ethiopia.

Tiruneh Kefyalew, Hailu Tefera, Kebebew Assefa and Mulu Ayele. 2000. Phenotypic diversity for qualitative and phenologic characters in germplasm collections of tef (*Eragrostis tef*). Hereditas 47: 73–79Vavilov I. 1951. The Origin, Variation, Immunity and Breeding of Cultivated Plants. Translated from the Russian by K. S. Chester, The Ronald Press Co, New York, USA.

2. Phenotypic and Molecular Diversity in Tef

Solomon Chanyalew*, Kebebew Assefa and Gizaw Metaferia
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O. Box 32, Debre Zeit Ethiopia. *Corresponding author: solchk2@gmail.com

Analysis of germplasm diversity and genetic relationships in tef (Eragrostis tef) constitutes an important component of crop improvement programs, where options for the introduction of genetic stocks from abroad are almost inexistent. Over the past years a number of methods have been employed to analyze the extent of genetic diversity in tef germplasm accessions and breeding lines. The methods have relied on morphological, agronomic performance, biochemical, and molecular markers. Broad genetic diversity in most of the analyzed traits has been reported in all the studies. Nevertheless, the observed variation for some of the most important traits such as lodging resistance is not enough to bring about a satisfactory level of lodging resistance. Results of the molecular work also indicated absence of significant associations between the analyzed markers including those flanking lodging QTLs and any of the lodging related traits. In this paper attempts are made to present an overview of the extent and patterns of genetic diversity in tef.

***Key words**: phenotypic diversity, genetic diversity, molecular diversity, *Eragrostis tef**

2.1. Introduction

Analysis of genetic relationships in tef [*Eragrostis tef* (Zucc.) Trotter] is an important component of improvement programs of the crop, because it provides information about the genetic diversity of the crop, and sets a platform for stratified sampling of breeding populations. Ethiopia is the origin and center of diversity for tef (Vavilov 1951), and the country harbors landraces with a wide array of phenotypic diversity, and also wild progenitors and related wild species. This genetic diversity is the capital for current and future improvement of the crop since options for introduction of genetic stocks from abroad are almost none-existent. Tef represents a unique biodiversity component in the agriculture and food security systems of millions of poor farmers in Ethiopia. It possesses excellent adaptation to drought and poor soils, providing a reliable harvest under such conditions, growing where most crops do not succeed, and providing good nutritional sources. However, the crop suffers neglect in science despite increasing awareness of plant genetic resource conservation and local food security concerns. The conservation, use and availability of tef genetic diversity are increasingly important in view of the evolving needs and manifold challenges of small-scale farmers in Ethiopia. This is primarily because tef signifies remarkable genetic resources available at the grassroots level to address and cope up with erratic climatic conditions prevailing in the country, and also in terms of household income and nutrition concerns. Moreover, it makes up a reliable basis for enhancing food security and developing crop diversification in the moisture stress and challenging agroecological areas of the country. Genetic diversity analysis of the tef germplasm accessions facilitates the development of improved varieties to achieve high productivity and yield stability. In view of this fact, efforts have been made in the past to assess and quantify the genetic diversity in the tef germplasm collections using different approaches. The first comprehensive review paper on tef genetic diversity was made about a decade ago by Kebebew et al. (2001a). In the present paper, we give the extent and patterns of genetic diversity in tef based on previously published data. Studies of the phenotypic and molecular diversity in tef were assessed based on phenological, morphological, and DNA markers.

2.2. Phenotypic and Morphological Diversity

Melak-Hail et al. (1965) examined the phenotypic diversity in tef germplasm in a pot experiment using 124 single panicle sample collections from the major tef producing areas in Ethiopia. The analysis showed substantial variability for traits such as plant height, panicle length, maturity, seed color, seed yield, lodging and panicle type. The study by Seyfu (1993) involving 2255 tef lines collected since 1958 from different parts of the country was an extensive evaluation of the germplasm for 15 morpho-agronomic traits. The results showed that out of the 15 morpo-agronomic traits assessed, relatively high simple coefficients of variation (SCV) were observed for flag leaf area (52%), single plant grain yield (48%), and straw yield (39%). The analyses of 9885 germplasm accessions collected from 14 former provinces of Ethiopia showed SCV estimates ranging from 32% for primary panicle branches to 160% and 217% for spikelet length, and grain yield/plant, respectively (Endeshaw, 1996). While using SCV, the extent of variation among traits is not affected by the magnitudes of values and units of measurement. Hence, rare but extreme traits might not be shown in the coefficient of variation. Better assessment of traits diversity could be done using phenotypic (PCV) and genotypic (GCV) coefficients of variation as they are based on partitioning of the total variance into components of genetic and non genetic factors.

Trait variances in tef were estimated using PCV and GCV in different tef genotypes. Tables 1 and 2 summarize the phenotypic (PCV) and genotypic (GCV) coefficients of variation and the range values, respectively, for different traits in tef as reported in different studies (Hailu et al., 1990; Fufa et al. 1999; Kebebew et al., 2000, 2001b; Solomon et al., 2009). Most of these studies revealed significant to highly significant differences among the genotypes for most of the traits examined and this variability would serve as a basis for the improvement the crop.

Since the magnitude of genetic variation is better assessed from GCV, breeders usually focus on traits with high GCV estimates. Accordingly, higher GCV values were reported for tiller number, panicle weight, grain yield per panicle, plant weight, and grain yield (Kebebew et al., 1999, 2001b; Alemayehu et al., 2003; Hailu et al., 2008; Solomon et al., 2009) (Table 1). The reported wide genetic variation presents the scope for improving the crop through direct selection and/or hybridization.

Given the ranges of plant height (20-156 cm), days to panicle emergence (25-81), grain filling period (29-76 days) and days to mature (50-140) observed in tef genotypes (Kebebew et al., 2001a) (Table 2), it should be possible to develop genotypes that flower or mature one to three weeks earlier or later than the medium maturing ones. The existence of variability in tef germplasm for culm internode diameter is one key factor among others to possibly identify tef lines with improved lodging resistance. On the other hand, no significant differences were obtained at diverse altitude zones for the parameters like days to panicle emergence, culm and panicle length, number of panicle branches, counts of fertile florets/spikelet, and shoot phytomass yield/plant (Kebebew et al., 2001a).

2.3. Clinal and Regional Diversity

Significant altitudinal diversity was reported in tef germplasm populations collected from different altitudinal zones for traits such as days to maturity, number of culm nodes, first and second basal culm internode diameter, and harvest index (Kebebew et al., 2001a). Likewise, (Kebebew et al., 2002) found significant altitudinal diversity in tef germplasm populations for traits such as main shoot culm node number, days to maturity, diameters of the first and second lowest primary shoot culm internodes, and harvest index. However, non significant differences for qualitative traits were reported among the altitudinal zones (Tiruneh et al., 2000). On the other hand, Kebebew et al. (2000) using 36 heterogeneous tef populations reported lower diversity levels for days to maturity between 1800m and 2400 m altitude. Highest diversity was reported for accessions obtained below 1800 m.a.s.l.

Table 1. Diversity levels for important traits as reported in different tef germplasm diversity evaluation studies*.

Trait	PCV (%)				GCV (%)			
	Ref. 1 (n=35)	Ref. 2 (n=20)	Ref. 3 (n=320)	Ref 4 (n=196)	Ref. 1 (n=35)	Ref. 2 (n=20)	Ref. 3 (n=320)	Ref. 4 (n=196)
Days to heading/ panicle emergence	12.3	4.3	28.1	8.7	12.2	3.8	19.4	6.1
Days to maturity	8.4	4.7	7.1	10.5	8.4	4.1	2.3	4.2
Grain filling period (days)	-	7.1	-	-	-	6.4	-	-
Plant height (cm)	13.5	2.8	-	15.5	13.4	1.9	-	9.1
Culm length (cm)	-	-	44.3	-	-	-	13.5	-
Peduncle length (cm)	23.3	-	23.6	-	-	-	0.1	-
Panicle length (cm)	18.8	10.8	38.5	16.8	18.7	8.6	35.3	10.4
Grain yield/panicle (g)	29.4	18.9	2.4	-	28.1	8.9	0.9	-
Grain yield/plant (g)	22.4	-	21.8	36.7	18.7	-	5.5	29.8
Shoot phytomass yield/plant (g)	-	-	48.0	22.5	-	-	10.4	23.7
Lodging index	-	9.9	-	17.9	-	-	-	15.3
Grain yield (kg/ha)	-	16.0	-	-	-	11.0	-	-
Harvest index (%)	-	15.7	71.8	16.3	-	10.2	27.1	25.8

*References: Ref. 1 = Hailu et al. (1990); Ref. 2 = Fufa et al. (1999); Ref 3 = Kebebew et al. (2000); Ref. 4 = Solomon et al. (2009)

Based on evaluations of 70 germplasm accessions of tef collected from different regions of Ethiopia, Dawit (1993) found significant variations within populations, among populations within regions, and among regions in most of the phenotypic trait. On the other hand, based on evaluations of 3600 tef lines which represent 36 populations collected from Central and Northern Regions of Ethiopia, Tiruneh et al. (2000) found significant regional diversity for seed color and days to maturity. In addition, Kebebew et al. (2002) reported significant regional diversity for lemma color, number of culm internodes, and counts of basal and middle spikelet florets in tef germplasm populations from different parts of the country.

Table 2. Ranges for important phenologic, morphological and agronomic traits of tef varieties (Source: Kebebew et al., 2001b)

Trait	Minimum	Maximum
Days to panicle emergence	25	81
Days to mature	60	140
Grain filling period (days)	29	75
Plant height (cm)	20	156
Culm length (cm)	11	82
First culm internode length (cm)	2.68	8.05
Second culm internode length (cm)	4.15	11.45
First and second culm internode diameter (mm)	1.2	4.5
Panicle length (cm)	10	65
Peduncle length (cm)	5.85	42.3
No. primary panicle branches	10	40
No. spikelet/panicle	30	1070
No. florets/spikelet	3	17
Grain yield/panicle (g)	0.11	2.5
No. tillers/plant (total)	4	22
No. tillers/plant (fertile)	1	17
Grain yield/plant (g)	0.54	21.9
Total phytomass/plant (g)	4	105
Hundred kernel mass (mg)	18.97	33.88
Grain yield (kg/ha)	1058	4599
Diameter of grains (mm)	0.5	1.0
Harvest index (%)	5	39
Lodging index	20	100

In an experiment at two locations using 144 germplasm accessions collected from different regions of Ethiopia, Temesgen et al. (2005) reported that germplasm accessions from the same origin clustered into different classes and those from different origins are also clustered into the same group. Kebebew et al. (2001a) also confirmed that the level of genetic diversity is higher in tef germplasm with in a region than between regions, and as a result, germplasm accessions originated from the same region and altitude were grouped into distinct and distant clusters. The observed results could be perhaps because of free exchange of germplasm between regions, and also due to the higher selection force applied for white seeded tef type, and loose panicle form by farmers in all regions. Farmer's interest to grow white seeded and high yielding tef types and as a consequence the expansion of improved varieties (particularly Quncho) by the current extension activities in many parts of the country could in the future be a threat to genetic erosion. The situation calls for systematic germplasm collection with the necessary passport data, evaluation, characterization, conservation and eventually utilization in the breeding program.

2.4. Molecular Diversity

Efforts have in the past been made to characterize and analyze the diversity levels in cultivars of tef, and its relatives based on approaches other than morphological or phenotypic data.

Of these, Endeshaw and Lester (1981) reported complex patterns of variation amongst tef cultivars using biochemical markers involving chromatography of leaf phenolics and electrophoresis of seed proteins. Endeshaw et al. (1995) using seed storage proteins (albumin, globulin and prolamin) based on SDS-PAGE reported polymorphism among tef cultivars, although it did not separate individual tef cultivars owing to the low number of protein markers. Likewise, sequence analysis of non-coding regions of chloroplast DNA, 18S rDNA, and the transcription factor VP1 (Pillay 1997, Epselund et al., 2000) did not show significant intra-specific variation among tef cultivars.

Genetic relationship among accessions of E. tef, E. pilosa and E. curvula which were collected from Ethiopia and USA were assessed based on AFLP (Mulu et al., 1999; Bai et al., 1999a; Mulu and Nguyen, 2000) and RAPD markers (Bai et al., 2000). These analyses depicted relatively low level (18%) of polymorphism and genetic variations within E. tef, and high similarity between E. tef and E. pilosa. In these studies, the Jaccard similarity coefficient among tef cultivars ranged from 84% to 96% for RAPD and from 73% to 99% for AFLP markers, thereby indicating very close similarity among accessions and consequently a low level of polymorphism. On the other hand, Kebebew et al (2003) using inter-simple sequence repeats (ISSR) analysis showed high diversity among tef cultivars with Jaccard similarity coefficients ranging from 26% to 86%.

Zeid et al. (2012) estimated genetic diversity and relationships among 326 tef accessions, 13 wild relatives, and four commercial varieties from the United States based on 39 SSR markers, 26 of which were flanking QTL intervals for stem strength related traits, yield and lodging index. The authors reported genetic similarity (GS) estimates of between GS=0.20 and GS=0.99 among tef accessions, and this is in contrast to the narrow genetic background suggested in earlier studies employing RAPD (Bai et al., 2000) and AFLP (Bai et al. 1999b) markers. Thus, the more recent study by Zeid et al. (2012) revealed a large base of genetic diversity, which could serve as a major source of diversity for the tef breeding program. However, the reported diversity particularly for lodging and related traits has never been sufficient to bring about the needed improvement in lodging resistance of the crop. Given the complexity of lodging and its component traits such as plant height, and culm internode length and diameter, it appears that for tef breeding, it is time to consider other alternative approaches including genetic transformation in line with marker assisted selection as a better biotechnological move towards improving the malignant lodging syndrome in the crop.

The study of Zeid et al. (2012) also revealed 27 cases where accessions were identical to one or more of the other accessions (Fig. 1). According to the authors, the high genetic similarity (GS) estimates from previous studies (Bai et al., 1999b; Mulu et al., 1999; Mulu and Nguyen 2000; Bai et al., 2000) using the same plant material (landraces), was a marker dependent issue rather than a low polymorphism in tef as previously suggested.

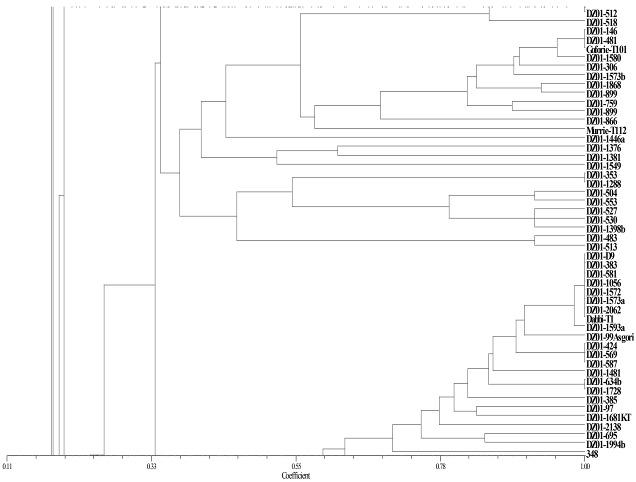

Fig. 1. Dendrogram showing the pattern of clustering for part of the 343 accessions analyzed based on SSR markers.

In the same study of Zeid et a l. (2012), 13 wild Eragrostis accessions were differentiated from the cultivated tef accessions on the PCoA coordinates from the cluster analysis (Fig. 2). Earlier studies using molecular markers (Mulu et al., 1999; Bai et al., 1999b; Mulu and Nguyen, 2000; Bai et al., 2000) also differentiated the three species; *E. tef*, *E. pilosa* and *E. curvula*.

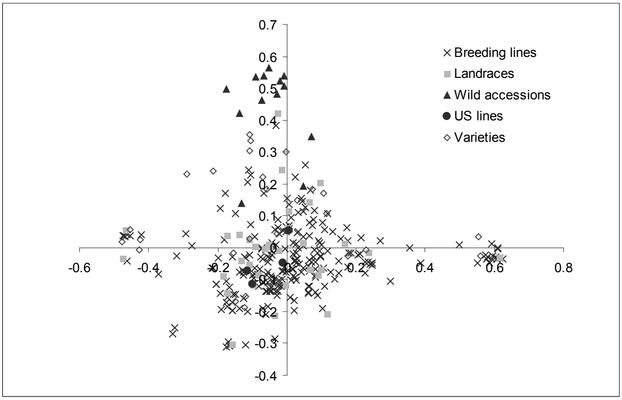

Fig. 2. Principal co-ordinate analysis of 326 tef accessions (breeding lines, landraces and varieties), 13 wild Eragrostis accessions, and four US commercial lines based on 47 loci (source: Zeid et al., 2012).

Seed admixture is a common problem in small grain cereals and can be detected using DNA markers. The seed admixture issue is more severe in tef because of the tiny seed size. To assess the effects of seed admixture on maintaining the genotype identity, Zeid et al. (2012) fingerprinted and compared two different seed lots of 12 tef lines based on SSR markers. The results revealed that only one line (DZ-CR-82) showed identical fingerprints between the seeds lots, and 3 lines shared a GS of less than 0.70, emphasizing the gravity of the seed admixture problem in tef. In general, maintaining pure seed stocks in tef is very hard because admixture can occur during any step of the seed handling process unless extreme care is practiced. According to the same authors, the close relationship between the line DZ-Cr-37 from the 2003 seed lot with DZ-Cr-385 (GS= 0.89) (a line derived from the cross of DZ-01-2785 x E. pilosa (30-5)) and Ho-Cr-136 (GS= 0.87) was unexpected.

2.5. Conclusions and the Way Forward

The range of variation in tef accessions is e normous and its agro-ecological amplitude can serve as a basis for developing genotypes for specific areas of adaptation. For example, the ranges of variation for days to heading (25-81) and maturity (60-120) in the tef germplasm offer opportunities to develop varieties suitable for both drought prone as well as high rainfall or optimum environments.

Although Ethiopia is the center of origin and diversity for tef, the current expansion of improved varieties (particularly Quncho) could in the future be a threat to genetic erosion due to the spread of improved varieties into many parts of the country. The situation warrants systematic germplasm collection with the necessary passport data, evaluation, characterization, conservation and eventually utilization in the breeding program. The use of DNA markers especially simple sequence repeats (SSR) or microsatellites in this regard is h ighly advised for fingerprinting/characterization and organizing of the entire tef germplasm, for reducing apparent duplications of lines, and to identify and verify hybrids from crosses between promising lines that lack morphological differences.

Given the complexity of lodging and its component traits in tef breeding, developing lodging resistant varieties using the usual classical breeding approach seems unachievable at least in the near future. Therefore, considering genetic transformation approach in line with marker assisted selection may be a better biotechnological move towards improving tef for lodging resistance.

2.6. Abbreviations

AFLP: amplified fragment-length polymorphism; **GCV**: genotypic coefficients of variation; **GS**: genetic similarity; **ISSR**: inter-simple sequence repeats; **PCoA**: Principal co-ordinate analysis; **PCV**: Phenotypic coefficients of variation; **RAPD**: random amplification of polymorphic DNA; **SCV**: simple coefficients of variation; **SSR**: Simple Sequence Repeats.

2.7. References

Alemayehu Balcha, Gretzmacher R and Vollmann J. 2003. Estimation of genetic parameters for grain yield and yield related traits in tef, Journal of Genetics and Breeding 57:251-257.

Bai G., Mulu Ayele, Hailu Tefera and Nguyen HT. 1999a. Amplified fragment length polymorphism analysis of tef [*Eragrostis tef* (*Zucc.*) Trotter], Crop Sci. 39, 819-824.

Bai G, Hailu Tefera, Mulu Ayele and Nguyen HT. 1999b. A genetic linkage map of tef [*Eragrostis tef* (*Zucc.*) Trotter] based on amplified fragment length polymorphism, Theor. Appl. Genet. 99, 599-604.

Bai G., Mulu Ayele, Hailu Tefera and Nguyen HT. 2000. Genetic diversity in tef [*Eragrostis tef* (*Zucc.*) Trotter] and its relatives as revealed by random amplified polymorphic DNAs, Euphytica 112, 15-22.

Dawit Tadesse. 1993. Study on genetic variation of landraces of tef [*Eragrostis tef* (Zucc.) Trotter] in Ethiopia, Genet. Resour. Crop Evol. 40: 101-104.

Endeshaw Bekele. 1996. Morphological analysis of *Eragrostis tef*: detection for regional patterns of variation, SINET: Eth. J. Sci. 19:117-140.

Endeshaw Bekeke, Fido RJ, Tatham AS and Shewry PR. 1995. Heterogeneity and polymorphism of seed proteins in tef (*Eragrostis tef*). Hereditas 122:67-72.

Endeshaw Bekele and Lester R.N. 1981. Biochemical assessment of the relationships of *Eragrostis tef* (Zucc.) Trotter with some wild *Eragrostis* species (Gramineae), Ann. Bot. 48:717-725.

Espelund M., Endeshaw Bekele, Holst-Jensen A, Jakobsen KS and Nordal I. 2000. A molecular genetic analysis of *Eragrostis tef* (*Zucc.*) Trotter: non-coding regions of chloroplast DNA, 18S rDNA and the transcription factor VP1, Hereditas 132: 193-202.

Fufa Hundera, Hailu Tefera, Kebebew Assefa, Tesfaye Tefera and Tiruneh Kefyalew. 1999. Genetic variability and correlation of morpho-agronomic characters in tef landraces, Trop. Sci. 39: 140-146.

Hailu Tefera, Getachew Belay and Kebebew Assefa. 2008. Genetic variation in F_2 populations and their potential in the improvement of grain yield in tef (*Eragrostis tef*), Euphytica 164, 105-111.

Hailu Tefera, Seyfu Ketema and Tesfaye Tesemma. 1990. Variability, heritability and genetic advance in tef [*Eragrostis tef* (*Zucc.*) Trotter] cultivars, Trop. Agric. 67: 317-320.

Kebebew Assefa, Hailu Tefera, Merker A, Tiruneh Kefyalew and Fufa Hundera. 2001a. Variability, heritability and genetic advance in phenol-morphic and agronomic traits of tef [*Eragrostis tef* (Zucc.) Trotter] germplasm from eight regions of Ethiopia, Hereditas 134: 103-113.

Kebebew Assefa, Hailu Tefera, Merker A, Tiruneh Kefyalew and Fufa Hundera. 2001b. Quantitative trait diversity in tef [*Eragrostis tef* (Zucc.) Trotter] germplasm from central and northern Ethiopia, Genet. Resour. & Crop Evol 48:53-61.

Kebebew Assefa, Merker A and Hailu Tefera. 2002. Qualitative trait variation in tef [*Eragrostis tef* (Zucc.) Trotter] germplasm from Western and Southern Ethiopia, Euphytica 127: 399-410.

Kebebe Assefa, Merker A and Hailu Tefera. 2003. Inter simple sequence repeat (ISSR) analysis of genetic diversity in tef [*Eragrostis tef* (Zucc.) Trotter], Hereditas 139, 174-183.

Kebebew Assefa, Seyfu Ketema, Hailu Tefera, Nguyen HT, Blum A, Mulu Ayele, Bai G, Belay Simane and Tiruneh Kefyalew. 1999. Diversity among germplasm lines of the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter], Euphytica 106: 87-97.

Kebebew Assefa, Seyfu Ketema, Hailu Tefera, Tiruneh Kefyalew and Fufa Hundera. 2000. Trait diversity, heritability and genetic advance in selected germplasm lines of tef [*Eragrostis tef* (Zucc.) Trotter], Hereditas 133:29-37.

Melak-Hail Mengesha, Picket R. C., Davis R. L. 1965. Genetic variability and interrelationship of characters in teff, *Eragrsotis tef* (*Zucc.*) Trotter, Crop Sci. 5: 155-157.

Mulu Ayele, Hailu Tefera, Kebebew Assefa, Nguyen H T. 1999. Genetic characterization of Eragrostis species using AFLP and morphological traits, Hereditas. 130, 33-40.

Mulu Ayele, Nguyen H. T. 2000. Evaluation of amplified fragment length polymorphism markers in tef, *Eragrostis tef* (*Zucc.*) Trotter, and related species, Plant Breed. 119, 403-409.

Pillay M. 1997. Variation of nuclear ribosomal RNA genes in *Eragrostis tef* (*Zucc.*) Trotter, Genome 40: 815-821.

Seyfu Ketema. 1993. Tef *(Eragrostis tef):* Breeding, Genetic Resources, Agronomy, Utilization and Role in Ethiopian Agriculture. Institute of Agricultural Research, Addis Ababa, Ethiopia.

Solomon Chanyalew, Hailu Tefera and Sigh H. 2009. Genetic variability, heritability and trait relationships in recombinant inbred lines of tef [*Eragrostis tef* (Zucc.) Trotter], Res. Journal of Agric. and Biol. Sci. 5: 474-479.

Temesgen Adnew, Seyfy Ketema, Hailu Tefera and Sridhara H. 2005. Genetic Diversity in Tef [*Eragrostis tef* (Zucc.) Trotter] Germplasm, Genetic Resources and Crop Evolution 52:891-902.

Tiruneh Kefyalew, Hailu Tefera, Kebebew Assefa and Mulu Ayele. 2000. Phenotypic diversity for qualitative and phonologic characters in germplasm collections of tef (*Eragrostis tef*), Genet. Resour. Crop Evol. 47: 73-80.

Vavilov I. 1951. The Origin, Variation, Immunity and Breeding of Cultivated Plants. Translated from the Russian by Chester KS, Ronald Press Co, New York, USA.

Zeid M, Kebebew Assefa, Aderajew Haddis, Solomon Chanyalew and Sorrells M. 2012. Genetic diversity in tef (*Eragrostis tef*) germplasm using SSR markers. Field Crops Research: 127: 64-70.

3. Conventional and Molecular Tef Breeding

Kebebew Assefa*, Solomon Chanyalew and Gizaw Metaferia
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O. Box 32, Debre Zeit, Ethiopia. *Corresponding author: Kebebew.Assefa@yahoo.com

Tef, Eragrostis tef (Zucc.) Trotter, is an important staple cereal crop in Ethiopia occupying the largest (28%) acreage of cereals in the country. In spite of its prime importance in the Ethiopian agriculture, the major bottlenecks constraining tef production are low yield of landraces under widespread cultivation, susceptibility to lodging and lack of basic knowledge concerning the genetic control of agronomic traits. Conventional tef breeding efforts started in the late 1950s, and since then a total of 32 varieties have been developed and released. The genetic grain yield gain through breeding for varieties released from 1970-1995 has been linear with an average annual increase of 0.8%. Tef genomics has provided much molecular genetic information on important agronomic traits. More than 1500 PCR-based molecular markers have been developed and several genetic linkage maps based on intra- and inter-specific crosses have been constructed. Although the results from quantitative trait loci studies have provided information necessary for marker-assisted selection, much work still remains before they can be used in practical tef breeding. Lodging still remains to be the number one constraint in tef production. It causes serious yield losses of up to 25%, while it also imparts various direct and indirect deleterious effects in tef husbandry. In recent years, modern genomics approaches and biotechnologies are being employed to understand the genetic control of lodging and develop lodging resistant or tolerant varieties.

Key Words: Conventional breeding, *Eragrostis tef*, lodging, molecular approaches, tef, varieties

3.1. Introduction

Tef is the most important cereal of Ethiopia accounting for about 28% of the total acreage and 21% of the gross grain production of all cereals (Table 1; CSA 2010). It is grown by over 5.6 million farmers' households, and constitutes the major staple food grain for over 50 million Ethiopian people. This implies that tef is very important in the overall national food security of the country.

Table 1. Cultivated area, gross grain production and average grain yield of cereals in 2009/10 main (*Meher*) season (CSA, 2010).

Crop	Cultivated area		Total grain production		Grain yield (ton ha^{-1})	No. of holders (million)
	Million ha	% of cereals	Million ton	% of cereals		
Tef	2.59	28.14	3.18	20.47	1.228	5.630
Maize	1.77	19.22	3.90	25.09	2.199	7.149
Wheat	1.68	18.23	3.08	19.80	1.827	4.666
Sorghum	1.62	17.53	2.97	19.13	1.421	4.072
Barley	1.13	12.30	1.75	11.27	1.550	4.365
Finger millet	0.37	4.00	0.52	3.37	1.421	1.347
Emmer/Oats	0.02	0.26	0.03	0.21	1.375	0.254
Rice	0.05	0.52	0.10	0.66	2.160	0.126
Total	9.23	100.00	15.53	100.00	-	-

The continued extensive cultivation of tef by the Ethiopian farmers is accentuated by a multitude of the relative merits of the crop over the other cereals with respect to both husbandry and utilization (Kebebew *et al.*, 2011; Seyfu, 1993). To this effect, its major relative merits in husbandry include: i) versatile agro-ecological adaptation (0-3000 m.a.s.l.) including conditions marginal for most other crops; ii) resilience to both drought and waterlogging conditions; iii) fitness for various cropping systems and crop rotation schemes; iv) use as a catch and low-risk reliable crop especially as a replacement crop at times of failures of long-season crops (such as maize and sorghum) due to drought, pest and/or other calamities; and v) relative healthiness of the crop in the field and store since it suffers little or no serious threats from disease and pest epidemics.

On the other hand, tef also offers some important merits with respect to utilization, and these include: i) best quality and consumer-preferred "*injera*" with good water holding capacity, long shelf-life, unique flavor (slightly sour but pleasant), pliability, smooth and glossy texture; ii) high returns in flour upon milling of 99% compared to 60-80% from wheat (Tadesse, 1969); iii) high returns in "*injera*" upon baking; iv) minimal post-harvest losses and high longevity during storage; v) importance of the straw mainly as fodder for cattle and as a binder of mud used for plastering walls of local houses; and vi) cash crop value owing to the high market prices of both the grains and the straw.

Furthermore, tef is generally a very nutritious cereal grain. Compared to most other cereals (except for finger millet), tef grain is relatively high in the contents of minerals such as iron, phosphorous, and calcium (Melak-Hail, 1966; Asrat and Tekabe 2001). In recent years, tef has been receiving global attention as health food because of its gluten-free nature that renders it suitable for people suffering from gluten allergy known as celiac disease, slow release carbohydrates that makes it suitable for diabetic people, and high iron content that makes it suitable for pregnancy-related and hookworm infestation related anemia (Spaenij-Dekking *et al.*, 2005).

The indispensable significance of tef in the Ethiopian agriculture and the national food security notwithstanding, however, the productivity of the crop is relatively low. Its overall national average grain yield is about 1.2 t ha^{-1} (CSA, 2010). The most important bottlenecks constraining the productivity and production of tef in Ethiopia are: i) low yield potential of farmers' varieties under widespread cultivation; ii) susceptibility to lodging particularly under growth and yield promoting conducive growing conditions; iii) biotic stresses such as diseases, weeds and insect pests; iv) abiotic stresses such as drought, soil acidity, and low and high temperatures; v) the culture and labor-intensive nature of the tef husbandry; vi) inadequate research investment to the improvement of the crop as it lacks global attention due to localized importance of the crop coupled with limited national attention; and vii) weak seed and extension system.

This paper gives an overview of the progress and achievements made to-date in tef breeding research with respect to both conventional and molecular approaches. Based on the review, the paper also suggests future strategies and approaches for bringing about breakthrough in the genetic improvement of tef.

3.2. Historical Milestones in Tef Breeding

In the overall history of tef breeding since the initiation of scientific research in Ethiopia, five inter-related phases can be distinguished (Kebebew et al., 2011). The first phase (1956-1974) was characterized by i) germplasm enhancement (collection/acquisition, characterization and evaluation, systematics and conservation); ii) genetic improvement relying entirely upon mass and/or pure-line selection directly from the existing germplasm; and iii) initiation of induced mutation techniques. The second phase (1975-1995) featured i) the discovery of the chasmogamous floral opening behaviour of tef flowers (from about 6:45-7:30 AM) and thereby the artificial crossing technique by Tareke (1975); and ii) incorporation of intra-specific hybridization in the genetic improvement program following the discovery of the crossing technique.

The third phase (1995-1998) was characterized by i) initiation of molecular approaches involving development of molecular markers and genetic linkage maps, and ii) analyses of molecular genetic diversity. The fourth phase (1998-2003) featured the incorporation of *in vitro* culture techniques and inter-specific hybridization, and re-appraisal of induced mutagenesis particularly for lodging and leaf rust disease resistance. The last and the fifth phase (from 2003 till present) involved the introduction of participatory breeding approaches (Getachew *et al*., 2006, 2008); and continued extensive molecular/genomic research approaches.

3.3. Objectives of the Tef Breeding

The overall objectives of the tef breeding program are: i) to enrich and improve the germplasm resource base; ii) to develop suitable varieties for different agro-ecologies and cropping systems; and iii) to generate basic scientific information on the crop species. Towards meeting the overall objectives, the specific objectives have been to attain: i) high productivity in terms of both grain and straw yield; ii) tolerance to low moisture stress; iii) improved lodging resistance; and iv) desirable grain quality mainly in terms of most farmer and consumer-preferred caryopsis color (white).

3.4. Conventional Tef Breeding

3.4.1. Breeding strategies and institutional set-up

Considering the vast acreage devoted to tef production in Ethiopia, and the level of investment in tef improvement research in general, our motto in the overall tef breeding philosophy is centered on "*Add a little, and it makes a difference*".

The major strategies of the current tef breeding focus include; i) shift from wide to specific adaptation due mainly to high genotype × environment interaction while still looking for broad adaptation; ii) market orientation with respect to quality, quantity and food security; and iii) expansion to non-conventional (new) growing areas.

The institutional set-up for tef improvement in Ethiopia involves the National Agricultural Research System (NARS). This includes the Debre Zeit Agricultural Research Center as the center of excellence for tef research with primary responsibilities of the national coordination of the overall research endeavors, and the development and execution of country-wide tef research projects. The actual implementation of the research involves the Federal Research Centers of the Ethiopian Institute of Agricultural Research (EIAR) (namely: Debre Zeit and its sub-centers, Holetta, Melkassa, Ambo, Pawe and Assosa), centers of the Regional Agricultural Research Institutes (RARIs) including Adet, Sirinka, Sekota, Axum, Alamata, Mekelle, Bako, Sinana, and Areka, and Haramaya University from the Higher Learning Institutes (HLIs). In addition, on-farm trials are carried on farmers' fields in different parts of the country through the various centers involved in tef research.

3.4.2. Genetic resources for breeding

The primary source of variability for the genetic improvement of tef is the indigenous germplasm resource. Ethiopia is the center of both diversity and origin for the tef crop species (Vavilov, 1951). Currently, the Institute of Biodiversity Conservation (IBC) of Ethiopia maintains over 5000 tef germplasm accessions in its genebank.

Generally, the tef germplasm accessions showed wide genetic variability in phenologic, morphologic and agronomic traits (Kebebew et al., 2001, 2011). In spite of this, there has been lack of sufficient variability in the tef germplasm for some valuable traits such as seed size, and lodging, shattering, and leaf rust disease resistance.

3.4.3. Breeding methodology and achievements

The general methodology employed in the variety development process is indicated on Fig. 1. Since genetic variation forms the fundamental basis for breeding, the tef variety development anchors primarily upon germplasm enhancement through three complementary ways.

i) Native germplasm: The indigenous germplasm constitutes the major source of variability for tef breeding. This is because, tef being a native and unique crop to Ethiopia, there have been no opportunities for introductions of germplasm and breeding materials from abroad. The major germplasm enhancement activities include germplasm acquisition through collections and repatriations from genebanks or other sources, characterization and evaluation of the germplasm, and mass and/or mostly pure-line selection of desirable genotypes. Selections made would be entered into nurseries for subsequent evaluation for direct yield tests or as parental lines for hybridization or induced mutagenesis.

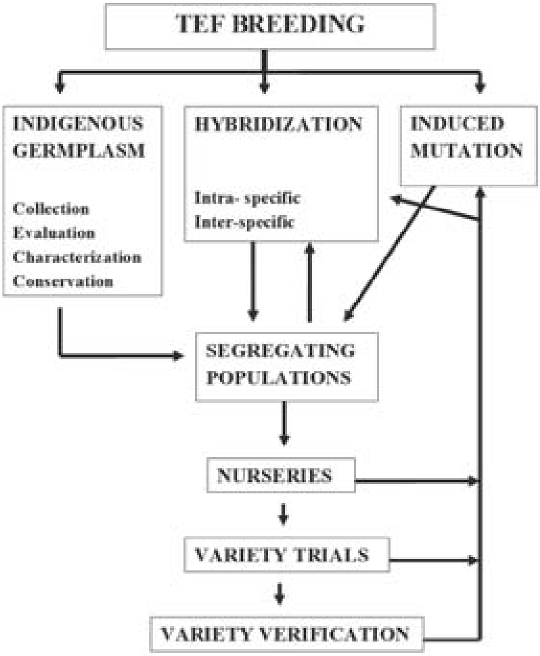

Fig. 1. Tef variety development process.

ii) Hybridization: This involves mainly intra-specific crosses and recently some inter-specific crossings especially with *E. pilosa*. A total of about 440 crosses have been made so far at Debre Zeit Agricultural Research Center. Crosses with high genetic variability were considered for further selection and generation advancement (Hailu *et al.*, 2001). Subsequent segregating populations are handled using the modified pedigree or bulk methods of breeding. However, some varieties have been developed as recombinant inbred lines (RILs) through F_2-derived single seed descent method (SDD).

iii) Induced mutation techniques: Artificial induction of mutation is also being used for generation of variability for some important traits such as lodging resistance since sufficient variability in the existing germplasm is lacking.

The next stage is the nursery for initial evaluations of selected genotypes from the three germplasm enhancement schemes followed by a series of yield trials including preliminary, pre-national and national variety trials. In the variety testing, genotypes are categorized into early and late sets depending on the maturity. The late types are mainly targeted for high potential or optimum environments, while the early sets are targeted for terminal moisture stress areas. At the last stage of the process, elite and promising genotypes selected as candidate varieties based on their performance in the various variety trials are entered into variety verification trials for evaluation by the National Variety Release Committee. At all stages, even after release as a variety, genotypes could be selected to be taken back to the earlier steps of hybridization and induced mutation schemes of germplasm enhancement.

Since the initiation of the improvement work in the late 1950s, a total of 18 varieties of tef have been released from the Debre Zeit Agricultural Research Center (Table 2). Of these, eight varieties were obtained from the hybridization program while the remaining 10 resulted from the direct mass or pure-line selections.

Four varieties namely, *Magna* (DZ-01-196), *Dukem* (DZ-01-974), *Enatite* (DZ-01-354), and *Quncho* (DZ-Cr-387 RIL355) are widely grown by farmers in areas of optimum rainfall, whereas *Tsedey* (DZ-Cr-37), *Gemechis*, and *Simada* are recommended for low-moisture areas. Generally, the improved and released tef varieties produce grain yield ranging from 1.4 to 2.7 t ha^{-1} on farmers' fields (Table 2).

In addition to the 18 varieties released by the Debre Zeit Agricultural Research Center, fourteen other tef varieties have been released by other research centers in Ethiopia (Table 3; MoA 2010). These include five varieties (*Gola, Genete, Zobel, Mechare and Laketch*) from Sirinka, three varieties (*Yilmana*, *Dima* and *Etsub*) from Adet, two varieties each from Holetta (varieties *Holetta Key* and *Ambo Toke*) and Bako (varieties *Guduru* and *Kena*), and one variety each from Melkassa (variety *Gemechis*) and Areka (variety *Ajora*) Agricultural Research Centers. Of the total of 32 varieties released in Ethiopia, only 10 were developed through hybridization, and the rest were developed through direct selection from germplasm accessions. Only one of the 10 varieties (*Simada*) from the crossing program resulted from an inter-specific hybridization between a selected tef line (DZ-01-2785) and *E. pilosa*.

Table 2. List of improved tef varieties released by Debre Zeit Agricultural Research Center from 1970-2010 (MoA, 2010).

Variety name	Common name	Year of release	Days to mature	Plant height (cm)	Seed color	Grain yield (ton ha^{-1})	
						On-station	On-farm
DZ-01-99	*Asgori*	1970	80-130	53-100	Brown	2.2-2.8	1.8-2.2
DZ-01-354	*Enatit*	1970	85-100	53-115	Pale white	2.4-3.2	2.0-2.4
DZ-01-196	*Magna*	1978	80-113	50-117	Very white	1.8-2.4	1.6-2.0
DZ-01-787	*Wellenkomi*	1978	90-130	50-110	Pale white	2.4-3.0	2.0-2.4
DZ-Cr-44	*Menagesha*	1982	95-140	85-110	White	1.8-2.4	1.8-2.2
DZ-Cr-82	*Melko*	1982	112-119	96-112	White	1.8-2.4	1.6-2.0
DZ-Cr-37	*Tsedey*	1983	82-90	67-92	White	1.8-2.5	1.4-2.2
DZ-Cr-255	*Gibe*	1993	114-126	63-116	White	2.0-2.6	1.6-2.2
DZ-Cr-358	*Ziquala*	1995	76-138	84-132	White	2.4-3.4	2.0-2.7
DZ-01-974	*Dukem*	1995	75-137	70-109	White	2.4-3.4	2.0-2.7
DZ-01-1281	*Gerado*	2002	73-95	83-100	White	1.7-2.4	1.6-2.2
DZ-01-1285	*Koye*	2002	104-118	80-92	White	1.7-2.4	1.6-2.2
DZ-01-1681	*Key Tena*	2002	84-93	74-85	Brown	1.7-2.4	1.6-2.2
DZ-01-899	*Gimbichu*	2005	118-137	46-68	Pale white	1.5-2.2	1.6-2.0
DZ-01-2675	*Dega Tef*	2005	112-123	47-91	Pale white	1.5-2.4	1.4-2.2
DZ-Cr-387 RIL355	*Quncho*	2006	86-151	72-104	Very white	2.0-3.2	1.8-2.6
Ho-Cr-136	*Amarach*	2006	63-87	67-81	Pale white	1.8-2.5	1.4-2.2
DZ-Cr-285 RIL295	*Simada*	2009	75-87	65-80	White	2.0-2.8	1.6-2.4

Analysis of the genetic gain through tef breeding for the first 10 varieties released until1995 (Hailu *et al.,* 1995) under no-lodging conditions on two soil types at Debre Zeit Agricultural Research Center (Yifru and Hailu, 2005) depicted the following (Fig. 2): i) averaged over the two experimental soil types, there has been a steady but slow increment in grain yield from 3.81 to 4.60 t ha^{-1}; ii) over the years of breeding, there has been a linear (R^2 = 0.368) genetic gain in grain yield with mean annual increment of rate of 0.8%, which amounts to about 31.6 kg ha^{-1} year^{-1}; iii) on the average, the varieties developed through intra-specific hybridization yielded 9% greater than those obtained through direct selection from germplasm; and iv) traits associated with the genetic improvement were increased biomass, plant height, number of spikelets/panicle, panicle weight, rate of phytomass production, and grain filling rate.

Table 3. List of improved tef varieties released in Ethiopia by research centers other than Debre Zeit Agricultural Research Center (MoA, 2010)

Releasing Center	Variety name	Common name	Year of release
Holetta	DZ-01-2053	Holetta Key	1998/99
	DZ-01-1278	Ambo Toke	1999/00
Melkassa	DZ-Cr-387 RIL127	Gemechis	2007
Sirinka	DZ-01-2054	Gola	2003
	DZ-01-146	Genete	2005
	DZ-01-1821	Zobel	2005
	Acc. 205953	Mechare	2007
	RIL273	Laketch	2009
Adet	DZ-01-1868	Yilmana	2005
	DZ-01-2423	Dima	2005
	DZ-01-3186	Etsub	2008
Bako	DZ-01-1880	Guduru	2006
	23-Tafi-Adi-72	Kena	2008
Areka	PGRC/E 205396	Ajora	2004

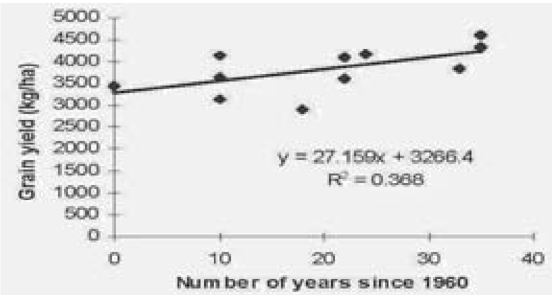

Fig. 2. Mean grain yield of tef varieties *versus* year of release (Source: Yifru and Hailu, 2005).

The trait changes in tef improvement generally revealed that harvest index and lodging susceptibility remained un-altered, and plant height (although not significantly) and biomass increased. In comparison, the global picture in the genetic improvement of other cereals like wheat and rice, in contrast reveals that the gain in yield potential in these cereals has been due mainly to m anipulation of photosynthate partitioning through increased harvest index while maintaining total biomass un-altered, and also due to reduced plant height and lodging (Table 4).

3.5. Molecular Approaches

The research achievement in tef molecular breeding approaches can be categorized into four parts as i) molecular marker development, ii) molecular analysis of genetic diversity and relationships, iii) development of molecular marker linkage maps, and iv) quantitative trait loci (QTL) analysis; v) comparative genomics; and vi) genetic transformation techniques.

Table 4. Changes in tef traits associated with genetic improvement as compared to that of the global picture in the improvement of wheat.

Trait	Tef	Wheat
Biomass	Increased	Same
Harvest Index	Same	Increased
Plant height	Increased (not significantly)	Reduced
Lodging	Same (Still a problem)	Reduced (tackled)
Phenology (maturity)	Same	Same
Head mass	Increased	Increased

3.5.1. Marker development

Molecular markers provide an invaluable tool for studying genetic diversity and relationships, classification of germplasm, construction of genetic linkage maps, and in marker-assisted selection or breeding. Recently, several marker systems have been developed in tef and used for various purposes. These included amplified fragment length polymorphism (AFLP) (Mulu *et al.*, 1999; Bai *et al.*, 1999a,b; Mulu and Nguyen 2000), random amplified polymorphic DNA (RAPD) (Bai *et al.*, 2000) and restriction fragment length polymorphism (RFLP) (Zhang *et al.*, 2001) that were applied to various tef genetic and genomic studies (Yu *et al.*, 2006a, b). Following generation of tef expressed sequence tag (EST) sequences from four cDNA libraries, tef sequence specific markers have been developed such as expressed sequence tag derived simple sequence repeat (EST-SSR), intron fragment length polymorphism (IFLP), and single nucleotide polymorphism/insertion and deletion (SNP/INDEL) (Yu *et al.*, 2006a).

The fact that EST sequences are derived from the coding regions of genes renders EST derived markers highly transferable to closely related species. To that end, testing of 812 EST-derived markers from other grass species on tef revealed successful amplification of approximately 30% of the markers, and markedly EST-SSRs developed from sorghum and pearl millet (both belonging to s ubfamily

Panicoideae which is taxonomically close to the subfamily of tef, *Chloridoideae,* in the grass family) showed a transferability rate higher than 80% on tef (Zeid *et al.*, 2010b).

More recently, tef genomic SSR markers (gSSRs) have been developed and thereby alleviated the problem of low rate of polymorphism of EST-SSRs (Zeid *et al.*, 2010a). The genomic libraries were enriched for (AG) and (AC) dinucleotide repeats, and in tef the (AG) repeat occurs at much higher frequency (=20 repeats/Mbp) as compared to other grass species such as barley, rice and wheat (=9 repeats/Mbp). A total of 561 gSSRs were developed and 48% of the markers showed polymorphism on *E. tef* (Kaye Murri) and *E. pilosa* (Zeid *et al.*, 2010a). This indicates that the rate of polymorphism of gSSRS is twice as high as the EST-derived markers in tef (24%) (Yu *et al,* 2006a). Presently, there are more than 1500 locus-specific tef markers available for use in genetic studies (Table 5).

Table 5. Summary of validated locus-specific markers in tef [Adopted from Kebebew *et al.*, 2011)]

Marker	Clones/sequences	No. of markers	Originating species	Reference
RFLP	cDNA	151	Tef	Zhang *et al.* (2001)
RFLP	cDNA	133	Barley, oat, rice	Zhang *et al.* (2001)
EST-SSR	EST	106	Tef	Yu *et al.* (2006)
EST-SSR	EST	770	Rice, wheat, tall fescue, rye	Zeid *et al.* (2010)
SNP/INDEL	EST	18	Tef	Zeid *et al.* (2011)
gSSR	Genomic SSR	561	Tef	Zeid *et al.* (2011)
gSSR	Genomic SSR	47	Tall fescue	Zeid *et al.* (2011)

3.5.2. Molecular genetic diversity

Different marker systems have been used to study genetic diversity in tef and related wild *Eragrostis* species. Earlier works using amplified fragment length polymorphism (AFLP) (Mulu *et al.* 1999; Bai *et al.*, 1999; Mulu and Nguyen, 2000) and random amplified polymorphic DNA (RAPD) (Bai *et al.*, 2000) generally showed low level of polymorphism (18%) in tef with Jaccard similarity coefficient ranging 84-96% for RAPD and 73-99% for AFLP. Later, using inter-simple sequence repeat (ISSR) markers, Kebebew *et al.* (2003) noted relatively high diversity with the Jaccard similarity coefficient ranging from 26-86%.

A more prolific genetic diversity study using molecular markers was made by Zeid *et al.* (2012). In this study, assessments were made on the genetic diversity and relationships among 326 cultivated tef accessions, 13 wild relatives, and four commercial tef varieties from the U.S. using 39 SSR markers, 26 of which were flanking QTL intervals for yield, lodging index and stem strength related traits. In addition, in this study the allelic diversity was estimated and markers associated with agronomic traits were identified in the tef germplasm collections. Forty-seven loci were sufficient to differentiate 80.8% of the tef accessions. In contrast to earlier studies, genetic similarity estimates ranged from 0.21 to 0.99, indicating a high level of genetic diversity. In the course of this investigation, it was discovered that seed admixture is a serious problem affecting the integrity of almost all released tef varieties. Association was observed between the marker CNLTs 540 and seed weight/plant. The majority of the alleles detected were present in tef breeding lines and varieties suggesting that tef plant breeders have been using a broad range of germplasm in their programs. The markers documented in this study will be useful to identify and verify hybrids from crosses between promising lines that lack morphological differences, an approach that was never attempted before in the tef breeding programs.

Overall, genetic diversity studies in tef using molecular (DNA) markers have been reviewed by Kebebew *et al.* (2011), and this has also been also been reviewed in greater details elsewhere in this compilation.

3.5.3. Genetic linkage map

In attempts to develop molecular (DNA) marker for eventual marker-assisted breeding, five linkage maps have so far been constructed for the species using both intra- and inter-specific recombinant inbred lines as mapping populations.

i) The first linkage map was constructed using 211 AFLP loci with 85 F_8 recombinant inbred lines (RILs) of the intra-specific cross Kaye Murri × Fesho (Bai *et al.* 1999a). This map consisted of 25 linkage groups as opposed to the gametic number for the species of 20 chromosomes, and covered 2149 cM of the genome while a polymorphism level of only 6.1% was detected between the parental lines.

ii) The second linkage map which is a restriction fragment length polymorphism (RFLP) based map was constructed by Zhang *et al.* (2001) on the basis of 116 RILs from the inter-specific cross *E. tef* (cv. Kaye Murri) x *E. pilosa* (30-5) using tef cDNA probes and heterologous cDNA probes from rice, barley and oats. This map comprised 149 cM of the tef genome based on 149 RFLP loci distributed among 20 linkage groups. As such, the RFLP map showed better genome coverage of 88% compared with the previous AFLP map which had genome coverage of 81%.

iii) The third linkage map was developed by Solomon *et al.* (2005) based on 124 F_8 RILs from the inter-specific cross *E. tef* (DZ-01-2785) x *E. pilosa* (30-5) using a combination of different markers including AFLP, ISSR, rice expressed sequence tagged-simple sequence repeat (EST-SSR) and tef specific EST-SSR markers. This map spanned 78.8% of the tef genome.

iv) The fourth linkage map was developed by Yu *et al.* (2006a, 2007) using 94 F_9 RILS from Kaye Murri x *E. pilosa* (acc. 30-5)] cross. Genetic markers applied were RFLP, IFLP, EST-SSR and ISSR. The map covered 2 082 cM of the tef genome and consists of 21 linkage groups.

v) The fifth linkage map was made by Zeid *et al.* (2010a) using 151 F_9 RILS from Kaye Murri x *E. pilosa* (acc. 30-5) cross. T he four genetic markers indicated above were used in this study. The map covered 1,277 cM of the genome and comprised 30 linkage groups.

3.5.4. QTL mapping

Some attempts have been made towards mapping of QTLs for important agronomic traits especially lodging, yield and yield related traits (Solomon *et al.* 2005, Yu *et al.*, 2007; Zeid *et al.* 2010a).

Using recombinant inbred lines from the inter-specific cross *E. tef* (cv. Kaye Murri) × *E. pilosa* (30-5), Yu *et al.* (2007) phenotyped 22 agronomic traits including eight yield related and 14 morphological traits evaluated at eight different locations for two growing seasons. In the genotyping with 94 RILs using composite interval mapping and a linkage map incorporating 192 loci, a total of 99 QTLs for 19 traits were identified on 15 of the 21 linkage groups with the phenotypic variances ranging from 11% to 34%. Clusters of more than five QTLs for various traits were identified on seven linkage groups, and the largest cluster of 10 QTLs was noted on LG8 and eight of these were for yield or yield-related traits suggesting linkage or pleiotropic effects of loci. A total of 12 QTLs on nine linkage groups were identified for grain yield. Of the total QTLs, 31% were observed in multiple environments, and two of the yield QTLs were consistent across all agro-ecological zones. There were 25 two-way interactions of loci to detect potential epistasis identified and 75% of the interactions were derived from grain and shoot biomass yield. For about 29% of the QTLS, the alleles from the wild relative *E. pilosa* had a beneficial effect indicating the potentials of introgressing beneficial genes from the wild *Eragrostis* species.

In general, for use in marker-assisted selection (MAS) tef breeding, the QTL mapping ventures so far indicated the need for further works, and validation and confirmation especially for those QTLs that have multi-QTL regions, QTLs identified across multiple environments, and QTLs having high phenotypic variances.

3.5.5. Comparative genomics

Zhang *et al.* (2001) mapped 149 loci of which nearly 40% were derived from rice, barley and oat, and all were previously mapped in rice. The alignment of the RFLP tef map with that of the rice genome depicted a number of syntenic chromosomal fragments between tef and rice, and the gene orders between the two crops were mostly collinear.

3.6. Genetic Transformation

In attempts towards fusion of tef and sorghum protoplasts, voltage of 230-270 V/cm for 2 minutes at a field strength of 1.35 MHz effected alignment of most of the protoplasts on the electrode with the non-detrimental fusion voltage at room temperature being 1360 V/cm at pulse duration of 40 s (Endashaw, 1995). On the other hand, electroporation conditions for electrogene transfer in tef comprised 700 V/cm at 20 ^{o}C and 40 µs field pulse duration.

Imbibing or soaking tef seeds and embryos in a solution of plasmid DNA for half to 24 h showed no direct uptake of introduced alien ß-glucordinase (GUS) gene as expected from its expression in the progeny seedlings of the treated seeds and callus resulting from the treated seeds or their embryos (Tesfaye, 1991).

In contrast, particle bombardment of chimeric constructs of ß-glucordinase (GUS) gene under the control of the cauliflower mosaic virus 35S promoter as a reporter gene into intact tef suspension culture cells, callus tissues and zygotic embryos revealed transient expression of the introduced alien GUS gene (Tesfaye, 1991).

In screening antibiotics for use as selective agents in Agrobacterium-mediated gene, transfer, Tesfaye (1991) found that G418 upon exhibiting inhibitory effects on callus growth at low concentrations is abetter selective agent for screening tef transformants than Kanamycin that inhibited callus production and growth and suspension cell culture growth only partially, while Carbenicillin didd not at all have inhibitory effect on callus growth.

3.7. The Way Forward

The major areas of focus in the future tef improvement include: i) tackling the lodging syndrome, which has still persisted as the major constraint in tef production even after more than 50 years of research with the sustained objectives of finding solutions to the problem; ii) improved productivity of the crop; iii) improved quality with respect to *injera* making quality, development of other food recipes, and quality for other recipes; iv) tolerance to major abiotic stresses such as drought, salinity, acidity, waterlogging, heat, and cold/frost; v) crop protection measures against major pets including diseases, weeds and insect pests; and vi) improved farm implements and machinery for sowing, harvesting and threshing.

The strategies envisaged towards addressing the suggested areas of focus are briefly outlined below.

i) Lodging Syndrome: A multi-faceted approach involving different disciplines has been suggested to combat the problem of lodging in tef (Fig. 3). This involves: a) cultural practices such as row planting, optimum plant population density (low seed rate), optimum nitrogen fertilization, and deep seeding; b) use of chemicals that reduce the height of the plant especially of the length of the culm and thereby indirectly increase the tolerance of the plant to l odging; c) use of improved farm implements and machinery for planting; and d) breeding for lodging tolerant cultivars. The latter, in turn, involves: i) direct selection for dwarf and semi-dwarf plant height, stem strength and large seed size; b) intra- and inter-specific hybridization with a view to i ncrease the number of crosses so as to i ncrease the chances for crossing over to get recombinants with breakage of the apparent linkage between plant height and stem thickness; c) induced mutagenesis to g et mutants with lodging resistance traits; and d) modern molecular or genomics approach including TILLING and Eco-TILLING, QTL analysis, comparative and association mapping, *in vitro* culture techniques, and genetic transformation.

ii) Conventional breeding strategies: In the overall tef breeding strategies the following approaches deserve attention: a) systematic germplasm collection/ acquisition coupled with subsequent characterization and evaluation; and b) enhancement of the hybridization program. In the tef crossing program, due focus is needed to be given to: a) increasing the number of crosses to get desirable recombinants; b) divergent crossing involving intra- but especially also inter-specific crosses to harness the potentials of wide crosses and useful alleles existing in related species; c) targeted crossing addressing various desirable traits; and d) ideo-type based breeding for different desirable agronomic, and biotic and abiotic stress tolerance traits.

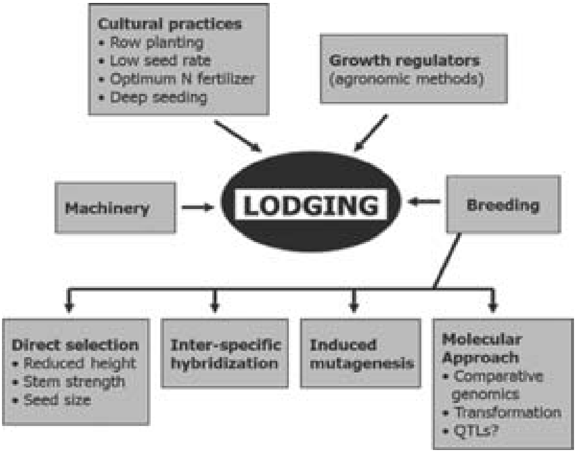

Fig. 3. Schematic diagram showing envisaged integrated methods for combating lodging in tef.

iii) Biotechnological approaches: In the biotech approaches, areas that need to be dealt with include: a) *in vitro* culture techniques especially di-haploid (DH) production systems; b) development of user-friendly molecular markers and sufficiently dense genetic linkage maps; c) QTL analysis and mapping; d) marker assisted selection (MAS); e) comparative genomics and association mapping; f) TILLING and Eco-TILLING; g) genome sequence and annotation (functional genomics); h) genetic transformation; and i) harnessing important tef genes.

iv) Agronomy: As equally important to improving the crop to make it fit to different agro-ecologies is the manipulation of the crop growing environment to make it fit for the crop. Important areas of focus with regard to agronomy and management are: a) soil fertility management; b) research in various cropping systems; iii) improved management of problematic soils (acidity, salinity and waterlogging); iv) management of drought stress; and v) potentials of irrigation use in tef.

v) Crop protection: Appropriate management methods need to be developed for major pests including diseases (especially leaf rust, head smudge and others), weeds (broad-leaved as well as grass weeds) and insect pests (e.g. shoot fly, red tef worm, Wello Bush cricket and others).

vi) Improved farm implements and machinery: There has been a growing and an urgent need for the development of improved pre-and post-harvest farm implements and machinery for the for sowing, harvesting and threshing.

vii) Food science: Work in the area of food science is essential with respect to injera making quality and value addition in terms of developing alternative tef recipes along identification of the desired qualities for the different recipes.

3.8. Abbreviations

AFLP: Amplified Fragment Length Polymorphism; **CSA**: Central Statistical Agency; **DH**: di-haploid; **DZARC**: Debre Zeit Agricultural Research Center; **Eco-TILLING**: TILLING implemented on natural population; **EIAR**: Ethiopian Institute of Agricultural Research; **EST**: Expressed Sequence Tag; **EST-SSR**: Expressed Sequence Tag derived Simple Sequence Repeat; **gSSR**: genomic SSR markers; **HLI**: Higher Learning Institutes; **IBC**: Institute of Biodiversity Conservation; **IFLP**: Intron Fragment Length Polymorphism; **INDEL**: Insertion and Deletion; **ISSR**: Inter-Simple Sequence Repeat; **MAS**: Marker-Assisted Selection; **m.a.s.l**: meter above See level; **MoA**: Ministry of Agriculture; **NARS**: National Agricultural Research System; **QTL**: Quantitative Trait Loci; **RAPD**: Random Amplified Polymorphic DNA; **RARI**: Regional Agricultural Research Institutes; **RFLP**: Restriction Fragment Length Polymorphism; **RIL**: recombinant inbred lines; **SDD**: Single Seed Descent; **SNP**: Single Nucleotide Polymorphism; **TILLING**: Targeting Induced Local Lesions in Genomes.

3.9. References

Asrat Wondimu and Frew Tekabe. 2001. Utilization of tef in the Ethiopian diet. ***In:*** Hailu Tefera, Getachew Belay and Mark Sorrells (eds). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia, 16-19 October 2000. p 239-244.

Bai G, Hailu Tefera, Mulu Ayele and Nguyen HT. 1999a. A genetic linkage map of tef [*Eragrostis tef* (Zucc.) Trotter] based on amplified fragment length polymorphism. Theor. Appl. Genet. 99:599-604.

Bai G, Mulu Ayele, Hailu Tefera and Nguyen HT. 1999b. Amplified fragment length polymorphism analysis of tef [*Eragrostis tef* (Zucc.) Trotter]. Crop Sci. 39: 819-824.

Bai G, Mulu Ayele, Hailu Tefera and Nguyen HT.2000. Genetic diversity in tef [*Eragrostis tef* (Zucc.) Trotter] and its relatives as revealed by random amplified polymorphic DNAs. Euphytica 112:15-22.

CSA. 2010. Central Statistical Agency. Agricultural Sample Survey 2009/2010 (2002 E.C.) (September – December, 2009). Vol. IV. Report on Area and Production of Crops (Private Peasant Holdings, *Meher* Season, Statistical Bulletin 446, Addis Ababa, Ethiopia.

Endeshaw Bekele. 1995. Electric field mediated fusion of *Eragrostis tef* and *Sorghum bicolor* protoplasts, and their electroporation conditions. Hereditas 123:199-203.

Getachew Belay, Hailu Tefera, Birhanu Tadesse, Gizaw Metaferia, Daniel Jarra and Tadelle Tadesse. 2006. Participatory variety selection in the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter]. Experimental Agriculture 42: 91–101.

Getachew Belay, Hailu Tefera, Anteneh Getachew, Kebebew Assefa and Gizaw Metaferia. 2008. Highly client-oriented breeding with farmer participation in the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter], African Journal of Agricultural Research 3:2228.

Hailu Tefera, Kebebew Assefa, Fuffa Hundera, Tiruneh Kefyalew, Yifru Teklu, Likyelesh Gugsa, Seyfu Ketema, Temesgen Adnew. 2001. Progress of tef breeding research in Ethiopia. *In*: Hailu Tefera, Getachew Belay and Mark Sorrells (eds.). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Addis Ababa, Ethiopia, 16-19 October 2000, Ethiopian Agricultural Research Organization pp157-163.

Hailu Tefera, Mulu Ayele and Kebebew Assefa. 1995. Improved varieties of tef (*Eragrostis tef*). Research Bulletin No. 1. Debre Zeit Agricultural Reasearch Center, Alemaya University of Agriculture, Debre Zeit Ethiopia, 32 pp.

Kebebew Assefa, Seyfu Ketema, Hailu Tefera, Fufa Hundera, Tiruneh.Kefyalew. 2001. Genetic diversity for agronomic traits in tef. *In*: Hailu Tefera, Getachew Belay and Mark Sorrells (eds.). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia, 16-19 October 2000, p33-48.

Kebebew Assefa, Yu JK, Zeid M, Getachew Belay, Hailu Tefera and Sorrells ME. 2011. Breeding tef [*Eragrostis tef* (Zucc.) Trotter]: conventional and molecular approaches (review). Plant Breeding 130: 1-9.

Kebebew Assefa, Merker A and Hailu Tefera. 2003. Inter simple sequence repeat (ISSR) analysis of genetic diversity in tef [*Eragrostis tef* (Zucc.) Trotter]. Hereditas 139: 174-183.

Melak Hail Mengesha. 1966. Chemical Composition of teff (*Eragrostis tef*) compared with that of wheat, barley and grain sorghum. Economic Botany 20: 268-273.

MoA. 2010. Ministry of Agriculture, Animal and Plant Health Regulatory Directorate. Crop Variety Register Issue No. 13, June 2010, Addis Ababa, Ethiopia, 227pp.

Mulu Ayele, Hailu Tefera, Kebebew Assefa and Nguyen HT. 1999. Genetic characterization of *Eragrostis* species using AFLP and morphological traits. Hereditas 130: 33-40.

Mulu Ayele and Nguyen HT. 2000. Evaluation of amplified fragment length polymorphism markers in tef, *Eragrostis tef* (Zucc.) Trotter, and related species. Plant Breed. 119: 403-409.

Seyfu Ketema. 1993. Tef *(Eragrostis tef*): Breeding, Genetic Resources, Agronomy, Utilization and Role in Ethiopian Agriculture. Institute of Agricultural Research, Addis Ababa, Ethiopia.

Solomon Chanyalew, Singh S, Hailu Tefera and Sorells ME. 2005. Molecular genetic map and QTL analysis of agronomic traits based on *Eragrostis tef* × *E. pilosa* recombinant inbred populations. J. Genet. Breed. 59: 53-66.

Spaenij-Dekking L, Kooy-Winkelaar Y and Koning F. 2005. The Ethiopian cereal tef in celiac disease. N. Engl. J. Med. 353: 16.

Tadesse Ebba. 1969. Tef (*Eragrostis tef*). The Cultivation, Usage and Some of Its Known Diseases and Insect Pests. Part I. Expt. Sta. Bull. No. 66. Haile Sellassie I University (HSIU), College of Agriculture, Dire Dawa, Ethiopia.

Tareke Berhe. 1975. A break-through in tef breeding techniques. FAO International Bulletin on Cereal Improvement and Production 12:11—13.

Tesfaye Mengsitie. 1991. Genetic transformation of *Eragrostis tef* by Direct DNA transfer. M.Sc. thesis, Univ. of London, UK.

Vavilov I. 1951. The Origin, Variation, Immunity and Breeding of Cultivated Plants. Translated from the Russian by K. S. Chester, The Ronald Press Co, New York, USA.

Yifru Teklu and Hailu Tefera. 2005. Genetic improvement in grain yield potential and associated agronomic traits of tef (*Eragrostis tef*). Euphytica 141:247-254.

Yu JK, Kantety RV, Graznak E, Benscher D, Tefera H and Sorrells ME. 2006a. A genetic linkage map for tef [*Eragrostis tef* (Zucc.) Trotter]. Theor. Appl. Genet. 113: 1093-1102.

Yu JK, Sun Q, Rota ML, Edwards H, Tefera H and Sorrells ME. 2006b. Expressed sequence tag analysis in tef (*Eragrostis tef* (Zucc) Trotter). Genome 49: 365-372

Yu JK, Graznak E, Breseghello F, Tefera H and Sorrells ME. 2007. QTL mapping of agronomic traits in tef [*Eragrostis tef* (Zucc.) Trotter]. BMC Plant Biol. 7: 30.

Zeid M, Getachew Belay, Mulkey S, Poland J and Sorrells ME. 2010a. QTL mapping for yield and lodging resistance in an enhanced SSR-based map for tef. Theor. Appl. Genet 122:77-93.

Zeid M, Yu JK, Goldowitz I, Jayasuriya CT, Saha M, Elshire R, Benscher D, Breseghello F, Munkvold J, Varshney R, and Sorrells ME. 2010b. Cross-amplification of EST-derived markers among sixteen grass species. Field Crops Res. 118:25-35.

Zeid M, Kebebew Assefa, Aderajew Haddis, Solomon Chnayalew and Sorrells ME 2012. Genetic diversity in tef (*Eragrostis tef*) germplasm using SSR markers. Field Crops Research 127: 64-70.

Zhang D, Mulu Ayele, Hailu Tefera and Nguyen HT. 2001. RFLP linkage map of the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter]. Theor. Appl. Genet. 102: 957-964.

4. TILLING as a High-Throughput Technique for Tef Improvement

Korinna Esfeld, Sonia Plaza-Wüthrich and Zerihun Tadele[*]
Tef Improvement Project, Institute of Plant Sciences, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland. [*]Corresponding author: zerihun.tadele@ips.unibe.ch

TILLING (Targeting Induced Local Lesions IN Genomes) is a reverse genetics and non-transgenic method of mutation detection with application in crop improvement. The technique uses traditional mutagenesis followed by high-throughput mutation detection. TILLING detects useful mutations in virtually any gene and allows rapid screenings. Detailed description of the TILLING procedure is presented as it is applied to crop plants in the last decade. Here, we show how TILLING is implemented to improve agronomically useful traits in tef. Candidate tef mutants obtained through this procedure were introgressed to locally adapted and high-yielding cultivars and currently being evaluated in the field in Ethiopia.

Key Words: TILLING, EcoTILLING, mutagenesis, EMS, mutation detection, LI-COR

4.1. Introduction

Although tef is economically a very important cereal in Ethiopia, it is one of the lowest in terms of productivity. The main factors contributing to poor yield in tef are lodging and drought. Tef breeding in the past five decades implemented mainly conventional methods to r elease over 30 improved cultivars to the farming community. Conventional methods applied were mass- and pure line-selections as well as hybridization techniques. Modern approaches comprise tissue culture studies as well as genetic markers such as AFLP (Amplified Fragment Length Polymorphism) and SSR (Simple Sequence Repeat).

Lodging is considered as the major bottleneck affecting productivity in tef. Despite concerted efforts by national and international institutions so far, no lodging tolerant tef cultivars were developed. This might be due to limited genetic variability in the available germplasm collections restricting the success of conventional breeding techniques (Assefa et al. 2011). Here, we describe the recently developed technique called TILLING (Targeting Induced Local Lesion IN Genomes) which is used for mutation detection and crop breeding and indicate its application to tef improvement.

4.2. The role of TILLING in Crop Improvement

TILLING was developed a decade ago in the model plant *Arabidopsis thaliana* (McCallum et al. 2000) and is nowadays successfully adopted to numerous animal and plant species (for review, Rashid et al. 2011). TILLING is a reverse genetics technique which uses 'traditional' mutagenesis followed by high-throughput mutation detection. It is a non-transgenic, fast, and relatively low-cost method to screen for induced mutation irrespective of genome size and ploidy level (McCallum et al. 2000, Till et al. 2003, Henikoff et al. 2004, Comai and Henikoff 2006). TILLING is the only reverse genetic technique that delivers an allelic series of mutations and thus numerous varying phenotypes could be obtained instead of single drastic ones as observed in gene knock-out studies (Haughn and Gilchrist 2006). As a reverse genetics method, candidate genes responsible for the expected phenotypes are first identified which enables targeted or focused screenings. TILLING is effective for targeting all mutations in a specific gene even those without detectable phenotypes (Dong et al. 2009). Genes responsible for the trait of interest can be analysed and subsequently the phenotype studied. Thus, TILLING goes beyond classical mutation breeding since the random mutagenesis is better exploited by screening for mutations in defined genes controlling the trait of interest (Wang et al. 2006). In addition, TILLING can directly introduce genetic variation on improved or elite germplasm. This avoids introgression of a mutant allele in a non-adapted background and the introduction of agriculturally undesirable traits in elite cultivars (Slade and Knauf 2005, Uauy et al. 2009, Sestili et al. 2010).

While TILLING identifies induced mutations in artificially mutagenized populations, a modified form known as EcoTILLING detects naturally occurring single nucleotide polymorphisms (SNPs) (Comai et al. 2004, Haughn and Gilchrist 2006). EcoTILLING is used for mutation detection especially in landraces and germplasm accessions, hence has additional applications in genetic mapping, breeding, and genotyping (Haughn and Gilchrist 2006).

4.3. The Procedure of TILLING as Applied to Tef

Here, we show the step-wise procedure and status of the tef TILLING designed to identify mutations for some genes responsible for valuable agronomic traits. The TILLING protocol comprises the following steps: i) mutagenesis, ii) development of a non-chimeric population, iii) DNA isolation, and iv) mutation detection (Comai and Henikoff 2006, Tadele et al. 2009, Wang et al. 2010). Confirmation for the presence of mutation and defining the type of mutation is also done as part of the TILLING procedure. Figure 1 shows the detailed procedure adopted for tef. The mutants identified by TILLING could be introgressed to desirable genotypes and the progenies tested for the traits of interest.

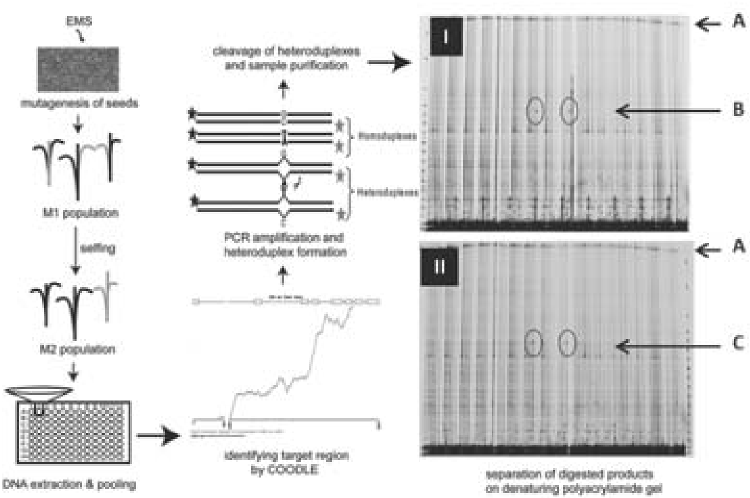

Figure 1. The TILLING procedure adopted for tef. Seeds are mutagenized with ethyl methanesulfonate (EMS; 0.2%, 8 h) followed by the generation of large numbers of M_1 and M_2 population. After DNA is isolated from individual M_2 lines a 4-fold two-dimensional pooling was done. The CODDLE software is used to identify the most promising region to be screened for each target gene. Primers are deduced in order to amplify a single gene copy at a time and labeled with two different fluorescent dyes. The PCR amplification is followed by the heteroduplex formation and the mismatches are afterwards cleaved by a single strand specific nuclease such as CEL I. Cleaved and purified samples are resolved on a 5-6% denaturing polyacrylamide gel using the two channel LI-COR DNA analyser system (I and II). In the mutant lines where the mutation occurs in the gene of interest, the sum of the two cleaved products from the two channels (B and C) gives the size of the PCR product prior to CEL I cleavage (A).

4.3.1. Mutagenesis, tissue sampling, and DNA extraction

The creation of a mutagenized population is the first step in TILLING. Mutagenesis is the critical step since the balance between an optimum mutation density and a feasible germination rate indicate the efficiency of TILLING (Haughn and Gilchrist 2006, Parry et al. 2009). Mutation breeding has a long history in crop improvement in which over 2000 crop cultivars were developed and released to the farming community (Ahloowalia et al. 2004, Wang et al. 2006). Mutagenesis can be applied to all species even if they lack advanced genetic tools. Although mutation breeding was also applied in tef improvement, no improved cultivars was developed using this technique (Assefa et al. 2009). This might be due to the masking of the expected phenotype in the forward genetics because of the presence of additional gene copy in this polyploidy species (tef is an allotetraploid with 2n=4x=40). As a reverse genetics approach, TILLING combines the advantages of mutagenesis with a focused screen from gene to phenotype.

Selecting the genotype for mutagenesis: It is desirable to mutagenize elite cultivars in order to minimize the number of introgressions once candidate mutants with the expected phenotypes are obtained. For the tef TILLING, two cultivars with wide adaptation and high yield namely *Tsedey* (DZ-Cr-37) and *Dukem* (DZ-01-974) were selected.

***Selecting the mutagen*:** Pilot studies need to be made in order to determine the right type and concentration of the mutagen before embarking large-scale mutagenesis (Tadele et al. 2009). Chemical mutagens which create point mutations are preferentially selected for TILLING. Ethyl methanesulfonate (EMS) is widely applied since it normally creates nucleotide transitions (from G:C to A:T) in the genome due to alkylation of G nucleotide residues which then pair with T instead of C (Comai and Henikoff 2006, Parry et al. 2009). Other commonly used mutagens are sodium azide (NaN_3) and N-methyl-N-nitrosourea (MNU) whereas physical agents such as gamma-ray are only seldom applied.

Mutagenesis and population generation: After defining the type and optimum concentration of the mutagen, large-scale mutagenesis is made using the explant of choice. For most plants seeds are mutagenized, except in the case of maize where pollen grains are treated followed by the introgression to the un-mutagenized female parent (Comai and Henikoff 2006, Till et al. 2007a). Plants from the first generation after mutagenesis (known as M_1 population) are chimeric, that is different cells make different genotypes due to the multicellular stage of embryos in seeds. In order to obtain non-chimeric M_2 populations, large numbers of M_1 populations are self-pollinated. Mutations in M_2 populations are considered stable and heritable (Till et al. 2007b, Cooper et al. 2008). Mutagenesis of the two cultivars of tef was done by treating the seeds with 0.2% EMS for 8 hours. About 10 000 M_1 and 7000 M_2 populations were generated for the Tef TILLING Project.

Tissue sampling and DNA extraction: Leaf tissues from 4200 M_2 tef families were harvested for DNA extraction. The seeds (M_3 populations) were also collected for further study. Genomic DNA was isolated using the NucleoSpin® 96 Plant extraction kit (Macherey-Nagel, Germany) following the protocol of the supplier. DNA extracted from each sample was normalized to a concentration of 5 ng.

4.3.2. DNA pooling

After achieving equivalent DNA concentrations for each sample, pooling was done using a certain number of samples in each pool. The normalization of DNA concentration ensures equal representation of each sample within a DNA pool and hence as template in PCR reactions. Most TILLING platforms follow 2- to 8-fold pooling in a one- or two-dimensional range. The number of mutated DNA samples which can be pooled depends on the quality of DNA as well as on the detection method. The dimension refers to the kind of pooling or how a pool plate is made. In one-dimensional pooling, each sample is represented only once in a pool plate while in two-dimensional pooling, each sample is represented twice at a unique position. Although the former increases the number of samples to be analysed per pool plate, the latter reduces the number of false positives and allows the immediate determination of the candidate line despite decreases in the throughput. The pooling adopted for tef is a 4-fold in a two-dimensional range.

A different kind of pooling is required for EcoTILLING where two samples are pooled in a 1:1 ratio and normally a single genotype is used as reference for all lines. This pooling strategy is necessary since more SNPs are expected between distantly related genotypes and pooling of individuals with too many nucleotide differences reduces the detection efficiency (Raghavan et al. 2007). In addition, the use of a common reference allows the immediate identification and classification of haplotypes within germplasm collections. Once the pools are made, the stock is used for screening large numbers of genes of interest.

4.3.3. PCR amplification and heteroduplex formation

PCR amplification and heteroduplex formation include the steps from designing primers, to amplifying genes of interest, and to forming heteroduplexes in which mismatches between amplified DNA strands are revealed at the molecular level.

Primer design: Virtually every gene can be targeted by TILLING, however, the method focuses on down-regulated genes instead of over-expressed ones. Genes of interest can be obtained using information from well-studied cereals including maize, rice, and wheat. To amplify the gene of interest the right set of primers have to be designed using either sequence information of the experimental organism or closely related species. Although prior sequence information from the experimental organism is not required, its availability increases the success rate by accelerating the development of suitable targets and design effective primers (Henikoff et al. 2004, Parry et al. 2009). CODDLE (Codons Optimized to Detect Deleterious LEsions; http://www.proweb.org/coddle/; accessed May 2012) can be used to define the most promising region to be screened for mutations as it identifies the region where point mutations are most likely to result in deleterious effects (Colbert et al. 2001).

Designing the right set of primers is critical and sometimes a challenge in TILLING projects. Primers need to be specific for the gene of interest and the appropriate gene region in order to avoid unspecific PCR amplification that reduces the efficiency of mutation detection. Primer specificity is important particularly for members of multi-gene families and polyploid species. Copy-specific primers are used to selectively amplify a single copy at a time (Slade and Knauf 2005, Tadele et al. 2009, Uauy et al. 2009). Uauy et al. (2009) suggested two criteria how to design appropriate primers: i) aligning the first nucleotide from the 3'-end of the primer to the genome-specific SNP, and ii) introducing a mismatch in the primer at the third or fourth position from the 3'-end.

In the Tef TILLING Project, the promising gene region for primer design was predicted by CODDLE using the sequence information of *Sorghum bicolor,* a closely related species with completed genome sequence. Since tef is an allotetraploid species, copy-specific primers were designed to specifically amplify one gene copy at a time. A set of primers comprise one common primer deduced from the conserved region and the other copy-specific primer from the unique genomic region. The primers were labeled with Infra-red dyes in order to use the LI-COR system for mutation detection. Since labeling reduces the efficiency of PCR amplification, unlabeled primers are added together with labeled primers in the PCR reaction.

PCR amplification and heteroduplex formation: Depending on the mutation detection method, the length of PCR products can range from 0.3 kb to a maximum of ~3 kb (Slade and Knauf 2005, Raghavan et al. 2007). In order to increase the specificity and yield of the amplicon, a touch-down PCR is applied. However, copy-specific primers deduced from unique gene regions allow the use of normal PCR protocols. PCR amplification is followed by the heteroduplex formation step (Table 1). Heteroduplexes are formed between the PCR amplified mutated and non-mutated DNAs by first denaturing and then slowly annealing the product (see Figure 1; Gilchrist and Haughn 2005).

Table 1. The PCR protocol used in the tef TILLING. The reaction is divided into the normal PCR step where the target gene is amplified and the heteroduplex formation step where mismatches are created.

	PCR step					Heteroduplex formation step			
Temperature (°C)	95	95	*	72	72	99	70	69.7	69.4
Time (min:sec)	3:00	0:50	0:50	‡	5:00	10:00	00:20	00:20	00:20
Temperature reduction per cycle							- 0.9°C	-0.9°C	-0.9°C
Number of cycles	1	33			1	1	23		

*Annealing temperature is dependent on the melting temperature of the primers
‡Elongation time is dependent on the length of the PCR product

4.3.4. Mutation detection

Mutations are detected after first cleaving or digesting the PCR products using the CEL I enzyme and followed by gel resolution. Mutation detection is mostly done on denaturing polyacrylamide gels although several alternative methods are also available.

***CEL I digestion and purification*:** CEL I is a single-strand specific nuclease used in most TILLING platforms. It is also known as celery juice extract (CJE) and can be isolated from celery stalks following the protocol of Till et al. (2006). CEL I cleaves single base pair mismatches in heteroduplex DNA at the 3'-side of the mismatch and produces two complementary fragments while leaving homoduplexes intact (Henikoff et al. 2004, Haughn and Gilchrist 2006).

In the tef TILLING CJE digestion is performed by treating the PCR products for 15 min at 45°C followed by purification using the Sephadex® system and resolution on denaturing polyacrylamide gels.

LI-COR system: The LI-COR DNA analyzer system (hereafter LI-COR) is used for mutation detection in which the cleaved samples are separated on denaturing polyacrylamide gels. Prior to loading, CEL I digested samples need to be purified using either the Sephadex® system (Till et al. 2006) or ethanol precipitation and volume reduction. Purified samples are resolved on 5-6% denaturing polyacrylamide gels following the instructions of the LI-COR manufacturer (see also, Till et al. 2006). Cleaved fragments are visible in both channels of a LI-COR since each primer of a pair is labeled with a different infrared dye. Mutation detection is made using the software GelBuddy (http://www.proweb.org/gelbuddy; accessed May 2011, Figure 1).

4.3.5. Alternative mutation detection methods

Mutation detection using the LI-COR system is an expensive procedure as it requires the LI-COR machine and labeled primers that are not only expensive but also sensitive to light exposure. Alternative and cheaper methods have been developed especially for laboratories with limited resources. Alternative detection methods are based on agarose gel and non-denaturing polyacrylamide gel systems (Sato et al. 2006, Raghavan et al. 2007, Dong et al. 2009, Uauy et al. 2009). Both alternative methods avoid the use of labeled primers (Raghavan et al. 2007, Uauy et al. 2009). The lower costs and simplicity of the alternative methods allow additional applications in germplasm characterization and mapping studies (Raghavan et al. 2007). Brief descriptions about the two alternative methods are given below:

Agarose gel based detection: Raghavan et al. (2007) established the mutation detection on conventional agarose gels, making TILLING more accessible. The same efficiency as with the LI-COR system can be obtained by screening up to eight samples in a particular pool. The throughput can be increased for the agarose gel system since longer PCR fragments, up to 3 kb, can be screened compared to the LI-COR system. The preparation and run of agarose gels take only 1-2 h as compared to 4-5 h for polyacrylamide gels. Lower costs are also obtained since primers are not labeled, samples are not purified and expensive equipment such as the LI-COR machine are not used. For mutation detection, the yield of PCR products have to be optimized and a complete digestion of the heteroduplexes or mismatches is required to maximize the amount of cleaved fragments. Since the agarose gel based detection method has lower resolution, compared to the LI-COR method, more sequencing is needed in order to confirm the mutations observed on the agarose gel. Despite this constraint, the agarose gel based mutation detection was successfully applied in wheat breeding (Dong et al. 2009).

Non-denaturing polyacrylamide gel detection: Uauy et al. (2009) used non-denaturing polyacrylamide gels and ethidium bromide staining to simplify and decrease costs of mutation detection. Although this modified detection method has similar sensitivity to the LI-COR system, the former has advantages over the latter in avoiding the use of labeled primers and reducing the time for running the experiment.

Confirmation by sequencing: The detected mutations are confirmed by sequencing the gene region for the candidate mutant line. Subsequent comparisons with the original line as well as with cDNA sequences allow the classification of the detected mutation (Table 2).

Table 2. The size of PCR product and the type and frequency of mutation for the *KO2* and *D11* genes used in tef TILLING. Both *KO2* and *D11* are known to control plant height in other plant species.

Gene name	Genome copy	PCR product		Total mutations	Mutation frequency	Mutations in exon region	
		Size (bp)	% GC			Total	Useful[1]
KO2	A	1470	43	13	413 kb	12	5
	B	1456	44	10	530 kb	7	4
D11	A	1242	46	8	550 kb	2	1
	B	1299	46	10	464 kb	9	5

[1]Useful mutations refers to radical missense mutations (replacement of one amino acid from one category with another amino acid from a different category, eg. hydrophobic to hydrophilic or vice-versa) as well as nonsense mutations.

Mutation frequency: The mutation frequency can be calculated based on the confirmed mutations as the total number of screened base pairs (amplicon size x screened individuals) divided by the number of detected mutants (Greene et al. 2003). The amplicon size needs to be adjusted since technical limitations hamper the detection of mutations within 100 bp of each primer binding site. Thus, up to 200 bp were excluded from the full-length PCR product (Xin et al. 2008). Mutation frequencies of the tef TILLING population range between 1/413 kb up to 1/550 kb. According to Weil (2009) a mutation rate of 1/500 kb or less is feasible in TILLING. Higher mutation frequencies imply that the number of individuals to be screened is too large in order to obtain reasonable numbers of mutations. Since mutation frequencies are determined by the type and concentration of the mutagen, genetic background as well as the gene region screened specific criteria should be applied like corrections for a target with 50% GC content or at least mention of the GC content of the screened gene region (Uauy et al. 2009). Since the mutation frequencies of the tef population are comparable to that of other crop species, the established population is feasible for TILLING. In addition, the numbers of detected missense, nonsense, and silent mutations are in line with other TILLING projects (data not shown) confirming the practicability of the Tef TILLING platform.

4.4. Application of TILLING in Tef Improvement

Most TILLING experiments implemented steps up to the mutation detection since their goals are to prove that the technique is efficient in mutation discovery. However, few studies apply the results from the TILLING to further improve the crop of interest for agronomically and nutritionally important traits. Here, wheat is an outstanding example in which TILLING generated more genetic diversity than 25 years of conventional breeding and a large allelic series of mutations ranging from wild type to null alleles (Slade et al. 2005). Based on their findings and mutations identified, Dong and colleagues (2009) bred new wheat varieties within 18 months.

Since the tef TILLING targets agronomically valuable traits, candidate mutant lines obtained from the screening are used in the subsequent breeding program. Priority is given for candidates with nonsense- and radical missense-mutations as they expect to result in strong phenotypic changes in the plant. Softwares such as PARSESNP (Project Aligned Related Sequences and Evaluate SNPs; http://www.proweb.org/parsesnp/; accessed January 2012) and SIFT (Sorting Intolerant from Tolerant, http://sift.jcvi.org/; accessed January 2012) provide valuable information in defining the candidate lines used for the subsequent steps of introgression and breeding. These programs investigate whether the detected mutations have an influence on the protein. PARSESNP reveals the changes in the nucleotide and amino-acid sequences (Taylor et al. 2003, Gilchrist and Haughn 2005) whereas SIFT uses comparisons between closely related sequences to predict whether the amino acid change is expected to have deleterious effects on the protein (Ng and Henikoff 2003, Henikoff et al. 2004).

Traits targeted so far in the Tef TILLING Project at the University of Bern include dwarfism, seed size, and drought tolerance. By screening the mutagenized population for two genes responsible for plant height (Table 2), five candidates with over 10% height reduction and a decent seed yield were selected for introgression. To use the mutant alleles for breeding, backcrossing to the original line or introgression to elite cultivar(s) is necessary to remove unlinked mutations caused by the random mutagenesis nature of EMS and other mutagens. As tef is tetraploid and a mutation in a single genome might not result in the expected phenotype, it might be necessary to identify mutations in each copy of the targeted gene and combine them by crossing. Thus, candidate lines are introgressed to each other to obtain plants harboring mutations in both copies of the genome. The crossing and field testing of the breeding materials are done at the experimental site of the Debre Zeit Agricultural Research Center in Ethiopia.

4.5. The Way Forward

TILLING is a reverse genetics method of mutation discovery and applied to diverse types of organisms including crop plants. The technique provides an allelic series of mutations leading to various phenotypes and can be used for crop improvement. Since TILLING is considered as a non-transgenic method, its products (e.g. mutants lines) are exempted from extensive regulatory restrictions and procedures imposed on transgenics (Slade and Knauf 2005).

The Tef TILLING platform at the University of Bern has generated over 7000 M_2 families for which the stocks of DNA and seeds are available for those who are interested. This population can be screened for valuable traits of interest by implementing either phenotypic screening or TILLING. In addition, the protocol developed for the tef TILLING could easily be adopted to other mutagenized populations and to EcoTILLING in order to i dentify useful polymorphisms in tef germplasm collections available at the Institute of Biodiversity and Conservation (IBC, Ethiopia). Once candidate lines harboring mutations of interest are identified, introgression to locally adapted and high yielding cultivars need to be done to be followed by multi-location field testing which will ultimately lead to the release of improved cultivars.

4.6. Abbreviations

AFLP: Amplified Fragment Length Polymorphism; **CJE**: as celery juice extract; **CODDLE**: Codons Optimized to Detect Deleterious Lesions; **EcoTILLING**: modified TILLING method applied to natural population; **EIAR**: Ethiopian Institute of Agricultural Research; **EMS**: ethyl methanesulfonate; **IBC**: Institute of Biodiversity and Conservation, Ethiopia; **M_1**: the first generation of mutagenized population; **M_2**: the second generation of mutagenized population; **M_3**:

the third generation of mutagenized population; **MNU**: N-methyl-N-nitrosourea; **PARSESNP**: Project Aligned Related Sequences and Evaluate SNPs; **SIFT**: Sorting Intolerant from Tolerant; **SNP**: single nucleotide polymorphisms; **SSR**: Simple Sequence Repeat; **TILLING**: Targeting Induced Local Lesions IN Genomes.

4.7. Acknowledgements

Our best gratitude goes to the Syngenta Foundation for Sustainable Agriculture and the University of Bern for financial and technical support to the 'Tef Improvement Project' and the Ethiopian Institute of Agricultural Research (EIAR) for excellent collaboration in testing breeding materials derived from our TILLING platform at the Debre Zeit Research Center. We also thank Nigussu Husein from the Debre Zeit Research Center for candidate line introgression and Christopher Ball and Nicole Signer from the Institute of Plant Sciences, University of Bern, for their technical help towards the execution of the experiments.

4.8. References

Ahloowalia BS, Maluszynski M, Nichterlein K (2004) Global impact of mutation-derived varieties. *Euphytica* 135: 187-204.

Assefa K, Belay G, Tefera H, Yu J-K, Sorrells ME (2009) Breeding tef: conventional and molecular approaches. In: Tadele Z (ed) New approaches to plant breeding of orphan crops on Africa. Proceedings of an I nternational Conference, 19-21 September 2007, Bern, Switzerland. Stämpfli, Switzerland.

Assefa K, Yu J-K, Zeid M, Belay G, Tefera H, Sorrells ME (2011) Breeding tef [*Eragrostis tef* (Zucc.) Trotter]: conventional and molecular approaches. *Plant Breeding* 130: 1-9.

Colbert T, Till BJ, Tompa R, Reynolds S, Steine MN, Yeung AT, McCallum CM, Comai L, Henikoff S (2001) High-throughput screening for induced point mutations. *Plant Physiol* 126: 480-484.

Comai L, Young K, Till BJ, Reynolds SH, Greene EA, Codomo CA, Enns LC, Johnson JE, Burtner C, Odden AR, Henikoff S (2004) Efficient discovery of DNA polymorphisms in natural populations by Ecotilling. *Plant J* 37: 778-786.

Comai L, Henikoff S (2006) TILLING: practical single-nucleotide mutation discovery. *Plant J* 45: 684-694.

Cooper JL, Till BJ, Laport RG, Darlow MC, Kleffner JM, Jamai A, El-Mellouki T, Liu S, Ritchie R, Nielsen N, Bilyeu KD, Meksem K, Comai L, Henikoff S (2008) TILLING to detect induced mutations in soybean. *BMC Plant Biol* 8:9.

Dong C, Dalton-Morgan J, Vincent K, Sharp P (2009) A modified TILLING method for wheat breeding. *The Plant Genome* 2: 39-47.

Gilchrist EJ, Haughn GW (2005) TILLING without a plough: A new method with applications for reverse genetics. *Curr Opin Plant Biol* 8: 211-215.

Greene EA, Codomo CA, Taylor NE, Henikoff JG, Till BJ, Reynolds SH, Enns LC, Burtner C, Johnson JE, Odden AR, Comai L, Henikoff S (2003) Spectrum of chemically induced mutations from a large-scale reverse-genetic screen in *Arabidopsis*. *Genetics* 164: 731-740.

Haughn GW, Gilchrist EJ (2006) TILLING in the botanical garden: a reverse genetic technique feasible for all plant species. *Floriculture Ornamental and Plant Biotechnology* 1: 476-482.

Henikoff S, Till BJ, Comai L (2004) TILLING. Traditional mutagenesis meets functional genomics. *Plant Physiol* 135: 630-636.

McCallum CM, Comai L, Greene EA, Henikoff S (2000) Targeted screening for induced mutations. *Nat Biotechnol* 18: 455-457.

Parry MA, Madgwick PJ, Bayon C, Tearall K, Hernandez-Lopez A, Baudo M, Rakszegi M, Hamada W, Al-Yassin A, Ouabbou H, Labhilili M, Phillips AL (2009) Mutation discovery for crop improvement. *J Exp Bot* 66: 2817-2825.

Raghavan C, Naredo MEB, Wang HH, Atienza G, Liu B, Qiu FL, McNally KL, Leung H (2007) Rapid method for detecting SNPs on agarose gels and its application in candidate gene mapping. *Mol Breeding* 19: 87-101.

Sato Y, Shirasawa K, Takahashi Y, Nishimura M, Nishio T (2006) Mutant selection from progeny of gamma-ray-irradiated rice by DNA heteroduplex cleavage using Brassica Petiole Extract. *Breeding Sci* 56: 179-183.

Sestili F, Botticella E, Bedo Z, Phillips A, Lafiandra D (2010) Production of novel allelic variation for genes involved in starch biosynthesis through mutagenesis. *Mol Breeding* 25: 145-154.

Slade AJ, Knauf VC (2005) TILLING moves beyond functional genomics into crop improvement. *Transgenic Res* 14: 109-115.

Slade AJ, Fuerstenberg SI, Loeffler D, Steine MN, Facciotti D (2005) A reverse genetic, nontransgenic approach to wheat crop improvement by TILLING. *Nat Biotechnol* 23: 75-81.

Tadele Z, Mba C, Till BJ (2009) TILLING for mutations in model plants and crops. In: Mohan Jain S, Brar DS (eds.) Molecular Techniques in Crop Improvement. Springer Netherlands.

Till BJ, Reynolds SH, Greene EA, Codomo CA, Enns LC, Johnson JE, Burtner C, Odden AR, Young K, Taylor NE, Henikoff JG, Comai L, Henikoff S (2003) Large-scale discovery of induced point mutations with high-throughput TILLING. *Genome Res* 12: 524-530.

Till BJ, Zerr T, Comai L, Henikoff S (2006) A protocol for TILLING and Ecotilling in plants and animals. *Nat Protoc* 1: 2465-2477.

Till BJ, Cooper J, Tai TH, Colowit P, Greene EA, Henikoff S, Comai L (2007a) Discovery of chemically induced mutations in rice by TILLING. *BMC Plant Biol* 7:19.

Till BJ, Comai L, Henikoff S (2007b) TILLING and EcoTILLING for crop improvement. In: Varshney RK, Tuberosa R (eds) Genomics-Assisted Crop Improvement, Vol. 1: Genomics Approaches and Platforms. Springer Netherlands.

Uauy C, Paraiso F, Colasuonno P, Tran RK, Tsai H, Berardi S, Comai L, Dubcovsky J (2009) A modified TILLING approach to detect induced mutations in tetraploid and hexaploid wheat. *BMC Plant Biol* 9:115.

Wang D-K, Sun Z-X, Tao Y-Z (2006) Application of TILLING in plant improvement. *Acta Genetica Sinica* 33: 957-964.

Wang T, Uauy C, Till B, Liu C-M (2010) Tilling and associated technologies. *J Integr Plant Biol* 52: 1027-1030.

Weil CF (2009) TILLING in grass species. *Plant Physiol* 149: 158-164.

Xin Z, Wang ML, Barkley NA, Burow G, Franks C, Pederson G, Burke J (2008) Applying genotyping (TILLING) and phenotyping analyses to elucidate gene function in a chemically induced sorghum mutant population. *BMC Plant Biol* 8: 103 -116.

5. Regeneration and Transformation Studies on Tef

Sonia Plaza-Wüthrich and Zerihun Tadele*
Tef Improvement Project, Institute of Plant Sciences, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland. *Corresponding author: zerihun.tadele@ips.unibe.ch

Biotechnological techniques such as in vitro regeneration and transformation significantly contributed towards the improvement of many crops. However, little research has been done on tef using these tools. These two techniques (i.e. genetic improvement and biotechnological methods) are basically very much inter-dependent. This is particularly true as the efficiency of transformation is significantly influenced by the efficacy of in vitro regeneration. Similar to other cereals, in vitro regeneration in tef is significantly influenced by genotype, type of explant, and composition and conditions of culture medium. Explants derived from diverse tef tissues were converted to callus which were later regenerated into the whole plant. So far, only few transformation studies were made on tef and all of them were on transient expression of the introduced genes. In these transient transformation studies, the efficiencies of biolistic bombardment and Agrobacterium-mediated transformation methods were investigated. In addition, promoters from a viral 35S and plant ubiquitin and actin were tested. However, not a single stable transformation study was so far made for tef. Hence, future research needs to focus on establishing stable transformation method for easy delivery of agronomically and nutritionally useful traits in this under-studied crop.

Key words: *in vitro* regeneration, embryogenesis, explant, transformation, particle bombardment, *Agrobacterium*-mediated transformation

5.1. Introduction

Tef research in the last five decades focused on conventional breeding that included selection and hybridization. Modern biotechnological methods such as genetic transformation were not extensively studied in tef and would offer promising approaches to complement and accelerate the conventional tef breeding and thereby bring to farmers new improved varieties by introducing agronomically and nutritionally useful traits. In general, *in vitro* regeneration has several advantages including i) the production of exact copies of plants with desirable traits, ii) the production of plants in the absence of seeds or pollinators, iii) the production of plants clean of viral and other pathogen infections, and iv) the regeneration of plants from cells that have been genetically modified. Moreover, *in vitro* regeneration can be used for induced mutation breeding program or for modern biotechnological methods such as somatic hybridization, doubled haploid development or genetic transformation.

However, these modern methods require an efficient *in vitro* regeneration system and therefore, optimization of tissue culture is needed. Different *in vitro* regeneration studies in tef have been done since 1995 (Endashaw *et al.*, 1995) showing, similar to other cereals, a strong dependence on the type of explant and genotype, and culture medium and conditions. Regarding genetic transformation attempts, so far only transient studies have been done proving that tef could be transformed *via* the biolistic and the *Agrobacterium tumefaciens*-mediated transformation protocols. For optimization, different promoters such as ubiquitin of maize, actin of rice and the cauliflower mosaic virus 35S have been compared. Hence, in this review we present studies made for tef in the area of *in vitro* regeneration and transformation and point out the way forward.

5.2. *In Vitro* Regeneration

An efficient *in vitro* regeneration system in tef is necessary for the genetic improvement of the crop species. The *in vitro* regeneration or plant tissue culture technique is an asexual method of propagation to produce from an explant clones in large quantities. In principle, any type of living cell has the ability to proliferate *in vitro* and regenerate into whole organism in the presence of adequate nutritional and environmental conditions. This ability of plants to regenerate from pieces of plant parts or even single cell is known as totipotency. However, monocots which include all cereal crops were shown to be more recalcitrant to *in vitro* regeneration than dicots. Regeneration is also influenced by the type of explants. Various studies were made in the last two decades in order to investigate optimum *in vitro* regeneration method for tef. Based on investigations made so far, it was noted that similar to the results found in other plant species, successful regeneration is dependent on the type of explant, media and growth regulators or hormones. The following review is structured according to the explants used for diverse regeneration experiments involving tef. Explants used for the studies include roots, leaf, mature and immature embryos and mature embryos. Table 1 shows summary of the *in vitro* culture and regeneration studies made on tef.

Table 1. The maximum percentage of callus and plantlet formation found in various tef in vitro culture studies (The values for callus formation were calculated based on the initial number of explants while those for plantlet formation were based on the number of calli used for the study. The type culture medium and plant growth regulators (PGRs) used are indicated. n.a. refers to data not available).

Explant	Callus		Plantlet		Reference
	Medium (PGR)	Formation (%)	Medium (PGR)	Formation (%)	
Mature seeds	MS (2,4-D or 3,6-D)	7.5		Very few	Endashaw *et al.* (1995)
	MS (2.4-D)	90.4		n.a.	Mulu (1995); Mulu *et al.* (1996)
	MS (2,4-D)	42.8	MS (GA_3)	81.0	Assefa *et al.* (1998)
	MS (2,4-D)	94.9		-	Fufa (1999)
Immature embryos	KBP (2,4-D)	94.2	K4NB (BAP)	88.4	Likyelesh and Kumlehn (2011)
	KBP (2,4-D)	92.5	K4NB (BAP)	95.8	Plaza-Wüthrich and Tadele (*in preparation)*
Immature spikelets or panicle segments	N6 (2,4-D)	76.5	n.a.	55.0	Mulu (1995)
	N6 (2,4-D)	95.2	n.a.	57.15	Hailu *et al.*(1999)
	MS (2,4-D)	38.6	MS	12.2	Likyelesh *et al.* (2006)
Anthers	N6 (2,4-D)	7.0		-	Mulu (1995)
	N6 (2,4-D)	12.6		-	Hailu *et al.* (1999)
	N6 (2,4-D)	43.4	MS (BAP; NAA)	26.0	Asfaw *et al.* (2009)
Ovary	N6 (2,4-D)	3	n.a.	-	Hailu *et al.* (1999)
Young seedling leaves	MS (2,4-D or 3,6-D)	27.5	MS	4.4	Endashaw *et al.* (1995)
	MS (dicamba)		MS (dicamba)	40.0	Firew *et al.* (1997)
Young seedling roots	MS (2,4-D or 3,6-D)	24.8	MS	2.2	Endashaw *et al.* (1995)

5.2.1. *Leaf and root segments*

Leaf and root segments from one-week-old seedlings gave up to 40% regeneration frequency (Firew *et al.*, 1997). Callus was initiated from these young leaves placed on the MS medium containing 2,4-D or 3,6-D (Endashaw *et al.*, 1995) or dicamba (Firew *et al.*, 1997). Pieces of roots also transformed to callus using the MS medium together with either 2,4-D or 3,6-D (Endashaw *et al.*, 1995). In these two cases, two types of calli were formed: embryogenic and non-embryogenic callus. The leaf base was shown to exhibit higher callus formation than the leaf tip as the former shows a continuous growth similar to meristematic region. According to Endashaw *et al.* (1995) leaves were more efficient than roots in callus formation particularly when using the hormone 3,6-D. Although the concentration of hormone considerably affects the efficiency of callus formation in leaves, it had negligible influence on the roots. Direct embryogenesis without callus formation step was not a common phenomenon in regenerants derived from both the leaves and roots (Endashaw *et al.*, 1995).

In order to regenerate the whole plant, the calli derived from leaves and roots were transferred to a medium containing 3,6-D or 2,4-D supplemented with ABA, BAP and kinetin for three weeks in the dark and two weeks with light in order to initiate and maturate embryos before their growth on compost (Endashaw *et al.*, 1995). In the other study, calli derived from leaf segments were maintained in the same medium but moved to light for three weeks before being transferred to pots (Firew *et al.*, 1997).

5.2.2. Mature seeds

Different studies have been done using mature seeds as explants. Huge variations in the efficiency of callus formation were reported when seeds were used as an explant. These variations ranged from less than 10 to over 90 percent (Endashaw *et al.*, 1995; Fufa, 1999 as cited in Kebebew *et al.*, 2001). Although genotypes of tef had substantial effect on the biomass of callus, different levels of auxin ranging from 2.5 to 10 mg/l of 2,4-D did not influence the callus formation process (Endashaw *et al.*, 1995). Unlike explants from young seedling roots and leaves, those from mature seeds mostly induced only mucilaginous and undifferentiated callus which resulted in very few regenerated plants. However, other researchers demonstrated that mature seed is a suitable explant for tef *in vitro* regeneration (Kebebew *et al.*, 1998).

The rate of callus formation is not only dependent on the genotypes but also on the type of culture media and the level of pre-culturing γ-ray irradiation treatment (Mulu *et al.*, 1996). Over 90% callus induction was obtained using MS media and 2.5mg/l dicamba or N6 media and 2mg/l 2.4-D. Moreover, in this experiment, semi-solid induction media were shown to produce better results than solid ones. The rate of somatic embryogenesis formation was higher in cultivar DZ-Cr-37 (*Tsedey*) compared to cultivar DZ-01-354 (*Enatite*). Increased levels of γ–ray irradiation of the pre-cultured mature seeds had significant deleterious effects on the callus formation. Although untreated seeds results in over 70% callus formation, those treated with 750 and 1000 Gy gave only 60% callus induction.

Various plant growth regulators (PGRs) were evaluated for their effects on callus induction and 2,4-D was found to be the best compared to TIBA and dicamba (Kebebew *et al.*, 1998). In the presence of 2,4-D, soft and creamy undifferentiated calli were induced which will afterwards developed embryogenic-like tissues on media with reduced 2,4-D concentration.

Significant influence of 2,4-D concentration (0.5 to 8 mg/l) was found on callus formation of DZ-Cr-37, and the highest percentage of somatic embryogenesis was found with 0.5 mg/l and the lowest was with 8 mg/l of 2,4-D (Fufa, 1999 referred in Kebebew *et al.*, 2001). Furthermore, no beneficial effects on callusing and somatic embryogenesis were obtained due to the addition of kinetin, zeatin or BAP to a MS medium containing 2,4-D.

5.2.3. Immature spikelets and embryos

The regeneration capacity of plants derived from immature spikelet and panicle segments depends on the type of media, growth regulators and sugar. The N6 medium supplemented with 2,4-D promoted higher callus formation. Moreover, immature spikelets grown on the solid medium gave higher percentage of callus than on the liquid one. The rate of callus formation was improved using maltose than sucrose as a sugar source (Mulu, 1995 reviewed in Kebebew *et al.*, 2001). Immature spikelets incubated in the dark resulted in higher percentage of callus formation than those in the light. Callus induction was also improved by treating seeds used as donor for immature spikelets with γ-irradiations doses of 750 and 1000 Gy. Regeneration efficiency was also influenced by the genotypes of tef. Improved cultivars such as DZ-01-99 (*Asgori*) gave superior callus induction than DZ-01-797, DZ-01-196 (*Magna*), DZ-Cr-82 (*Melko*), DZ-Cr-44 (*Menagesha*) and DZ-Cr-255 (*Gibe*; Mulu, 1995 cited in Kebebew *et al.*, 2001).

In contrast with these results, Hailu and colleagues found no callus formation differences of cultured immature spikelets due to the different genotypes tested and also due to gamma irradiation treatments (Hailu *et al.*, 1999 mentioned in Kebebew *et al.*, 2001). Immature spikelets were also successfully regenerated into whole plant particularly by pre-incubation of the central panicles at 4 °C for 36 hours (Likyelesh *et al.*, 2006).

Recently, immature embryos were found to be the best explant yielding over 80% regeneration (Likyelesh and Kumlehn, 2011; Plaza-Wüthrich and Tadele *in preparation*). The optimum medium for this regeneration is composed of the KBP minerals supplemented with maltose, glutamine and phytagel (Likyelesh and Kumlehn, 2011). Preliminary results showed huge variability in the frequency of embryogenesis and regeneration among 18 tef genotypes (Plaza-Wüthrich and Tadele *in preparation).* Fig. 1 shows the steps and time interval from immature embryo to fully developed plant. Two genotypes with contrasting performance are *Manyi* and *Tsedey* (DZ-Cr-37). Both embryogenesis and plantlet formation were significantly higher for *Manyi* than for *Tsedey* (Fig. 1B).

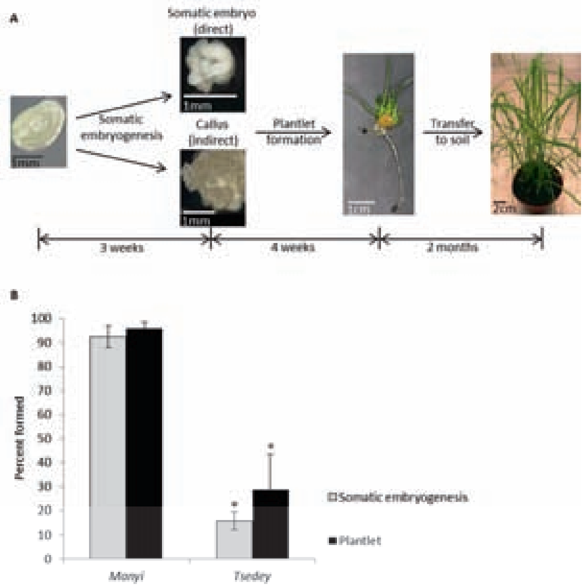

Figure 1. *In vitro* regeneration in tef using immature embryos as an explant. A) Steps in regeneration process. Somatic embryogenesis can either either directly or indirectly through callus formation. Plantlets were transferred to long-day growth chamber (16 h light) for three weeks before transferring to 8 h light for flowering and seed setting. B) The frequency of embryogenesis and plantlet formation in two genotypes of tef (Plaza-Wüthrich and Tadele *in preparation*). *Manyi* is one of the tef genotypes while *Tsedey* is an early maturing improved cultivar. Somatic embryogenesis was performed in KBP minerals media plus 90 g/l maltose, 1 g/l glutamine and 2 mg/l 2,4-D in the dark while plantlet formation was done at 14 h light in KBP minerals media with 36 g/l maltose, 0.15 g/l glutamine and 0.4 mg/l BAP.

5.2.4. Anthers and ovaries

Anthers from three tef genotypes, namely: DZ-Cr-37 (*Tsedey*); DZ-01-354 (*Enatite*); and DZ-01-196 (*Magna*) formed callus and regenerated into whole plants (Asfaw *et al.*, 2009). The best medium in anther culture with about 40% of callus formation was a semi-solid N6 supplemented with 2,4-D. Once the callus was formed, MS media supplanted with BAP and NAA facilitated the regeneration process.

Tef ovaries *in vitro* regeneration on same medium used for anthers showed poor callus induction (Hailu *et al.*; 1999 cited in Kebebew *et al.*, 2001). Moreover, callus formation occurred in 3% of ovaries of the tef cultivar *Fesho* irradiated with 700 Gy of gamma ray and less than 1% for DZ-01-354 with no gamma ray treatment.

The same medium used for immature spikelet *in vitro* regeneration (i.e. solid N6 with maltose and 2,4-D) was also used for anther regeneration. Pre-treatment of anthers with mannitol, medium containing glutamine or MS medium showed no callus formation. Variation between the genotypes was also observed (DZ-Cr-37, DZ-01-354, cultivars *Alba* and *Fesho*) (Mulu, 1995; Hailu *et al.*, 1999 both referred in Kebebew *et al.*, 2001). The callusing frequency of anthers was far lower than the frequency noted for immature spikelets. In contrast to the stimulatory effect of gamma irradiation of seeds giving donor plants on callusing from immature spikelets, a depressing effect of irradiation was found in the case of anthers.

5.3. Transformation

For delivering DNA encoding a desirable trait, two methods, namely physical and biological are used. The physical techniques include particle or microprojectile bombardment and electroporation. The only successfully applied biological method is an *Agrobacterium tumefaciens*-mediated transformation. So far, only limited studies were made on tef transformation. Table 2 shows a summary of methods, explants and promoters used in these transformations. The review in this section is structured based on the method of transformation implemented. Although the ultimate goal of transformation is to deliver to crop plants agronomically or nutritionally important traits that are inherited to next generations, studies made so far on tef transformation dealt with only the transient expression in which the investigations were made only several days after transformation. Hence, the results from these types of experiments do not indicate the heritability of the new or transferred traits to next generations and the integration pattern of the transgene.

Table 2. Summary of transformation studies in tef indicating the transformation method and promoter used are indicated (n.a. refers to data not available).

Explant	Transformation method	Promoter	Reference
Protoplast	Electroproration	n.a.	Endashaw (1995)
Callus tissues	Microprojectile bombardment	Ubiquitin, actin, 35S	Plaza-Wüthrich and Tadele (*in preparation)*
Zygotic embryos, mature seeds, seedlings, leaf base segments and callus tissues	*Agrobacterium*	n.a.	Firew *et al.* (2001)
Callus tissues	*Agrobacterium*	Ubiquitin, actin, 35S	Plaza-Wüthrich and Tadele (*in preparation)*

5.3.1. Agrobacterium-mediated transformation

In order to investigate whether the *Agrobacterium* can attach itself to the surface of tef explants used for transformation, Firew and colleagues tested six *Agrobacterium* strains with different virulence level (Firew *et al.*, 2001). Diverse types of explants were investigated including zygotic embryos, mature seeds and callus. In addition, the effects of mechanical wounding and acetosyringone on the attachment of *Agrobacterium* were investigated. Acetosyringone is a chemical proven to induce the virulence genes of *Agrobacterium* and thereby promote transformation (Sheikholeslam and Weeks, 1987). The attachment to the surface of tef explants were observed for all *Agrobacterium* strains (Firew *et al.*, 2001). Higher and uniform bacterial attachment was obtained only using acetosyringone, suggesting that mechanical wounding cannot substitute acetosyringone in producing phenolic compounds that induce the attachment. While increased level of attachment was obtained for meristematic and embryogenic seedlings, the lowest binding was reported for mature seeds.

Transient expression of the reporter gene β-glucordinase (GUS) indicated that the *Agrobacterium* was not only attached to the surface of the explant, but also entered the cell (Plaza-Wüthrich and Tadele *in preparation*). The transient expression was observed for all three promoters and the three A*grobacterium* strains tested.

5.3.2. Particle bombardment

Particle bombardment using callus tissues derived from immature embryos revealed equal transient expression for the GUS gene under the control of the three promoters namely ubiquitin and actin from monocot and 35S from virus (Plaza-Wüthrich and Tadele, *in preparation*).

5.3.3. *Electroporation*

The only report available for using electroporation in tef transformation was where the viability of protoplasts were tested after treating with various field pulse strengths (Endashaw, 1995). Higher transformation was observed using 700 V/cm for 40 □s although at this leve

5.4. The Way Forward

Although both regeneration and transformation play key role in crop improvement, sufficient studies were not made on tef using these techniques. Hence, the following suggestions are given for future research.

5.4.1. *Regeneration*

In vitro regeneration is widely applied to crop improvement. The optimization of the technique is a pre-requisite for establishing efficient transformation method. Although various parameters regulate the effectiveness of regeneration, the two dominant factors influencing the regeneration are the type of explant and the composition of culture media. Achievements made for rice and millets such as pearl millet could be applied to tef (Plaza-Wüthrich and Tadele, 2012).

Explants: Although every plant part has the ability to regenerate, significant variations were observed in the frequency of regeneration among different explants. Recent studies indicated that immature embryos are becoming the explant of choice for tef regeneration. The main problem associated to immature embryos is the need for continuous growth of donor plants. Hence, efforts should be made to investigate for alternative explants regarding accessibility, quantity and cost. Explants such as the transverse thin cell layers (tCLPs) proved to increase the regeneration capacity in recalcitrant genotypes of rice, sorghum and maize (Nhut *et al.*, 2003). Studies in other crops indicated that the viability of an explant could be prolonged by shortening the somatic embryogenesis phase using TDZ (thidiazuron), a cotton defoliant with cytokinin-like activity (Mok *et al.*, 1982). TDZ has been used for the enhancement of morphogenic competence in *Poaceae* since the mid-1990s (Wenzhong *et al.*, 1994) and in millets (Gupta and Conger, 1998; Vikrant and Rashid, 2002; Ceasar and Ignacimuthu, 2008).

Genotype: As indicated above, diverse genotypes of the same crop species show huge variability in the efficiency of regeneration. Preliminary investigation using 18 tef genotypes also confirmed similar results (Plaza-Wüthrich and Tadele *in* *preparation*). Hence, large scale screening methodology is needed in order to determine the regeneration capacity for diverse genotypes of tef as it was investigated for rice (Dabul *et al.* 2009).

Culture media: The composition of the culture medium is another important factor affecting the efficiency of the *in vitro* regeneration in crop species including millets. Regarding tef *in vitro* regeneration, diverse types of growth media were suggested by different investigators. Although MS is widely used in tef regeneration, N6 medium was preferentially applied for explants such as immature spikelets, panicle segments and anthers (Mulu, 1995; Hailu *et al.*, 1999 both cited in Kebebew *et al.*, 2001; Asfaw *et al.*, 2009). Media composed of the KBP minerals was also proved to be conducive to regenerate tef plants from immature embryos (Deutsch *et al.*, 2004; Kumlehn *et al.*, 2006; Likyelesh and Kumlehn, 2011; Plaza-Wüthrich and Tadele *in preparation*). Although different media were suggested for different types of explants, studies were not made to compare the relative advantage of each media in terms of cost and efficiency of regeneration. The amount of gelling agent (for example, agar, phytagel) also influenced the regeneration efficiency by regulating the ease with which water and nutrients are available for the plant (Likyelesh and Kumlehn, 2011). Hence, comparative advantage among diverse culture media and explant need to be done using widely grown genotypes and/or cultivars of tef.

Plant growth regulators (PGRs): PGRs influence largely the *in vitro* regeneration steps; hence, optimization of the right types and amounts of PGRs is necessary. Several studies showed that auxin in the form of either 2,4-D or 3,6-D is necessary for tef regeneration, although some other reports indicated that tef can regenerate into whole plant without exogenous application of any growth hormone (Endasahw *et al.*, 1995; Likyelesh *et al.*, 2006).

Carbon sources: The carbon source type and concentration also influence *in vitro* regeneration of major crops. An increased osmolarity due to sucrose, sorbitol, mannitol and maltose improved embryo formation and maintenance in maize (Lu *et al.*, 1983). Moreover, the substitution of sucrose by maltose improved the rate of embryogenesis and regeneration in tef cultures of immature spikelets, anthers and embryos, and as such maltose was preferred to sucrose (Mulu, 1995; Asfaw *et al.*, 2009; Likyelesh and Kumlehn, 2011).

Environmental conditions: Environmental factors such as light, temperature, and humidity significantly influence the efficacy of *in vitro* regeneration. Somatic embryogenesis normally occurs under dark conditions while plantlet formation requires light. Light related parameters such as intensity, duration and quality (wavelength) have huge impact on the efficiency of plantlet formation. The changes in temperature have drastic effect on tef regeneration. Our experience showed that a decrease of 2°C in the growth room for 2 days resulted in a complete failure to form plantlets from immature embryo-derived explants (Plaza-Wüthrich and Tadele, unpublished).

5.4.2. Transformation

The main goal of establishing optimum transformation method is to facilitate the delivery of valuable traits to crop plants. Hence, using efficient transformation technique, agronomically and nutritionally important traits could be transferred to enhance crop productivity and nutritional quality. Significant progresses have been made in transforming major cereals such as rice, maize and wheat (for review Repellin *et al.*, 2001) but not for minor cereals such as tef. Moreover, the few transformation studies made so far for tef focused only on transient expression and not on the stable transformation. Transient expression shows some indications about the transgene only for a few days after transformation, but does not indicate heritably transferred transgene to next generation. Hence, future research needs to focus on establishing optimum transformation method for tef that facilitates the delivery of transgene with desirable traits. The following parameters need to be considered in developing optimum transformation method for tef.

Method of transformation: *Agrobacterium*-mediated transformation is becoming the main mode of transformation for major cereals (Komari and Kubo, 1999; Koichi *et al.*, 2002) especially due to its simple integration pattern in the plant genome. Preliminary investigation done with somatic embryos derived from immature embryos showed that the two methods (i.e. microprojectile bombardment and Agrobacterium-mediated transformation) proved to work equally (Plaza-Wüthrich and Tadele *in preparation*).

Agrobacterium strains: The *Agrobacterium*-mediated transformation is dependent on the choice of appropriate strain. Our preliminary results showed that LBA4404 and EHA105 strains gave higher transformation efficiency than the strain GV3101.

Promoters: Promoters play key role in determining the time, location and strength of transgene expression. For tef transient expression studies, two monocot promoters, namely: ubiquitin (from maize); and actin (from rice) as well as a viral 35S promoter resulted in modest transformation. Since no stably transformed tef was reported to d ate, the right type of promoter was not yet determined. Hence, future research needs to focus in identifying the best promoters for stable transformation using *Agrobacterium*-mediated and bombardment methods. Promoter derived from plant (e.g actin and ubiquitin) is preferred to non-plant promoter (e.g. 35S) as the former partly reduce the concern of consumers regarding the use of promoters from micro-organisms. Transformation method in which plant-specific promoters are employed is known as cis-genesis (Schouten *et al.*, 2006).

Selectable markers: Commonly used selectable markers include antibiotic resistance (e.g., *hygromycin phosphotransferase gene* that confers resistance against hygromycin, and *neomycin phosphotransferase* gene that confers resistance against kanamycin) and herbicide resistance (*phosphinothricin acetyl transferase* gene against bialaphos or basta). Selectable markers developed from the *phosphomannose isomerase* (*manA*) gene and the modified α-tubulin gene were shown to give promising results in millet transformation (O'Kennedy *et al.*, 2004; Yemets *et al.*, 2008). The latter two selectable markers have advantages over the other selectable methods since they avoid the use of antibiotics or herbicides along the transgene. Hence, future transformation studies need to investigate the application of these selectable markers.

In conclusion, although extensive studies were made on tef regeneration, only limited transient transformations were reported. However, so far no stable transformation was investigated. Hence, future research on tef transformation needs to develop robust transformation protocols for diverse genotypes and/or ecotypes of tef.

5.5. Abbreviations and Acronyms

2,4-D: (2,4-dichlorophenoxy)acetic acid; **3,6-D**: dichloromethoxybenzoic acid; **ABA**: abscisic acid; **BAP**: 6-benzylaminopurine; **Dicamba**: 3,6-Dichloro-2-methoxybenzoic acid; **GA_3**: Gibberellic acid; **GUS**: β-glucordinase; **KIN**: kinetin; MS: Murashige and Skoog; **NAA**: α-naphthaleneacetic acid; **PGR**: Plant growth regulator; **tCLPs**: transverse thin cell layers; **TDZ**: thidiazuron; **TIBA**: 2,3, 5-triiodobenzoic acid.

5.6. Glossary

Embryogenesis: the process by which an explant produces an embryo; **Explant**: part of the plant such as plant cells, tissues and organs that are used to regenerate a whole plant; ***In vitro* regeneration**: asexual method of propagation to produce from an explant clones in large quantities; **Transformation** (or **genetic engineering**): a process by which a foreign gene is inserted to the target tissue or plant.

5.7. Acknowledgements

We would like to thank Syngenta Foundation for Sustainable Agriculture and the University of Bern for financial support provided to our Tef Improvement Project.

5.8. References

Asfaw Tadesse, Hailu Tefera, Guzmann M, Zapata FJ, Afza R and Mba C. 2009. Androgenesis. *In*: Tournaev A (eds). Advances in Haploid Production in Higher Plants. pp: 274- 283.

Ceasar SA and Ignacimuthu S. 2008. Efficient somatic embryogenesis and plant regeneration from shoot apex explants of different Indian genotypes of finger millet (*Eleusine coracana* (L.) Gaertn.). *In Vitro* Cell Dev. Biol.-Plant 44:427-435.

Dabul ANG, Belefant-Miller H, RoyChowdhury M, Hubstenberger JF, Lorence A and Philips GC. 2009. Screening of a broad range of rice (*Oryza sativa* L.) germplasm for *in vitro* rapid plant regeneration and development of an early prediction system. *In Vitro* Cell Dev. Biol.-Plant 45: 414-420.

Deutsch F, Kumlehn J, Ziegenhagen B and Fladung M. 2004. Stable haploid poplar callus lines from immature pollen culture. Physiol. Plant 120: 613-622.

Endashaw Bekele. 1995. Electric field mediated fusion of *Eragrostis tef* and *Sorghum bicolor* protoplasts and their electroporation conditions. Hereditas 123: 199-203.

Endashaw Bekele, Klock G and Zimmermann U. 1995. Somatic embryogenesis and plant regeneration from leaf and root explants and from seeds of *Eragrostis tef* (Gramineae). Hereditas 123: 183-189.

Firew Mekbib, Mantell SH and Buchanan-Wollaston V. 1997. Callus induction and *in vitro* regeneration of tef [*Eragrostis tef* (Zucc.) Trotter] from leaf. J. Plant Physiol. 151: 368-372.

Firew Mekbib, Buchanan-Wollanton V and Mantell SH. 2001. Attachment study of *Agrobacterium tumefaciens* to tef (*Eragrostis tef* (Zucc.) Trotter), yam spp. and tobacco (*Nicotiana tabaccum*) explant. Ethiop J Sci 24: 185-195.

Fufa Hundera. 1999. Final Technical Report Submitted to the International Atomic Energy Agency Office, TJ2115, National Academy of Science, National Research council, Washington D.C., 2018.

Gupta SD and Conger BV. 1998. *In vitro* differentiation of multiple shoot clumps from intact seedlings of switchgrass. *In Vitro* Cell Dev. Biol.-Plant 34: 196-202.

Hailu Tefera H, Zapata-Arias FJ, Afza R and Codym A. 1999. Response of tef genotypes to anther culture. Agritopia 14 (1): 8-9.

Kebebew Assefa, Gaj MD and Maluszynski M. 1998. Somatic embryogenesis and plant regeneration in callus culture of tef, *Eragrostis tef* (Zucc.) Trotter. Plant Cell Reports 18: 154-158.

Kebebew Assefa, Hailu Tefera, Likyelesh Gugsa, Fufa Hundera and Tiruneh Kefyalew. 2001. *In vitro* manipulation of tef. *In*: Hailu Tefera, Getachew Belay and Mark Sorrells (eds.). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia, 16-19 October 2000, Ethiopian Agricultural Research Organization. pp:131-144.

Koichi T, Bae CH, Seo MS, Song LJ, Lim YP, Song PS and Lee HY. 2002. Overcoming of barriers to transformation in monocot plants. J. Plant Biotechnol. 4: 135-141.

Komari T and Kubo T. 1999. Methods of genetic transformation: *Agrobacterium tumefaciens*. *In*: Vasil IK (ed): Molecular improvement of Cereal Crops. Kluwer pp 43-82.

Kumlehn J, Serazetdinova L, Hensel G, Becker D and Loerz H. 2006. Genetic transformation of barley (*Hordeum vulgare* L.) *via* infection of androgenetic pollen cultures with *Agrobacterium tumefaciens*. Plant Biotechnol. J. 4: 251-261.

Likyelesh Gugsa, Sarial AK,˜Lörz H and Kumlehn J. 2006. Gynogenic plant regeneration from unpollinated flower explants of *Eragrostis tef* (Zuccagni) Trotter. Plant Cell Reports 25: 1287-1293.

Likyelesh Gugsa and Kumlehn J. 2011. Somatic embryogenesis and massive shoot regeneration from immature embryo explants of tef. Biotechnol. Res. Int. 2011. doi: 10.4061/2011/309731.

Lu C, Vasil V and Vasil JK. 1983. Improved efficiency of somatic embryogenesis and plant regeneration in tissue cultures of maize (*Zea mays* L.) Theor. Appl. Genet. 66:285-289.

Mok MC, Mok DW, Amstrong DJ, Shudo K, Isogai Y and Okamanto T. 1982. Cytokinin activity of N-phenyl-N'-1,2,3-thiadiazol-5-urea(thidiazuron). Phytochemistry 21: 1509-1511.

Mulu Ayele. 1995. Final technical report submitted to the fellowship and training section of the International Atomic Energy Agency. Vienna, Austria.

Mulu Ayele, Zapata FJ, Afza R and van Duran M. 1996. Plant regeneration from seed derived calli of tef: Effects of callus induction media and radiation treatment. IAR Newsl. Agric. Res. 11: 3-4.

Nhut DT, Silva JAT, Bui VL and Tran Thanh Van K. 2003. Organogenesis of cereals and grasses by using thin cell layer technique. *In*: Nhut DT, Van Le B, Tran Thanh Van K and Thorpe T (eds.). Thin cell layer culture system: regeneration and transformation applications. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 427-449.

O'Kennedy MM, Burger JT and Botha FC. 2004. Pearl millet transformation system using the positive selectable marker gene phosphomannose isomerase. Plant Cell Reports 22: 684-690.

Plaza-Wüthrich S, and Tadele Z. 2012 Millet improvement through regeneration and transformation. Biotech Mol Biol Rev 7: 48-61.

Repellin A, Baga M, Jauhar PP and Chibbar RN. 2001. Genetic enrichment of cereal crops *via* alien gene transfer: New challenges. Plant Cell Tissue Organ Culture 64: 159-183.

Schouten HJ, Krens FA and Jacobsen E. 2006. Cisgenic plants are similar to traditionally bred plants: International regulations for genetically modified organisms should be altered to exempt cisgenesis. EMBO Rep 7: 750-753.

Sheikholeslam SN and Weeks DP. 1987. Acetosyringone promotes high efficiency transformation of *Arabidopsis thaliana* explants by *Agrobacterium tumefaciens*. Plant Molecular Biology 8:291-298.

Vikrant and Rashid A. 2002. Induction of multiple shoots by thidiazuron from caryopsis cultures of minor millet (*Paspalum scrobiculatum* L.) and its effect on the regeneration of embryogenic callus cultures. Plant Cell Reports 21: 9-13.

Wenzhong T, Rance I, Sivamani E, Fauquet C and Beachy RN, 1994. Improvements of plant regeneration frequency *in vitro* in Indica rice. Chinese Journal of Genetics 21: 105-112.

Yemets AI, Radchuk V, Bayer O, Bayer G, Pakhomov A, Vance Baird W and Blume Y. 2008. Development of transformation vectors based upton a modified plant α-tubulin gene as the selectable marker. Cell Biol. Int. 32: 566-570.

II. Genetic & Genomic Mapping

6. Genetic Mapping of Tef

Mahmoud Zeid[1*], Solomon Chanyalew[2] and Mark E. Sorrells[3]

[1]Crop Science Dept., Faculty of Agriculture, Alexandria University, Alexandria, Egypt; [2]Ethiopian Institute of Agricultural Research, Debre Zeit Research Center, P.O.Box 32, Debre Zeit, Ethiopia; [3]Department of Plant Breeding and Genetics, 240 Emerson Hall, Cornell University, Ithaca, NY 14853, USA. [*]Corresponding author: mkzeid@yahoo.com

Tef linkage maps have been adopted only recently as an essential step towards a marker assisted breeding program to detect quantitative trait loci (QTL) controlling traits of a quantitative nature. The main reason behind this delay was insufficient funding to develop and test molecular markers for the crop species. The first map was developed in 1999 for an intra-specific cross between two tef cultivars, Kaye Murri and Fesho. The map was AFLP-based and comprised 25 linkage groups. Since then, various PCR-based markers have been evaluated and used to update available linkage maps. The most recent linkage map was established using simple-sequence repeat markers (SSR) and 151 F_9 *individuals from the inter-specific cross (E. tef × E. pilosa), and it comprised 30 linkage groups. The future of linkage mapping relies on the utilization of high throughput marker techniques that are constantly becoming cheaper. Also, mapping using sequence-based markers is an important platform for comparative genomics studies with model species and better-researched grass crops. In addition, linkage maps for intra-specific tef crosses rather than inter-specific crosses will become the main target of future studies, as SSR markers have shown that enough variation existed within the tef germplasm to construct dense linkage maps. Intra-specific mapping populations will be more relevant to breeding programs, and the maps will likely have fewer distorted loci that are characteristic of inter-specific crosses. QTL identification, especially for lodging resistance, will also benefit from the improvement of linkage maps provided that an improved, standard measuring technique for this trait is established.*

Key words: genetic map, tef, *Eragrostis tef*, quantitative trait loci (QTL), simple-sequence repeat (SSR) markers

6.1. Linkage Mapping in Tef

A linkage map represents a 'road map' of the chromosomes derived from two different parents (Paterson, 1996), and indicates the position and relative genetic distances between markers along chromosomes. The two main components to construct a linkage map are a mapping population and a large number of polymorphic molecular markers (Collard *et al.*, 2005). Linkage mapping in tef started in the late nineties when the first linkage map was constructed using 85 recombinant inbred lines (RILs) from an intra-specific cross (Kaye Murri × Fesho) employing 211 AFLP loci (Bai *et al.*, 1999). The map comprised 25 linkage groups and covered 2,149 cM of the genome; however, the level of polymorphism between the two parental lines was extremely low (6.1%). To overcome this unexpected low level of marker polymorphism between two morphologically diverse varieties, and at the same time to combine contrasting levels of lodging-related traits, attention was drawn to an inter-specific population that was developed earlier using the short statured wild relative *Eragrostis pilosa* that at the same time is crossable with tef (both are allotetraploids), and the cultivar Kaye Murri. Zhang *et al.* (2001) utilized 116 RILs of this new cross (*E. tef* (Kaye Murri) × *E. pilosa* (30-5)) and restriction fragment length polymorphism (RFLP) markers (using tef cDNA probes and heterologous cDNA probes from rice, barley and oat) to develop a new map. The linkage map defined 1,489 cM of the tef genome comprising 149 RFLP loci distributed among 20 linkage groups. This study of Zhang *et al.* (2001) realized a substantial increase in the level of polymorphism (67%) and initiated comparative mapping of tef with other members of the *Poaceae*, since 40% of the mapped markers were probes from other grass species. Utilizing 94 RILs of the same inter-specific cross, (Yu *et al.*, 2006) updated the map by mapping a set of tef-specific expressed sequence tag (EST) derived simple sequence repeats (SSR), commonly known as EST-SSR markers in addition to heterologous markers based on EST sequences from finger millet, rice and wheat. Markers were grouped into 21 linkage groups with a mean distance of 12.3 cM between markers. A second linkage map from an inter-specific cross between another variety (*E. tef* cv. DZ-01-2785) and the same *E. pilosa* accession (30-5) was published by (Solomon *et al.*, 2005). For this linkage map, 120 RILs were screened using AFLP, EST-SSR markers from tef and wheat, SSR markers from rice, and a set of inter-simple sequence repeats (ISSR) markers. The linkage map covered 78% of the genome and the average distance between markers amounted to 12.7 cM.

In all previous four linkage mapping studies in tef, the number of available polymorphic markers was always the limiting factor in saturating the map, and the best polymorphism level (24%) was observed with RFLP markers and EST-SSRs markers in the study (Zhang *et al.*, 2001) and (Yu *et al.*, 2006), respectively. Since genomic SSRs are known to be more polymorphic than EST-SSR markers in many other grass species *(Cho et al., 2000; Eujayl et al., 2001; Chabane et al.*, 2005), Zeid *et al.* (2011) utilized the DNA of the parental line Kaye Murri to develop more than 500 SSR markers. Fifty three percent of the tef-specific SSR markers developed proved to be polymorphic between the parental lines (Kaye Murri) and *E. pilosa* (30-5), and these were applied to 151 of their F_9 RILs. After excluding 33.5% of the markers due to distortion from the expected 1:1 ratio, a linkage map comprising 252 loci distributed across 30 linkage groups was constructed (Fig. 1). The individual linkage groups varied in length from 6.8 to 116.1 cM. The map covered an estimated 78.7% of the genome with an average distance of 5.7 cM between markers (Zeid *et al.*, 2011). Of the 252 loci present on the map 35 (14%) were shared with the map of Yu *et al.* (2006).

From the previous studies, continuous improvement in both the number of markers and size of the RIL populations used in linkage mapping in tef has been realized over time. The number of available polymorphic markers had been the limiting factor in improving the linkage mapping in tef until the SSR markers were developed. The size of the mapping population on the other hand was only a matter of optimizing the marker technique to handle larger sized populations. Zeid *et al.* (2012) fingerprinted more than 340 *Eragrostis* accessions using fluorescent labeled primers with PCR-multiplexes indicating that, even with a limited budget, good sized mapping populations could be screened with a large number of markers in a short period of time. Another significant result from the SSR-based study of Zeid *et al.* (2012), was the polymorphism level of 70% observed between the parents of the intra-specific cross (Kaye Murri × Fesho) employing SSR markers as opposed to the 6.1% polymorphism level employing AFLP markers (Bai *et al.*, 1999). This result suggests that revisiting this population using the newly developed SSR markers and focusing future mapping efforts on this and other intra-specific crosses would be useful. Intraspecific crosses often relate more to breeding populations and generally have fewer distorted markers making map construction less problematic (Doerge, 2002; Kassa *et al.*, 2006).

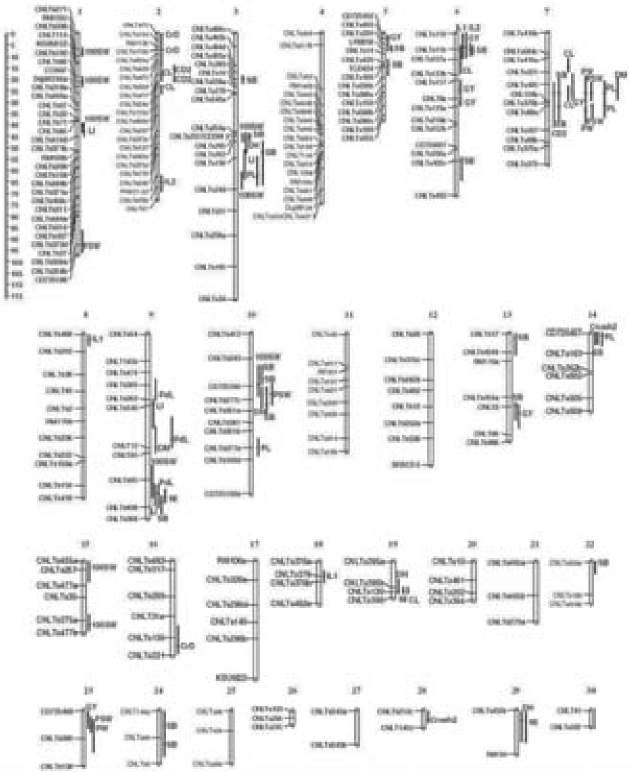

Fig. 1 Genetic linkage map of tef showing 83 QTL identified for 17 traits. Marker names are positioned equivalent to their cM distances on the left of the bars. Intervals for each QTL are indicated by the length of the vertical closed bars to the right of the linkage groups and the name of the trait underlying each QTL is given to the right of the linkage map (Zeid et al. 2011).

6.2. QTL Identification on Linkage Maps

Linkage maps are useful to identify chromosomal locations containing genes and quantitative trait loci (QTL) associated with traits of interest (Collard *et al.*, 2005). Three studies have identified QTLs for important traits in tef. The study of Solomon *et al.* (2005) identified 34 QTLs for yield and yield-related traits based on field studies in two locations for two years in Ethiopia. The other two studies of Yu *et al.* (2007) and Zeid *et al.* (2011) with different linkage maps utilized the same field data (twenty-two traits were evaluated at eight different locations in Ethiopia during the two-year period of 1999-2000). Grain yield showed significant positive correlation with panicle weight, panicle seed weight and panicle length. Also QTLs for those traits co-located with QTLs for grain yield in all three studies. Although the later two studies shared only 35 marker loci (14%) between their maps, the positions of the QTLs for grain yield on linkage group (LG13) and for peduncle length on LG9 in the study of Zeid *et al.* (2011) were identical with those in the study of Yu *et al.* (2007). QTL for lodging, an important negative trait in tef, were also identified in all three studies; however, none shared a similar position in any two of the three studies.

Association mapping using 26 primer pairs that were flanking QTL for various traits in tef including 100 seed weight, plant height, and lodging index was conducted by Zeid *et al.* (2011, 2012). They labeled primers using fluorescent dye and used the labeled primers to fingerprint 271 tef accessions. Their results have indicated that markers previously linked to QTL in the latest study of Zeid *et al.* (2011) were not associated with any of the expected traits. Despite the fact that these results did not meet the hopes of researches, it only reflects the challenges facing tef researches to saturate the current linkage map with more markers because the genome of tef is quite large, being an allotetraploid. It also draws attention to the importance of introducing new, more reliable phenotyping methods to measure complicated traits such as lodging (see Zeid *et al.*, 2011, 2012 for more details), so as to be able to facilitate and carefully locate QTL for such traits.

Current on-going projects on whole genome and transcriptome sequencing of tef (see Cannarozzi *et al.* in this compilation of proceedings), on the mechanics of lodging (see Vos *et al.* in this compilation of proceedings), and on dwarf tef lines (see Zerihun in this compilation of proceedings) are a promising start for identification and annotation of lodging resistance genes in tef. Comparative mapping could then be implemented in the tef crop that until today appears to be an "unexplored" grass species.

6.3. Abbreviations

LG: linkage group; QTL: quantitative trait loci; RFLP: restriction fragment length polymorphism; RIL: recombinant inbred line; SSR: simple-sequence repeat markers.

6.4. References

Bai G, Hailu Tefera, Mulu Ayele, and Nguyen HT. 1999. A genetic linkage map of tef [Eragrostis tef (Zucc.) Trotter] based on amplified fragment length polymorphism. Theor Appl Genet 99: 599-604.

Chabane K, Ablett GA, Cordeiro GM, Valkoun J and Henry RJ. 2005. EST versus genomic derived microsatellite markers for genotyping wild and cultivated barley. Genetic Resources and Crop Evolution 52: 903-909.

Cho YG, Ishii T, Temnykh S, Chen X, Lipovich L, McCouch SR, Park WD, Ayres N and Cartinhour S. 2000. Diversity of microsatellites derived from genomic libraries and GenBank sequences in rice (Oryza sativa L.). Theor Appl Genet 100: 713-722.

Collard, BCY, Jahufer MZZ, Brouwer JB and Pang ECK. 2005. An introduction to markers, quantitative trait loci (QTL) mapping and marker-assisted selection for crop improvement: The basic concepts. Euphytica 142: 169-196.

Doerge RW. 2002. Mapping and analysis of quantitative trait loci in experimental populations. Nature Reviews Genetics 3: 43-52.

Eujayl I, Sorrells M, Baum M, Wolters P and Powell W. 2001. Assessment of genotypic variation among cultivated durum wheat based on EST-SSRs and genomic SSRs. Euphytica 119: 39-43.

Kassa Semagn, Bjornstad Å and, Ndjiondjop MN. 2006. Principles, requirements and prospects of genetic mapping in plants. African Journal of Biotechnology 25: 2569-2587.

Paterson, AH. 1996. Making genetic maps. In: Paterson, A.H. (Ed.), Genome mapping in plants. Academic Press; Austin, Texas, R. G. Landes Company, San Diego, California, pp 23-39.

Solomon Chanyalew, Singh, H, Hailu Tefera and Sorrels M. 2005. Molecular genetic map and QTL analysis of agronomic traits based on a Eragrostis tef x E-pilosa recombinant inbred population. Journal of Genetics & Breeding 59: 53-66.

Yu JK, Graznak E, Breseghello F, Hailu Teferaand Sorrells ME. 2007. QTL mapping of agronomic traits in tef [Eragrostis tef (Zucc) Trotter]. BMC Plant Biol. 7: 13.

Yu JK, Kantety RV, Graznak E, Benscher D, Hailu Tefera and Sorrells ME. 2006. A genetic linkage map for tef [Eragrostis tef (Zucc.) Trotter]. Theor Appl Genet 113: 1093-1102.

Zeid M, Getachew Belay, Mulkey S, Poland J and Sorrells ME. 2011. QTL mapping for yield and lodging resistance in an enhanced SSR-based map for tef. TAG Theoretical and Applied Genetics 122: 77-93.

Zeid M, Kebebew Assefa, Aderajew Haddis, Solomon Chanyalew abd Sorrells, ME. 2012. Genetic diversity in tef (Eragrostis tef) germplasm using SSR markers. Field Crops Research 127: 64-70.

Zhang D, Mulu Ayele, Hailu Tefera and Nguyen HT. 2001. RFLP linkage map of the Ethiopian cereal tef [Eragrostis tef (Zucc) Trotter]. Theor Appl Genet 102: 957-964.

7. Genome and Transcriptome Sequencing of Tef

Gina Cannarozzi and Zerihun Tadele*
Tef Improvement Project, Institute of Plant Sciences, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland. *Corresponding author: zerihun.tadele@ips.unibe.ch

To support the molecular techniques being used to develop new cultivars as well as to discover new genes controlling traits of interest, the genome and transcriptome of tef have been sequenced. Here, the process of sequencing, assembling and analyzing the genome and transcriptome of tef is presented. Genomic sequences collected using 454 and Illumina platforms to a depth of 47x coverage were assembled using the SOAP de novo assembly software. A normalized library of transcripts from various tissues was sequenced and RNASeq experiments were performed to discover transcripts expressed under conditions of drought and water logging. Currently, the first draft of the genome has been produced and is being analyzed. Several transcriptomes using various assembly packages and data sets are being analyzed and annotated.

Key words: genome transcriptome sequencing, RNAseq, sequence assembly, sequence annotation

7.1. Introduction

Each living being contains DNA organized into chromosomes and containing a set of instructions that control the replication and function of the organism. Technological advances have made it possible to obtain the complete DNA sequence for any organism (the genome) and now whole genome sequencing is commonplace, providing an enormous amount of information to researchers in many fields. To date, many grass genomes have been completed: rice (Yu *et al.* 2002, Goff et al. 2002), barley, sorghum (Paterson *et al.* 2009), maize (Schnable, *et al.* 2009) foxtail millet (Zhang *et al.* 2012, Bennetzen et al. 2012) and brachypodium (The International Brachypodium Initiative, 2010), providing enormous amounts of information about the most vital source of human nutrition, the grasses.

Whole-genome sequencing of tef has been initiated for the following four reasons:

i) The sequence information of any gene including its promotor region will be available. This is e specially beneficial for designing primers for amplifying regions of interest, cloning genes and controlling gene expression.
ii) It facilitates the developing of genetic markers such as Simple Sequence Repeats (SSRs) and Single Nucleotide Polymorphisms (SNPs) useful for marker-assisted breeding (Wang, 2009).
iii) Tef has many desirable properties such as tolerance to diverse biotic and abiotic stresses, richness in human nutrition, and gluten-free seed. Access to the genomic sequences of the genes controlling these traits will shed light on their pathways and mechanisms and allow them to be isolated in the laboratory.
iv) The tef genome will be the first sequenced member of the family Chloridoideae (see Fig. 1), an important addition for comparative genomics.

The steps of a genome sequencing project — preparation, sequencing, assembly and analysis— are described in the following sections.

7.2. Preparation for Sequencing

Knowledge of the size of the genome is essential for allocating sequencing and human resources. Tef (*Eragrostis tef*) is an allotetraploid, usually the result of an inter-specific hybridization of two diploid parents, resulting in 4 chromosomes of 2 distinct types (the A and the B genomes). It has 2n = 4x = 40 chromosomes (Tareke, 1981; Tavassoli, 1986).

Nuclear genome size can be estimated by flow cytometry, a method in which size and other characteristics of particles are detected by measuring light-scattering as the particles flow through a light beam. The 2C genome size is measured in picograms (1 picogram being equivalent to roughly 980 million base pairs). Normally, the 1C genome size is reported which is simply half of the nuclear DNA content. In the case of a diploid species, this would be the haploid genome size. For the allotetraploid tef, 2C=2n=4x (AABB). So, 1C=1n=2x (AB) and the 1C genome size refers to the size of one A and one B genome (reviewed in Dolezel and Bartos, 2005). One such flow cytometry study estimated the 1C genome size of ten tef cultivars as ranging from 647 to 926 Mbp (Fufa *et al.*, 2000) while in another study, the 1C genome size of one cultivar was found to be 714-733 Mbp (Mulu *et al.*, 1996). Li and Waterman (2003) also introduced a method of estimating the repeat structure and size of the genome sequence based on an analysis of substrings of a given length.

7.3. Genome and Transcriptome Sequencing

DNA sequencing, the process of determining the nucleotides and their order in a biological sample, is becoming fundamental to all areas of biology, from crop research to immunology and medicine. Consequently, the technologies generating the sequences are developing at a rapid pace. The basic sequencing technologies are Sanger sequencing, Next Generation Sequencing (454 (Margulies *et al.*, 2005), Illumina (Bently *et al.*, 2008), SOLiD (McKernan *et al.*, 2009) and Third Generation Sequencing (IonTorrent (Rothberg *et al.*, 2011), Pacific Biosciences (Eid *et al.*, 2009) (compared in Table 1).

Table 1. Comparison of Sequencing Technologies. Sanger sequencing, Next-generation sequencing (454-FLX, Illumina HiSeq 2000 and SOLID) and Third-generation sequencing (IonTorrent and PacBio) are compared in terms of cost, yield, error rate, advantages and disadvantages. As the development of these technologies is rapid, all numbers are approximate and subject to change. (adapted from http://en.wikipedia.org/wiki/Ion_semiconductor_sequencing, http://en.wikipedia.org/wiki/Massive_parallel_sequencing and Margulies *et al.*, 2005).

Platform	Clonal Plasmid amplificat-ion	454FLX	Illumina HiSeq 2000	SOLID 5500	Ion-Torrent	PacBio RS
Chemistry	Chain Terminatio n	Pyroseque ncing	Reversible termination	Ligation	Synthesis	Synthesis
Instrument cost (USD)	$370,000	$500,000	$600,000	$600,000	$50,000	$700,000
Yield per run	60 kb	900 Mb	600 Gb	155 Gb	1Gb	20-80 Mb
Average read length (bases)	650	400	100	75 + 35	200	<1800 ->5000
Cost per Mb	$1600	$7	$0.039	$0.068	$0.93	$3-13.6
Error rate	0.1 – 1%	1%	> 0.1%	> 0.01%	1%	15%
Advantages	Low cost for small study; high accuracy	Long read lengths	Highest output to cost ratio	High-throughput	Fast run, low cost, longer reads coming	Longest read length, single molecule , real time sequencing
Disadvantages	High cost for large projects	Not good a homo-polymers; High cost	High initial and computation al cost	Short reads more gaps in assembly	Has difficulty with homo-polymers	High error rates, low output

Sanger sequencing (or dideoxy termination), first published in 1977, was a breakthrough that allowed long stretches (800 bp) of DNA to be accurately sequenced and earned Sanger a second Nobel prize. Due to vast improvement over existing technologies, it was the technology behind the first genome project, that of a bacteriophage (Sanger *et al.*, 1977). Sanger sequencing is still widely used for sequencing single genes or when high accuracy is necessary and can sequence up to 1000 bp. The disadvantage to Sanger sequencing is that the yield per run is very low making the cost per base sequenced very high.

Around 2005, commercialized pyrosequencing was introduced by 454 Life Sciences. (Margulies *et al.*, 2005) This sequencing method produced reads around 100 bp, now around 400-500 bp and in the next generation of the sequencing machines 800-900 bp. It has a much higher throughput than Sanger sequencing, reducing the cost of each base enormously. In 2006, Illumina sequencing, producing 100 million reads per run, became available and dropped the price per base sequenced even further (Bently *et al.*, 2008). These together with other sequencing methods such as SOLID are called 'Next Generation Sequencing'.

Currently many new 'third-generation' technologies are being developed which further reduce the cost per base. Ion semiconductor sequencing from Ion Torrent released in 2010 is a method of sequencing based on the detection of hydrogen ions released during DNA polymerization (Rothberg *et al.*, 2011). This offers the advantages of fast sequencing at a low cost plus the time between bases incorporated can be measured, adding beneficial information. Currently, the read size is small but the promise of longer read lengths is real. Another developing technology first offered in 2011 is that of Pacific Biosystems (Eid *et al.*, 2009). It has the notable feature of sequencing a single molecule and thus does not rely on PCR amplification of the DNA sequence, eliminating a major source of error. Although the reads produced are long (up to 5 kb), the error rate is high and the throughput is low. It remains to be seen which of the latest generation sequencing technologies will prevail. Depending on the technology used for sequencing, different kinds of DNA libraries can be prepared: single-end, paired-end, mate-pair reads, BAC ends and Fosmid pools as well as different-sized insert libraries. In shotgun sequencing (single-end), many short stretches of DNA, from 50-500 base pairs long, are sequenced. Later, it was noticed that sequencing both ends of a longer pieces of DNA resulted in two sequence fragments with a known distance between and a known orientation to each other. This additional information is invaluable to the reconstruction of longer sequence fragments and in reconstructing regions of the genome containing repeat sequences. There are two ways to prepare paired libraries: paired-end; and mate-pair (discussed in Medvedev, 2009). Paired-end reads have shorter inserts and are much less prone to e rror while mate-pair reads are more prone to error but are very valuable because of their long insert sizes.

The amount and kind of sequencing data collected for the tef genome can be found in Table 1. A combination of Illumina and 454 sequencing were produced from libraries made of pieces of DNA varying from 300 to 20,000 base pairs and were provided by various sequencing platforms. The tef genome was sequenced to 7-fold sequence depth (each base in the genome sequenced 7 times, if the sequencing were random) with the 454-FLX technology and to 47-fold with the Illumina HighSeq technology, thereby offering sufficient coverage to produce a draft genome.

For the transcriptome, two different kinds of data sets were collected: a normalized library and RNASeq experiments (Table 2). First, a normalized library was sequenced using the 454-FLX technology. Normalized libraries are prepared in such a way as to reduce the variation in sequence expression. Ideally, every sequence transcribed should be represented with the same expression level. The library was prepared from five different tissue types under various stress conditions, and thus should result in a representative sample of the sequences expressed in tef.

Table 2. Tef genome sequencing showing the next generation sequencing platform, the number of reads produced and the insert sizes of each library are shown.

NGS Platform	Provider	Type of sequence	Insert size (bp)	Amount of sequence (Mbp)	Fold coverage
454-FLX	Macrogen FGCZ	Mate-pair Single-end	3 000, 13,000 6,500	5,282	7
Illumina HiSeq2000	Fasteris	Paired-end Mate-pair Single end	300 4000	34,523	47

For the RNASeq experiments, three replicates were collected for three samples: normal tissue, tissue exposed to drought conditions and tissue exposed to flooding conditions (Table 3). Here, Illumina sequencing was used because of the large amount of sequencing data it produces is necessary to quantify the expression levels of the genes. Comparison of the set of proteins expressed under stress conditions to those expressed under normal conditions provides valuable information about the subset of genes expressed under stress conditions. These are then potential targets for developing enhanced cultivars resistant to these stresses.

Table 3. Tef Transcriptome Sequencing (The 454-FLX technology was used to sequence a normalized library while the Illumina HiSeq 2000 technology produced the reads for the RNASeq experiments.

Library	Provider	Technology	Replications	Number of reads (bp)
Normalized	MWG, Germany	454- FLX		1,065,255
Normal watering	Fasteris, Geneva	Illumina HighSeq 2000	3	61,524,739
Drought	Fasteris, Geneva	Illumina HighSeq 2000	3	72,345,270
Waterlogging	Fasteris, Geneva	Illumina HighSeq 2000	3	70,891,388

Before assembly, the data should be controlled for quality. The sequences should be trimmed based on the quality score produced by the sequencing machine (the Phred score). Adaptor and primer sequences should also be removed before assembly. FastQC is a convenient tool that allows visualization of the quality of raw sequencing data (http://www.bioinformatics.bbsrc.ac.uk/projects/fastqc/). Based on the information obtained from FastQC, the data were cleaned using standard tools.

7.4. Genome Assembly

Genome assembly is a complex and computationally difficult task requiring extensive resources in terms of hardware and software. Although eukaryotic genomes are hundreds to thousands of millions of base pairs long, genome sequencing technologies produce sequences (called reads) that are from 100 base pairs to at most a few thousand base pairs.

Two strategies for assembling genomes are used. If there is a reference genome, a genome close enough to be used to aid assembly, comparative genome assembly can be done, rendering the problem much easier to solve. If there is no reference genome, then the genome must be assembled *de novo*, without using outside information (Baker, 2012). Tef belongs to the Grass or *Poaceae* family and the sub-family of *Chloridoideae* as shown in Fig. 1. The closest sequenced genome is sorghum, which is too divergent to be used as a reference genome, thereby making *de novo* assembly necessary.

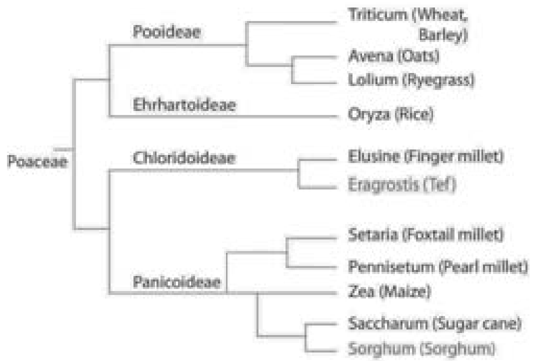

Figure 1. Phylogeny of the family *Poaceae*. Tef is in the subfamily *Chloridoideae* and is closely related to Finger millet. Presently, the closest sequenced genome is sorghum, too distant from tef to be used as a reference genome in assembly. Thus the tef assembly is *de novo* (assembled without outside information) and becomes a harder problem than if a reference genome were available.

The main problem with assembling the tef genome is that tef has a tetraploid genome, while genome assembly programs have been designed for diploid genomes. A summary of grasses and their ploidy levels can be found in Table 4. Even a strongly heterozygous diploid genome is difficult for most assembly programs because the heterozygosity results in nearly duplicated contigs. Often strategies are applied to reduce the ploidy of the genome such as obtaining a haploid (the male drone in ants) or a doubled haploid, which involves producing a haploid genome from pollen or seeds (with haploid embryos) and then doubling it to form a homozygous diploid, as done for the potato (Xu *et al.*, 2011) or sequencing the diploid parents of the polyploid as doene for the domestic apple (Velasco *et al.*, 2010). Alternatively, Bacterial Artificial Chromosomes (BAC) libraries, collections of segments of DNA that can be amplified by bacteria, can be used to piece together the entire genome, an accurate although time-consuming and expensive procedure. *Eragrostis pilosa* and *Eragrostis heteromera* have been suggested as the progenitors of tef (Ingram and Doyle, 2003) but as they are also tetraploids, the true diploid parents of tef remain unknown.

The steps of assembly are outlined in Fig. 2 (also see Baker, 2012). First, the DNA sample is extracted and the DNA sheared into fragments of various sizes, which are then sorted by size. All fractions of a given size are then sequenced resulting in sequence reads- the raw data consisting of a sequence of DNA nucleotides each with a corresponding quality score. Ideally, the raw reads are randomly distributed across the DNA although in practice this is not always true. The sequence target is over-sampled such that the reads contain very high levels of overlap. Using assembly software that joins reads based on stringent overlap requirements, the reads are then assembled into contigs (short pieces of assembled DNA). Paired-end and mate-pair reads separated by a known distance are used to join the contigs into scaffolds. As the distance between the paired reads is approximately known, the software will order the contigs and join them using enough 'N's such that the distance between the paired reads is correct. Closing is the last step in which a final pass is made to close the gaps within scaffolds (Boetzer, 2012).

Table 4. Grasses, their genome sizes, ploidy and genome information

Common Name	Latin Name	Ploidy level	Genome Size (Mbp)	Reference
Bread Wheat	*Triticum aestivum*	2n = 6x = 42	17,000	
Durum Wheat	*Triticum durum*	2n = 4x = 28		
Barley	*Hordeum vulgare*	2n = 2x = 14	5,000	
Oats	*Avena sativa*	2n = 6x = 42	11,000	
Ryegrass	*Lolium*		4,000	
Rice	*Oryza sativa*	2n = 2x = 24	400	Yu *et al.* (2002) Goff *et al.* (2002)
Finger millet	*Eleusine coracana*	2n = 4x = 36	300	
Tef	*Eragrostis tef*	2n = 4x = 40	733	
Foxtail millet	*Setaria italica*	2n = 2x = 18	513	Zhang *et al.* 2012; Bennetzen *et al.* (2012)
Pearl millet	*Pennisetum glaucum*	2n = 2x = 14	2616	
Maize	*Zea Mays*	2n = 2x = 20	2500	Schnable *et al.* (2009)
Sugar Cane	*Saccharum officinarium*	5× to 14× (× = 5, 6, 8, 10, 12, or 14)	10,000	
Sorghum	*Sorghum bicolor*	2n = 2x = 20	800	Paterson *et al.* (2009)

As the coverage, read length and error profiles vary between the different kinds of sequencing data, many assembly algorithms have been created to treat the different data sets. Most of these are based either on the de Bruijn graph approach or the consensus/overlap approach to assembly (see Miller *et al.*, 2010 for an overview of genome assembly). The de Bruijn graph method analyzes the entire set of reads in terms of k-mers (nucleotides of length k). For example, for a k-mer value of 45, the entire data set will be broken into sequences of length 45. As the size of the k-mer used to analyze the data changes, the sensitivity and specificity also change, requiring a search for the optimal k-mer value.

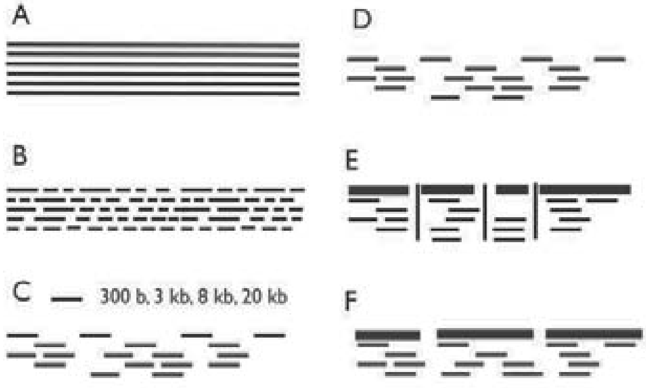

Fig. 2. Assembly procedure. A) Multiple copies of DNA are extracted from tissue. B) This DNA is sheared into different size fragments which are then size-fractionated (C). All fractions of a given size (for example, 300 bases, 3 kb, 8 kb or 20 kb) are sequenced to produce reads shown in D. The reads are normally between 100 and 400 base pairs long. E) Overlapping reads are assembled into contigs (short pieces of assembled DNA) represented by thick lines F) Paired-end reads and mate-pair reads separated by a known distance and have a known orientation to each other are used to join the contigs into scaffolds. Here the two middle contigs have been joined into a s caffold. Unknown bases, revealed due to the defined length between paired sequences, are assigned as 'N'. Closing is the last step in which a final pass is made to try and reduce the number of N's.

Many different software packages exist for assembling genomic and transcriptomic data (reviewed in the summary of the Assemblethon contest by Earl *et al.*, 2011). After comparison of different assembly softwares, SOAPdenovo (Li *et al.*, 2009) and Newbler ulies *et al.*, 2005) were used for the tef genomic assembly while Trinity (Grabherr *et al.*, 2011), Oases/Velvet (Zerbino *et al.*, 2008) and Newbler were used for the transcriptomic data. Most assemblies were carried out on a machine with 16 CPUs and 250 GB RAM while the Trinity assembly of the transcriptome required a machine with 48 CPUs and 500 GB RAM.

7.5. Status of the Tef Sequencing and Assembly

7.5.1. Genome

The status of the genomic assembly can be assessed in terms of its accuracy and size. Assembly size can be measured by statistics such as maximum length, average length, combined total length, and N50 (Miller *et al.*, 2010). The contig N50 is the length of the smallest contig in the set of the largest contigs containing half of the number of the assembled bases. The tef assembly resulted in a genome with 680 Mbp, approximately 92% of the size expected from flow cytometry, including around 110 Mbp of N's representing unknown bases. There were 405,558 scaffolds, and the length of the largest scaffold was 659,152 bases.

7.5.2. Applications of genome sequencing

Having the genomic sequence is in valuable for designing PCR primers to amplify genes and regions of interest for study. Some of the other applications of the genomic sequencing include the discovery of SSRs markers, TILLING, discovery of miRNAs and comparative genomics. A high quality genome can also be used for Genome Wide Associate Mapping (Zhao *et al.*, 2011) and Mutmap (Abe *et al.*, 2012).

SSR (Simple Sequence Repeats) markers are short sequences (dinucleotides, trinucleotides or larger) that are found repeated from 5-20 times in a genome (Wang, 2009). As they have a high rate of polymorphism, they can be used in marker-assisted plant breeding, the creation of genetic and phenotypic maps as well as a range of diversity studies. The entire genome can be analyzed to find these markers with software such as MISA (MIcroSAtellite), a microsatellite mining tool (Thiel *et al.*, 2003, reviewed in Sharma *et al.*, 2007). Then, the genomic sequence can again be used to design primer sequences for PCR amplification. Once the region containing the SSR has been successfully amplified, the markers can be tested to see if they can differentiate between different subtypes or if they co-segregate with certain traits.

TILLING is a non-transgenic method of genotypic screening used in molecular breeding (McCallum et al., 2000). The starting point of TILLING is a population of seeds treated with mutagens to speed up the process of random mutation. In TILLING, new cultivars are sought which may have mutations implicated in a trait of interest, for example, drought tolerance. Genes already known to affect this trait are screened for mutations that co-segregate with the desired phenotype. The genes of interest can be obtained from other well-studied species such as rice or RNASeq studies as described below.

7.5.3. Transcriptome

Several different data sets were assembled, each using a different combination of data subset (Illumina, 454 or both) and assembly program (Trinity, Newbler, Oases/Velvet). The assembly of the 454 data from the normalized library with the Newbler assembler resulted in an assembly with 38, 461 transcripts, comparable to the number of transcripts reported for the sorghum genome (29,448). The other assemblies are now being compared.

7.5.4. RNASeq experiments

RNASeq experiments use high-throughput sequencing to determine the content and quantity of RNA transcripts in a sample (reviewed in Oshlack *et al.*, 2010). Tissues were collected from normal plant, from a plant subjected to drought, from a plant subjected to water-logging, from root and from shoot. A library from each of these samples is prepared and then sequenced using Illumina High-Seq 2000 sequencing. Three replicates of each condition were collected to improve the accuracy of the expression analysis. Using the software RSEM (Li and Dewey, 2011), the reads produced for each sample, were mapped back to a reference transcriptome (e.g. the transcriptome produced from the normalized library). The number of reads mapping to each transcript was counted and the counts used to find differential expression using the DESeq package of R Bioconductor (http://www-huber.embl.de/users/anders/DESeq/). In both the counting and the determination of differential expression, statistical models were used to improve accuracy. Some examples of genes up- and down-regulated under the conditions of drought and water-logging can be found in Table 6.

Table 6. Genes induced under conditions of drought and water-logging under RNASeq experiments conducted to reveal the genes that are expressed under these conditions (Some of the candidates and their fold-change in expression level induced under the given conditions are shown).

Stress condition	Up-regulated		Down-regulated	
	Gene Name	Fold-change	Gene Name	Fold-change
Drought	LEA 3	272	Chlorophyll binding	121
	Salt-induced	216	Wax2	673
	Dehydrin	136	RGH1	118
Water-logging	LHY	50	DSP1	61
	GA-induced	30	ThiC	51
	Inositol	20	DHN1	23

7.6. Summary and the Way Forward

Tef genome and transcriptome sequencing has been initiated to aid the discovery of genes implicated in tef's numerous beneficial traits, to enable the amplification of any gene of interest and to support the use of molecular breeding techniques in the laboratory. We currently project the release of the genomic data by late 2012. We plan on making functional analysis of the genome, implementing the results of this analysis in a breeding program and investigating traits of importance like tef's gluten-free property as well as its biotic and abiotic stress tolerance/resistance.

7.7. Acknowledgements

We would like to acknowledge the Syngenta Foundation for Sustainable Agriculture and the University of Bern for financial and technical support.

7.8. Abbreviations

BAC: Bacterial Artificial Chromosome; **SNP**: Single Nucleotide Polymorphism; **SSR**: Simple Sequence Repeat.

7.9. References

Abe A, Kosugi S, Yoshida K, Natsume S, Takagi H, Kanzaki H, Matsumura H, Yoshida K, Mitsuoka C, Tamiru M, Innan H, Cano L, Kamoun S and Terauchi R. 2012. Genome sequencing reveals agronomically important loci in rice using MutMap, Nat. Biotechnol. 30:174-178.

Baker M. De novo genome assembly: what every biologist should know, Nature Methods. 9:333-337.

Bennetzen et al. 2012. Reference genome sequence of the model plant setaria, Nat.Biotechnol. 30:555–56.

Bently et al. 2008. Accurate whole human genome sequencing using reversible terminator chemistry. Nature 456:53-9.

Boetzer M and Pirovano, W. 2012. Toward almost closed genomes with GapFiller, Genome Biology 13:R56.

Earl D et al. 2011. Assemblathon 1: A competitive assessment of de novo short read assembly methods, Genome Research 21(12):2224-2241.

Eid J, Fehr A, Gray J, et al. 2009. Real-time DNA sequencing from single polymerase molecules, Science 323:133–8.

Dolezel, J and Bartos, J. 2005. Plant DNA Flow cytometry and Estimation of Nuclear Genome Size, Annals of Botany 95:99-110.

Fufa Hundera, Arumuganathan K and Baenziger PS. 2000. Determination of relative nuclear DNA content of tef using flow cytometry, J. Genet. and Breed. 54:54:165-168.

Goff SA et al. 2002. A draft sequence of the rice genome (Oryza sativa L. ssp. japonica), Science 296:92-100.

Grabherr MG, Haas BJ, Yassour M, Levin JZ, Thompson DA, Amit I, Adiconis X, Fan L, Raychowdhury R, Zeng Q, Chen Z, Mauceli E, Hacohen N, Gnirke A, Rhind N, di Palma F, Nusbaum C, Lindblad-Toh K, Friedman N and Regev A. 2011. Full-length transcriptome assembly from RNA-Seq data without a reference genome, Nature Biotechnology 29:644-652.

Ingram AL and Doyle JJ.**Error! Bookmark not defined.** 2003. The origin and evolution of Eragrostis tef (Poaceae) and related polyploids: Evidence from nuclear waxy and plastid rps16, American Journal of Botany 90:116-122

Li B and Dewey CN. 2011. RSEM: accurate transcript quantification from RNA-Seq data with or without a reference genome, BMC Bioinformatics 12:323.

Li R, Zhu H, Ruan J, Qian W, Fang, X, Shi, Li Y, Li S, Shan G, Kristiansen K, Yang H, Wang H, 2009. De novo assembly of human genomes with massively parallel short read sequencing, Genome Res. 20:265–272.

Li X and Waterman MS. 2003. Estimating the repeat structure and length of DNA sequences using L-tuples, Genome Res. 13:1916-1922.

Margulies M et al. 2005. Genome sequencing in microfabricated high-density picolitre reactors, Nature 437:376-80.

McCallum CM, Comai L, Greene EA et al. 2000. Targeted screening for induced mutations, Nature Biotechnology 18:455-457.

McKernan et al. 2009. Sequence and structural variation in a human genome uncovered by short-read, massively parallel ligation sequencing using two-base encoding, Genome Research 19:1527-1541.

Miller JR, Koren S and Sutton G. 2010. Assembly algorithms for next-generation sequencing data, Genomics 95(6):315-327

Mulu Ayele, Dolezel J, VanDuren M, Brunner H and Zapata-Arias FJ.. 1996. Flow cytometric analysis of nuclear genome of the Ethiopian cereal, tef. Genetica 98:211-215.

Oshlack A, Robinson M, and Young M. 2010. From RNA-seq reads to differential expression results, Genome Biology. 11:220.

Paterson AH. et al. 2009. The Sorghum bicolor genome and the diversification of grasses. Nature. 457:551-556.

Sanger F, Air GM, Barrell BG, Brown NL, Coulson AR, Fiddes CA, Hutchison CA, Slocombe PM and Smith M. 1977. Nucleotide sequence of bacteriophage phi X174 DNA, Nature 265:687-695.

Schnable PS et al. 2009. The B73 Maize Genome: Complexity, Diversity, and Dynamics. Science 326(5956):1112-1115.

Sharma PC, Grover A, and Kahl G. 2007. Mining microsatellites in eukaryotic genomes, Trends Biotechnol. 5:490-498.

Tareke Berhe. 1981. Inheritance of lemma color, seed color and panicle form among four cultivars of Eragrostis tef (Zucc.) Trotter. PhD Thesis, University of Nebraska, Lincoln, USA.

Tavassoli A. 1986. The cytology of Eragrostis with special reference to E. tef and its relatives. PhD Thesis, University of London, Royal Holloway and Bedford New College, UK.

Thiel T, Michalek W, Varshney RK and Graner A. 2003. Exploiting EST databases for the development and characterization of gene-derived SSR-markers in barley (Hordeum vulgare L.), Theor. Appl. Genet. 106:411–422.

Velasco R et al.. 2010. The genome of the domesticated apple (Malus x domestica Borkh.), Nat. Genet. 42(10):833-841.

Wang, ML, Barkley, JA and Jenkins TM. 2009. Microsatellite Markers in Plants and Insects. Part I: Applications of Biotechnology, Genes, Genomes and Genomics 3:54-67.

Xu X et al. 2011. Genome sequence and analysis of the tuber crop potato. The Potato Genome Sequencing Consortium, Nature 475:189-195.

Yu J et al. 2002. A Draft Sequence of the Rice Genome (Oryza sativa L. ssp. indica), Science 296, 79-92.

Zerbino DR and Birney E. 2008. Velvet: algorithms for de novo short read assembly using de Bruijn graphs. Genome Res. 18:821–829.

Zhang G et al. 2012. Genome sequence of foxtail millet (Setaria italica) provides insights into grass evolution and biofuel potential. Nat Biotechnol. 30:549–554.

Zhao K, Tung CW, Eizenga GC, Wright MH, Ali ML, Price AH, Norton GJ, Islam MR, Reynolds A, Mezey J, McClung AM, Bustamante CD and McCouch SR. 2011. Genome-wide association mapping reveals a rich genetic architecture of complex traits in Oryza sativa. Nat. Commun. 2:467.

III. Agronomy, Physiology & Implements

8. Crop Management Research for Tef

Tesfa Bogale[1*], Solomon Jemal[2], Yifru Abera[3], Minale Liben[4] and Waga Mazengia[5]

[1]Jimma Agricultural Research Center, Ethiopian Institute of Agricultural Research (EIAR), P.O. Box 192, Jimma, Ethiopia; [2]Melkassa Agricultural Research Center, EIAR, P.O. Box 436, Adama, Ethiopia; [3]Debre Zeit Agricultural Research Center, EIAR, P.O. Box 32, Debre Zeit, Ethiopia; [4]Amhara Region Agricultural Research Institute (ARARI), Adet Agricultural Research Center, P.O. Box 527, Bahir Dar, Ethiopia; [5]South Agricultural Research Institute (SARI), Hawassa Agricultural Research Center, P. O. Box 6, Hawassa, Ethiopia. [*]Corresponding author: tesfabogalemk@gmail.com

Over the past several decades, agronomic studies on tef were made in order to develop optimum crop management practices for diverse agro-ecological regions so that the productivity of the crop increases. Minimum and conservation tillage were found beneficial in the central highlands and in the central rift valley areas, respectively. Tef is commonly mixed cropped with oilseeds such as safflower (Carthamus tinctorius L.*) by farmers in the lowland areas of North Shewa and Wello. A study at Holetta showed the benefit of mixed cropping tef with leguminous crops such as faba bean, while at Hawassa sowing tef as relay crop in maize by broadcast sowing of tef at 35 days after maize silking revealed high benefits.*

Key words: Agronomy, cultural practices, crop management, cropping systems, rotation, intercropping

8.1. Introduction

Although tef is annually cultivated on a large area of land in Ethiopia, it gives relatively low yield compared to the other cereals (CSA, 2010). The main causes for the low yield of tef are: i) biotic factors such as diseases, insects, weeds and unimproved seeds ii) a biotic factors such as poor soil fertility and moisture scarcity iii) lack of proper crop and soil management practices and iv) socio-economic factors such as lack of access to c redit system and market information. In general, tef is grown on nutrient depleted soils due to continuous cropping, and on rugged and undulating topography that are repeatedly tilled up to eight times, thereby, aggravating high soil and nutrient loss (Hurni and Perich, 1992). In the central highlands where tef is the major crop, the farming population increased tremendously (CSA, 2008). As a consequence, the land holdings have become smaller and smaller, thereby hindering farmers from using fallow periods between cropping seasons. In addition, inappropriate crop management practices that mainly include seeding methods, weeding practice, harvesting stage, cropping systems and soil fertilization contributed towards the lowering of the productivity of tef.

Because of high soil loss, yield reduction in tef, high labor requirement and high cost of tef production, there is a great need to replace the conventional tillage by an alternative conservation or minimum tillage system. Some studies already showed benefits of conservation tillage in major tef producing agro-ecologies of Ethiopia (Worku *et al.,* 2005; Balesh *et al.* 2008; SG2000, 2004). Crop management practices such as tillage and cropping systems were studied for tef in order to develop improved practices for various tef producing regions in Ethiopia. The major achievements of agronomy research on tef were comprehensively reviewed by Fufa *et al.* (2001). In this review, we present the major findings of agronomic studies made on tef since then, and forward suggestions for future research directions.

8.2. Effect of Seed Bed Management and Tillage

In order to alleviate the cumbersome work load and soil loss due to conventional tillage in tef production, diverse types of tillage studies were made. The study made in the Central Highlands where reduced tillage was compared to conventional tillage on Nitosol and Vertisol soil types showed that inferior tef yield was obtained from zero-tillage mainly due to high grass weed infestation as these were not controlled by pre-planting spray of non-selective herbicide (Balesh *et al.*, 2008). On the other hand, the tef seed yield obtained with reduced tillage involving one time plowing supplemented with manual hand weeding was comparable to those from conventional or four times plowing and broad bed and furrow (BBF) seedbeds. On Vertisols, BBF planting system showed better yield performance, although it requires more labor than reduced tillage (Table 1). In general, zero-tillage gave the lowest economic margin mainly because of high labor cost incurred during land preparation, frequent hand-weeding and lower yields (Table 2). From similar reduced tillage experiment, 8% grain yield advantage was reported over a conventional tillage when non-selective herbicide was sprayed for the reduced tillage tef grown on Vertisols (Teklu *et al.*, 2006).

According to Worku *et al.* (2005), conservation tillage gave higher tef seed yield than the conventional tillage in the Central Rift Valley while zero- tillage was effective in controlling noxious weeds due to pre-planting and post-planting herbicide application. The tef yield was increased by 20-25% when tillage frequency was reduced (Table 3).

Table 1. Effect of tillage on the grain yield of tef (kg ha^{-1}) on two soil types at Gare, Central Ethiopia, in the year 2001 and 2002.

Tillage type	Nitosols			Vertisols		
	2001	2002	Mean	2001	2002	mean
Zero tillage (No plowing but weeds were cut by machete at planting)	561a	890b	726	1486a	1368b	1427
Minimum tillage (one time plowing during planting)	506a	1151a	829	1647a	1520ab	1584
Conventional tillage (four times plowing)	470a	1272a	871	1424a	1560ab	1492
Broad bed furrow(three times plowing followed by 0.8 x 0.4 m raised beds just before planting)	–	1309a	1309	1520a	1768a	1644

Source: Balesh *et al.* (2008)

Table 2. Cost distribution (Birr ha^{-1}) for different tillage practices of tef on two soil types at Gare, Central Ethiopia.

Tillage type	Nitosols			Vertisols		
	Total cost	Gross income	Gross margin	Total cost	Gross income	Gross margin
Zero tillage (No plowing but weeds were cut by machete at planting)	2494a	2386b	-108c	2358a	2879b	520c
Minimum tillage (one time plowing during planting)	1804b	2739ab	935b	1827b	3225b	1398b
Conventional tillage (four times plowing)	1991b	3364a	1374a	2032b	3352ab	1319b
Broad bed furrow(three times plowing followed by 0.8 x 0.4 m raised beds just before planting)	1863b	3367a	1504a	1845b	3770a	1924a

Source: Balesh *et al.* (2008)

The general trend of increasing tef yield with decreasing tillage frequency suggested the beneficial effect of no-tillage in the Central Rift Valley and other similar agro-ecologies in Ethiopia. Production costs were lower by 50-70% in conserved and no-tillage fields than conventionally prepared plots. In addition, the net returns were higher for the reduced tillage than for the conventional tillage with five plowings (Table 4) mainly due to increased yield and lower production costs. Similar results were also obtained in different tef growing areas from research and demonstration plots of Sasakawa-Global 2000 and the Ministry of Agriculture (SG2000, 2004). However, conservation tillage was poorly adopted since farmers were reluctant to apply additional inputs mainly on herbicides. According to Melese (2007), improved tillage that includes soil ripping sub-soiling increased the tef yield by about 9% (Table 5).

Table 3. Tef grain yield as affected by tillage systems in the Central Rift valley of Ethiopia for four years from 2000 to 2003. Source: Worku *et al.* (2005).

Tillage systems		Grain yield during four seasons (kg ha^{-1})*				
		2000	2001	2002	2003	Mean
T1	Conservation Tillage + No-tillage (3.0 l ha^{-1} glyphosate + 1.0 l ha^{-1} 2,4-D + 1 time hand weeding)	1360bc	340g	850de	1570ab	1030a
T2	Conservation Tillage + No-tillage (3.0 l ha^{-1} glyphosate + 1.0 l ha^{-1} 2,4-D)	740def	270g	1090cd	1720a	960ab
T3	Conservation Tillage + No-tillage (3.0 l ha^{-1} glyphosate + 1 time hand weeding)	750def	270g	720ef	1560ab	820b
T4	Conventional Tillage + Tilled (four times plowing + 1.0 l ha^{-1} 2,4-D + 1 time hand weeding)	800de	430fg	890de	1480ab	900ab
T5	Conventional Tillage + Tilled (four times plowing + two times hand weeding)	980de	420fg	700ef	1310bc	850b
Mean		920B	350C	850B	1530A	-

*Means in the same column or row followed by diffrent letters are significantly different at $P_{<}$ 0.05.

Table 4. Economic analysis of five tillage systems for tef described in Table 3. Source: Worku *et al.* (2005).

Parameter	Tillage systems				
	T1	T2	T3	T4	T5
Grain yield (kg ha^{-1})	1260	1190	1010	1060	1000
Straw yield (kg ha^{-1})	4030	4230	4290	4190	4260
Grain production (@260 Birr 100kg^{-1})	3276	3094	2626	2756	2600
Straw production (@4 Birr 100kg^{-1})	161	169	172	168	170
Return (Birr ha^{-1})	3437	3263	2798	2914	2770
Production cost (Birr ha^{-1})	2568	2539	2478	2664	2576
Net Benefit (Birr ha^{-1})	869	704	320	250	194
Net Benefit (USD ha^{-1})	99	81	37	29	22

Table 5. Effect of four tillage systems on grain yield (kg ha^{-1}) of tef at two locations and three years. Source: Melese (2007).

Treatments	Melkawoba				Welenchiti		
	2003	2004	2005	Mean	2004	2005	Mean
Conventional tillage	900	960ab	920b	930	1260ab	1070ab	1170
Improved tillage with sub-soiling	930	1160a	1230a	1110	1460a	1180a	1320
Minimum tillage without sub-soiling	850	730b	850b	810	1200b	890b	1050
Improved tillage without sub-soiling	900	890b	920b	900	1260b	960b	1110

8.3. Effect of Sowing and Harvesting Time

A single year field experiment at Alem Tena indicated that when sowing dates were delayed by one and two weeks, the biomass and grain yields were reduced by 35% and 60-80%, respectively (Abdul Shukor *et al*., 2009) (Table 6). It was also observed that sowing time had more considerable effect on tef yield than weeding time, although weeds such as nut-sedge can reduce the tef biomass by up to 30% during the first six weeks after crop emergence. Hence, keeping tef fields free of nut-sedge for the first six weeks is important in Alem Tena and other similar areas in order to obtain optimum biomass and grain yields of tef.

Table 6. Effect of delayed sowing and weed removal on the grain yield of tef at Alemtena, Central Ethiopia. *** means of delayed sowing followed by same letters in rows are not significantly different (P<0.05). Source: Abdul Shukor *et al*. (2009).

Weeding removal	Grain yield (kg ha^{-1}) for different sowing dates			Mean
	July 10	July 17	July 24	
Weedy check	1600^{abc}	1320^{bc}	1280^{c}	1400^{d}
Weeded at 2 weeks after emergence	1580^{abc}	1375^{abc}	1440^{abc}	1465^{d}
Weeded at 4 weeks after emergence	1800^{a}	1250^{c}	1220^{c}	1423^{d}
Weeded at 6 weeks after emergence	1740^{ab}	1520^{abc}	1660^{abc}	1620^{d}
Weed-free check	1760^{ab}	1480^{abc}	1320^{bc}	1420^{d}
Delayed sowing Mean***	1636^{e}	1389^{f}	1372^{f}	

8.4. Weed Management Studies

A combination of tillage and weeding experiment was conducted for three years on Nitosols at Yielmana-Densa Woreda in Northwestern Ethiopia (ADARC, 2002-2004). Although frequent tillage and twice hand weeding gave high grain yields (1771 kg ha^{-1}) (Table 7), the costs of production were high for this particular treatment, and hence, it was not profitable. On the other hand, reduced tillage (pre-emergence Round-up herbicide spray followed by one oxen plow) combined with one hand weeding at tillering stage gave the second highest grain yield of 1659 kg ha^{-1} (Table 7) and the highest marginal rate of return and net benefit (Table 8). Therefore, under the current tef production system of Yielmana Densa Woreda, reduced tillage using pre-emergence herbicide 2-3 weeks before planting followed by one oxen plow in late June about a week before planting and combined with one hand weeding at tillering stage of tef could be recommended. Moreover, if intensified and long seasonal rains occur at this location, the same tillage operation should be combined with another one hand weeding at stem elongation.

Table 7. Grain yield (kg ha^{-1}) of tef as affected by tillage frequency and weeding on Nitosols of Yilmana Densa, north-western Ethiopia.

Frequency of tillage (TF)	Hand weeding operation (W)				Mean
	Un-weeded	Weeding at tillering	Weeding at stem elongation	Weeding at tillering & stem elongation	
Seven plowings	1394	1409	1475	1771	1512
Five plowings	1226	1589	1269	1575	1415
Three plowings	1120	1441	1257	1557	1344
One plowing + Round-up	904	1659	1216	1528	1326
Mean	1161	1524	1304	1608	
Tillage frequency (TF)	111				
Weeding (W)	59				
TF X W	118				

Source: ADARC (2002-2004)

Table 8. Net benefit (Birr ha^{-1}) of plowing frequency and weeding in tef fields on Nitosols of Yilmana-Densa, North-Western Ethiopia.

Frequency of tillage	Weeding operation			
	Un-weeded	Weeding at tillering	Weeding at stem elongation	Weeding at tillering + at stem elongation
Seven plowings	2313	2096	2065	2200
Five plowings	2127	2115	1800	2354
Three plowings	2068	2470	1936	2479
One plowing + Round-up	1603	2648	1831	2399

Source: ADARC (2002-2004)

8.5. Cropping Systems Studies

Although crop rotation is the dominant cropping system practiced by farmers, other systems including intercropping and double cropping of tef with oil crops, legumes and cereals are also used to some extent (Fufa *et al.,* 2001).

8.5.1. Crop Rotation

In most tef growing areas of the country continuous tef monoculture is the most dominant crop production system. However, previous reviews indicated that tef has been rotated with legumes and other cereals (Zerihun, 1994; Hailu et al., 2001). In recent studies, Worku *et al*., 2006 observed that the integration of tillage system and crop rotation. In his two years (2003-04) study at two locations, Melkassa and Wolenchiti, significantly higher mean grain yield (1231 kg ha^{-1}) was obtained from rotation plots compared to continuous tef monoculture plot yield (851 kg ha^{-1}). It was also observed that the same trend, as grain, was observed for straw and above ground biomass in addition to improved soil organic matter and total N concentrations in rotational cropping.

Farmers in the north-western parts of Ethiopia grow tef in rotation with leguminous crops such as faba bean and chickpea or cereals such as barely (Hailu and Chilot, 1989). In Eastern Shewa, tef is rotated with wheat or chickpea on black soils, and with wheat, field pea or faba bean on light-gray soil (Zerihun, 1994). In western Shewa and eastern Wallega, noug and maize are the most preferred rotation crops with tef (Tolera *et al*., 2005c).

Effects of precursor crops (faba bean and noug) and nitrogen fertilizer (40, 27 and 20 kg ha^{-1} N) on tef were studied for two years on the Nitosols at Adet Agricultural Research Center in north-western Ethiopia. In this study, substantially high grain and biomass yields of tef were obtained when tef was preceded by faba bean and received 40 kg ha^{-1} N (Table 9). The same treatment also gave high net benefits (Table 10) and was, thus, recommended for Adet and other similar areas where tef is grown on Nitosols.

8.5.2. Double cropping

In a double cropping experiment carried out on Vertisols of woreta and Bichena areas of northwestern Ethiopia testing the possibility of tef-chickpea double cropping system showed the role of planting date adjustment in relation to drainage system and varieties of different maturity groups increased the productivity of the

Vertisols. Higher grain yield of tef was obtained from Bichena Vertisols which is 392 and 271 kg ha^{-1} higher than the early planting with and without BBF.

Table 9. Effect of precursor crops and nitrogen rates on grain and biomass yields of tef on the Nitosols of Adet, north-western Ethiopia.

Precursor crop	Grain yield (kg ha^{-1})				Biomass yield (kg ha^{-1})*			
	40 kg ha^{-1} N	27 kg ha^{-1} N	20 kg ha^{-1} N	Mean	40 kg ha^{-1} N	27 kg ha^{-1} N	20 kg ha^{-1} N	Mean
Faba bean	1619	1563	1578	1560	6319a	5864ab	5417bc	5867
Niger seed	1525	1553	1509	1529	5681ab	5403bc	4750c	5278
Tef-tef	1348	-	-	1348	5167	-	-	5167

*Mean biomass yields of treatment combinations followed by different letters are significantly different as judged by LSD at P ˛ 0.05. Source: ADARC (2006-2007).

Table 10. Net benefit analysis of precursor crops and nitrogen rates on tef on Nitosols of Adet, north-western Ethiopia.

N rates	Faba bean		Noug		Tef-tef	
	Tef yield (kg ha^{-1})	Ethiopian Birr	Tef yield (kg ha^{-1})	Ethiopian Birr	Tef yield (kg ha^{-1})	Ethiopian Birr
20 kg ha^{-1} N	1578	5790.27	1509	5529.50	-	-
27 kg ha^{-1} N	1563	5675.10	1553	5637.30	-	-
40 kg ha^{-1} N	1619	5770.69	1525	5415.40	1348	4746.31

Source: ADARC (2006-2007)

In woreta Vertisols the biological yield was found higher than the grain yield which implied the crop performance was more of vegetative than grain filling. Planting of tef with the BBF system in Vertisols of both localities was associated with low grain yield. It was observed that the possibility of tef-chickpea double cropping system in Bichena Vertisols was found impossible under natural conditions whereas, in woreta Vertisols it was possible through adjustments of tef planting dates one month earlier than farmers planting time (Alemayehu *et al.*, 2011).

8.5.3. Intercropping

Like any small-scale farmers in the tropics, there are regions in Ethiopia where farmers prefer intercropping of legumes with cereals to sole cropping of either of the crops. Most farmers intercrop tef with other crops due to the following reasons: i) since some early maturing crops in the intercropping are harvested, farmers can obtain some grains for the family at times of food scarcity; ii) since cereals are usually intercropped with legumes, farmers can satisfy their requirement for balanced diet; iii) due to diversification of crops, farmers minimize risks of crop failure due to adverse environmental factors such as diseases and pests; and iv) it improves the harvest and income (Dapaah *et al.*, 2003; Jensen, 1996).

Tef intercropping with other crops has been the common practice in the warm and moist valleys of Northern Shewa of Amhara Regional State (Geleta *et al.,* 2002; Adamu *et al.,* 2011). A recent study showed that up to 64% of the tef fields were intercropped with oil crops (Adamu and Kemelew, 2011) (Table 11). In descending order of importance, the crops commonly intercropped with tef are sesame, safflower, sesame, sorghum, gomenzer (*Brassica carinata*) and sunflower. In this system, cultural practices such as seed rates, sowing dates, planting depth, weeding frequency and fertilizer management of intercropping were found to be determined by the experience of the individual farmers. Other factors such as soil types, onset and duration of rainfall were also identified as system determinants.

Table 11. Relative area coverage (%) of tef based cropping systems in two regions in North Shewa in October 2006.

Cropping systems	Jeweha to Asfachew (n = 368)	Shewa Robit to Medina (n = 316)
Tef-sesame intercrop	60.33	59.87
Tef-sesame-safflower intercrop	0.27	6.05
Tef-sorghum intercrop	0.54	1.59
Tef-gomenzer intercrop	0.54	0.00
Tef-safflower intercrop	2.72	11.15
Tef-sesame-safflower-sorghum intercrop	0.00	0.32
Sole cropped tef	35.60	21.02

Source: Adamu and Kemelew (2011)

A tef–fababean mixed cropping field experiment at Holetta using different seed rates of faba bean indicated that increasing the seed rate of fababean increased fababean seed yield but decreased tef grain yield (Getachew *et al.*, 2006). Likewise, mixed cropping of fababean with tef increased land use efficiency and gave higher total yields compared to growing either species in sole culture. Tef yield equivalent, land equivalent ratios (LERs) and system productivity index (SPI) of the mixtures exceeded those of sole crops especially when the seed rate of fababean in the mixture was increased to 50 kg ha^{-1}(Table 12). The highest tef yield equivalent of 1697 kg ha^{-1} and LER value of 1.32 were obtained when fababean was mixed at a rate of 62.5% with the full seed rate of tef. This suggested that, at the current prices of the respective crops, up to 62.5% of fababean can be mixed in normal tef to get better total yield and income than sole culture of either species. Similarly, at Hawassa tef relay intercropped in maize by broadcasting at 35 days after maize silking gave higher LER of 1.3 in wide inter-row spaces of maize, and this study also identified that yield of both component crops were significantly affected at narrower spaces (Walelign, 2004) Table 13).

Table 12. Effects of mixed cropping on grain yield of tef and faba bean, tef yield equivalent and land equivalent ratio (LER) at Holleta from 2002 to 2003.

Cropping system	Grain yield (kg ha^{-1})		Yield equivalent of tef (kg ha^{-1})	LER values		
	Tef	Faba bean		Tef	Faba bean	Total
Sole tef	1480	-	1480	1.00	-	1.00
Sole faba bean	-	1586	1085	-	1.00	1.00
Tef/faba bean (100:12.5)	1362	341	1595	0.92	0.21	1.13
Tef/faba bean (100:25)	1262	584	1662	0.85	0.36	1.21
Tef/faba bean (100:37.5)	1165	767	1689	0.79	0.47	1.26
Tef/faba bean (100:50)	1016	948	1664	0.69	0.59	1.28
Tef/faba bean (100:62.5)	912	1147	1697	0.60	0.72	1.32
Mean	1200	893	1553	0.81	0.56	1.20

Source: Getachew *et al.* (2006)

Table 13. Average of Land equivalent ratio (LER) for maize-tef relay intercropping with various planting pattern and leaf removal 1996-97 at Hawassa, Ethiopia.

Planting pattern	Leaf removal			
	L1 (No leaf removal)	L2 (Removal below the ear)	L3 (L2 + two leaves removal at 10 days interval)	Mean
Broadcast	1.23	1.30	1.33	1.29
60 x37.5 cm	1.20	1.30	1.35	1.28
75 x30 cm	1.32	1.48	1.51	1.44
100 x 22 cm	1.34	1.50	1.50	1.45
Mean	1.26	1.40	1.42	1.36

Source: Adopted from Walelign (2004)

Maize leaf removal below the ear improved tef grain yield without reducing maize grain yield significantly (Walelign, 2004). It was also realized that in maize-tef association, maize has a deeper root system than tef which allows for exploitation of soil nutrient and moisture at different soil layers. Wondimu et al. (2007) also looked into the tef sunflower mixed cropping yield benefits due to their complimentary rather than competitive use of resources. As these crops have different growth durations, canopy positions and rooting depth, their mixed planting (10-50 % sunflower) gave 20-30 % and 58-77 % yield advantages at two different sites (Sirinka and Kobo) and had no major effect on growth parameters of tef. In monetary terms, mixed cropping increased the income at every level of supplementation by USD 211-

515 ha^{-1} at Sirinka and USD 30-69 ha^{-1} at Kobo over growing tef in monoculture (Wondimu *et al.*, 2007). In this study it was observed that the optional level of mixture of the compatible crops depends on different factors such as variety, location and weed population.

8.6. Conclusions and the Way Forward

The number of tef growing farmers' and area coverage of the crop are increasing from time to time (Hailu and Seyfu, 2001). Nonetheless, wide gaps have been noted between the real productivity obtained on farmers' field and the potential productivity of tef recorded on research stations and on on-farm verification trials. To narrow down this yield gap, efforts should be made to improve crop productivity while sustainably conserving and increasing the soil. The first step is to scale up conservation tillage in line with rotations of oil crops and grain legumes in tef based farming systems. Intercropping of tef with oil crops that has been in practice in the lowlands of North Shewa should be taken as best bet local technology, and soon scaled up to other similar sub-agro-ecologies of Ethiopia. Similarly, fababean-tef intercropping could be applied to enhance land productivity of tef-legume based farming systems of the Ethiopian highlands.

The following points are suggested for future research in the area of tef agronomy:

i) Tef research agenda in the next generation should base on conservation farming so as to reverse the resource degradation;
ii) Further research needs to be solicited on tef seeding methods to generate better agronomic data that are substantiated with social assessment/data for generation of practically valid scientific information in the country;
iii) Evaluation of tef-oil crops intercropping for system compatibility must be done, and basic scientific information must promptly be generated;
iv) For different tef growing regions, suitable crops for rotation with tef must be identified; and
v) Interacting factors for integrated soil nutrient, crop, insect, disease and weed are lacking in tef production systems of Ethiopia, and thus research on integrated crop management has to be re-initiated.

8.7. Abbreviations

BBF: broad bed and furrow; **CONV**: conventional tillage; **CSA**: Central Statistical Agency; **HW**: hand weeding; **IT**: improved tillage without sub-soiling; **ITS**: improved tillage with sub-soiling; **MT**: minimum tillage without sub-soiling.

8.8. References

Abdul Shukor Juraimi, Mahfuza Begum, Ahmed M. Sherif and Rajan A., 2009. Effects of sowing date and nutsedge removal time on plant growth and yield of tef [*Eragrostis tef* (Zucc.)Trotter]. African Journal of Applied Sciences 6(10): 1820-1825.

Adamu Molla and Kemelew Muhie. 2011. Tef (*Eragrostis tef*) based cropping systems in the hotto warm moist valleys of North Shewa, Ethiopia. Scientific Research and Essays 6(6): 1411-1416.

ADARC 2002-2004. Adet Agricultural Research Center, Progress Report 2002-2004, Bahir Dar, Ethiopia.

ADARC. 2006-2007. Adet Agricultural Research Center Progress of Report 2006-2007, Bahir Dar, Ethiopia.

Alemayehu Assefa,Tilahun Tadesse and Minale Liben, 2011.Tef-Chickpea double cropping system on Vertisols of Woreta and Bichena areas, northwestern Ethiopia. Proceedings of the 13th Annual conference of Crop Science Society of Ethiopia. 31st 2008-2nd January 2009, Addis Ababa, Ethiopia. Sebil 13:pp340-350.

Balesh Tulema, Jens BA, Fred HJ and Bernard V., 2008. The prospects of reduced tillage in tef (*Eragrostis tef* Zucc.) in Gare Arera, West Shawa Zone of Oromiya, Ethiopia. Soil and Tillage Research 99:58-65.

CSA. 2010. Central Statistical Agency. Agricultural Sample Survey 2009/2010 (2002 E.C.) (September – December, 2009). Vol. IV. Report on Area and Production of Crops (Private Peasant Holdings, *Meher* Season, Statistical Bulletin 446, Addis Ababa, Ethiopia.

CSA. 2008. Central Statistical Agency, Statistical bulletin for crop production forecast sample survey.CSA, Addis Ababa, Ethiopia

Dapaah HK, Asafu-Agyei JN, Ennin SA and Yamoah CY. 2003. Yield stability of cassava, maize, soybean and cowpea intercrops. Journal of Agricultural Science Cambridge 140:73–82.

Teklu Erkossa, Stahr K and Gaiser T. 2006. Soil tillage and crop productiviton a Vertisol in Ethiopian highlands. Soil Till. Res. 85, 200–211.

Fufa Hundera, Tesfa Bogale, Hailu Tefera, Kebebew Assefa, Tiruneh Kefyalew, Aberra Debelo and Seyfu Ketema. 2001. Agronomy research in tef. *In*: Hailu Tefera, Getachew Belay and Sorrells M (eds.), Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16–19 October 2000, Debre Zeit, Ethiopia, pp 167–176.

Geleta M, Asfaw Z, Bekele E and Teshome A. 2002. Edible oil crops and their integration with the major cereals in North Shewa and South Wello, Central Highlands of Ethiopia: an ethnobotanical perspective. Hereditas, 137: 29-40.

Getachew Agegnew, Amare Ghizaw and Woldeyessus Sinebo. 2006. Crop productivity and land use-efficiency of Tef/faba bean mixed intercropping in a tropical highland environment. Expl. Agric. 42: 495-504.

Hailu Beyene and Chilot Yirga. 1989. Initial result of informal survey: Inewary and Sendafa- Aleltu areas on Northern Shewa, Working Paper No.10. IAR, Addis Ababa, Ethiopia.

Hailu Tefera and Seyfu Ketema. 2001. Production and importance of tef in Ethiopian agriculture. *In*: Hailu Tefera, Getachew Belay and Sorrells M (eds), Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16–19 October 2000, Debre Zeit, Ethiopia, pp 3-7.

Hurni H and Perich I. 1992. Towards Tigray regional environmental and economic strategy. Development and Environment Reports No. 6. Group for Development and Environment (GDE). Institute of Geography. University of Bern, Switzerland.

Jensen ES. 1996. Grain yield, symbiotic N_2 Fixation and interspecific competition for inorganic N in pea-barley intercrops. Plant and Soil 182:25–38.

Melese Temesgen. 2007. Conservation tillage systems and water productivity implication for small-holder farmers in semi-arid Ethiopia, Doctorial thesis, Delft University of Technology and of the Academic Board of the UNESCO-IHE, Institute for Water Education, D elft the Netherlands.SG2000. 2002. Sasakawa Global 2000, Proceedings of the Workshop on Conservation Tillage, April 4, 2002, Melkassa, Ethiopia, pp 48–49.

Tolera Abera, Daba Feyisa, Hassan Yusuf and Tesfaye G/Giorgis. 2005. Influence of precursor crops on inorganic and organic fertilizers response of maize at Bako, western Oromia, Ethiopia. Pakistan Journal of Biological Sciences. 8(12) 1678- 1684.

Walelign Worku. 2004. Maize-tef relay intercropping as affected by maize planting pattern and leaf removal in southern Ethiopia. African Crop Science Journal. 12(4):358 367

Wondimu Bayu, Molla Addisu, Besufekad Tadesse and Legesse Admassu*, 2007.* Intercropping tef and sunflower in semi-arid areas of Wello, Ethiopia. *Trop. Sci.*, 47(1): 16–21.

Worku Burayu, Sombat C., Rungsit S., Thongchai M.,and Sunanta J., 2005.Conservation Tillage-Alternative Systems of Tef (*Eragrostis tef*) Production for a Semi-Arid, Central Rift Valley of Ethiopia. *Kamphaengsaen Acad. J.* 3(3): 1-10.

Zerihun Tadele, 1994. Tef in the farming systems of the Ada area. Ethiopian Agricultural Research Organization (EARO), Research Report 24, Addis Ababa, Ethiopia.

9. Soil Fertility Management Studies on Tef

Wakene Negassa and Yifru Abera*
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O. Box 32, Debre Zeit, Ethiopia. *Corresponding author: yifrua@yahoo.com

Tef [Eragrostis tef (Zucc.) Trotter] is the principal crop that takes the largest share of cultivated land and imported chemical fertilizer in Ethiopia. Here, we present soil fertility management technologies generated for tef-based farming systems and forward future research and development interventions. The recommended fertilizer rates for tef production in Ethiopia are in the range of 15-90 kg ha^{-1} for nitrogen (N) and 0-30 kg ha^{-1} for phosphorus (P). The integrated use of inorganic fertilizers with organic fertilizers such as green manure, compost, farmyard manure and agro-industrial by-products were also found to improve the yield of tef and reduce the amount of recommended inorganic N fertilizer at least by half. Hence, future research and development interventions should focus on revisiting the recommended NP fertilizers, scaling-up promising soil fertility management technologies and investigating micronutrient requirement of diverse tef varieties cultivated in the various growing regions in the country.

Key words: soil fertility, inorganic fertilizer, organic fertilizer, fertilizer recommendation

9.1. Introduction

Tef is an indigenous and major staple food crop that takes the largest share of cultivated land and imported chemical fertilizers in Ethiopia. According to CSA (2010), about 30% of the total fertilizers used in the country during the 2009/10 cropping season were applied to tef. The two dominant fertilizers used in Ethiopia are urea (46% N) and di-ammonium phosphate (18% N, 46% P_2O_5).

Tef is adapted to a broad range of agro-ecological conditions in Ethiopia. Some of the soil related constraints in tef production are poor soil fertility, salinity, acidity and waterlogging. The latter is particularly a problem on Vertisols found in areas with high amount of precipitation. Nitrogen and phosphorus deficiencies are wide-spread problems throughout the country and the necessity of fertilizing tef especially with N has been shown by nation-wide and site-specific fertilizer trials. Phosphorous (P) is of secondary importance and is recommended at low level of application, except on highly weathered red soils that fix considerable quantity of the applied P (Tekalign *et al.*, 2001). Recently, some studies showed that sulfur (S) and zinc (Zn) are also limiting nutrients for tef production (Habtegebrial and Singh, 2006; Bereket *et al.*, 2011).

Soil fertility research on tef has been previously reviewed by Tekalign *et al.* (2001). The objective of the present review has been to compile improved soil fertility management technologies in the past decade and forward future research and development intervention with respect to soil fertility management for tef production in Ethiopia.

9.2. Soil Fertility Management Recommendations

9.2.1. Fertilizer rates

Most of fertilizer studies in the past focused on the response of tef to the application of N and P fertilizer in Ethiopia, however; recent studies revealed that the application of S and Zn increased grain and straw yields of tef in Tigray region (Habtegebrial and Singh, 2006; Bereket *et al.*, 2011). The N and P fertilizer recommendations are available for diverse soil and agro-ecologies of tef cultivation (Table 1).

Agronomic and fertilizer recommendations are location specific; however, in most parts of the country the national and/or regional fertilizer recommendations are used for tef and other crops regardless of the presence of site-specific recommendations. Such blanket fertilizer recommendations have negatively influenced chemical fertilizer efficiency and profitability since tef fertilizer requirement is affected by soil moisture, soil fertility status, cropping history and cropping systems. Improved technology transfer under the Ethiopian context stands only for crop varieties without considering other important parameters such as soil fertility management.

Table 1. Optimum N and P fertilizer recommendations for major tef growing regions and soil types in Ethiopia.

Description of the area			Fertilizer recommendations		Reference
Region	Location	Soil Type	N (kg ha^{-1})	P (kg ha^{-1})	
Oromia	Ada'a, Akaki	Vertisols	60	10-15	Tekalign *et al.* (2001)
	Ada'a	Andosol	90	15	Teklu (2003)
	Melkassa	Fluvisol	23	10	Olani *et al.* (2005)
	Wolenchiti, Wonji	Andosol	23	10	Olani *et al.* (2005)
	Holetta	Nitisols	40	26	Balesh et al. (2008)
	Holeta	Vertisols	60	26	Balesh et al. (2008
	Arjo, Shambu	Nitisols	15	10	Abdenna *et al.* (2006)
SNNP	Humbo, Jinka	Nitisols	23	30	Abay *et al.* (2010) (unpublished)
	Areka	Nitisols	18	20	Kelsa (1998)
	Areka	Alisols	9-18	10-20	Abay (2011)
	Bobicho (Hossana)	Luvisols	9-27	10-30	Abay (2011)
Tigray	Tahtay Koraro	Cambisols/Luvisols/Vertisols	46	10	Abreha and Yesuf (2008)
Amhara	Yilmana Densa, Estie, Ebinat	Nitisols	40-41	18-26	Minale *et al.* (2004); Alemayehu *et al.* (2007)
	Achefer, Gozamin	Nitisols	60	26	Alemayehu *et al.* (2007)
	Dembecha, Dangila, Bure	Nitisols	20	18	Alemayehu *et al.* (2007)
	Dejen, Belesa	Vertisols	41	20	Alemayehu *et al.* (2007)
	Bichena	Vertisols	80	9-18	Minale *et al.* (2004)
	Huleteju-Enebssie, Awobel, Simada, Dembia	Vertisols	60-80	18-26	Alemayehu *et al.* (2007)
	Kelela, Tenta (Wata), Tehulederie, Habru, Wadla	Brown soil	46	0-20	Sirinka progress report (2007)
	Sayint, Kalu (Adamiya)	Red soil	46	10-30	Sirinka progress report (2007)
	Mekdela, Kobo Zuria, Sayint (Waro), Kalu (Harbu)	Black soil	46	0-30	Sirinka progress report (2007)

The tef N and P fertilizer requirement studies were made more extensively in the Amhara region than in the other regions of Ethiopia (Table 1). The highest grain yield benefit of more than 1 t ha^{-1} was obtained at Estie, Bichena, and Huleteju-Enebissie, whereas the lowest yield was obtained at Habru, North Wello. However, the average grain yield benefit obtained from NP fertilizers at 52 sites in the region was 0.59 t ha^{-1}. Therefore, crop suitability studies and search for other promising tef varieties and/or other crops should be made for achieving food security in locations where the lowest tef grain yields were recorded with N and P fertilizers applications.

Not only the amount but also the time of N-fertilizer application is critical for tef production as N is mostly lost due to high denitrification in waterlogged soils and due to leaching in sandy soils. The type of the preceding crop alters the amount of N fertilizer to be applied to tef crop. Studies showed that N-fertilizer could be either omitted or halved when the precursor crops are legumes (Tekalign *et al.*, 2001; Alemayehu *et al.*, 2010) or oil crops (Abdenna *et al.*, 2006; Alemayehu *et al.*, 2010).

Many studies in Ethiopia revealed that tef responds positively to N fertilizer application, but not to P-fertilizer particularly in the central highlands of Ethiopia where Vertisols are the dominant soils (Tekalign *et al.*, 2001) or in other parts of the country where tef is widely cultivated (NFIU 1993; Minale *et al.*, 2004). However, farmers prefer to apply DAP (di-ammonium phosphate) fertilizer which contains both N and P to urea which contains only N. A recent study on Vertisols also showed that P fertilization did not bring about significant increases in the grain and straw yields of tef (Yifru, unpublished). This calls for systematic and in-depth investigation into the phosphors chemistry and effect of tef rhizosphere on soil biochemistry on Vertisols and other soils types in Ethiopia. It is particularly important to study the effect of different soil phosphorus pools (fractions) on the uptake of P by the tef plant. The findings from such experiments might suggest to policy makers to substantially cut down the huge cost of importing P fertilizers.

9.2.2. Timing of N fertilizer Application

Split application of N fertilizer is recommended to improve N-use efficiency of crops so that the availability of N is synchronized with the crop stage of maximum N demand (Tekalign *et al.*, 2001). Nitrogen is a highly mobile nutrient that can be lost through leaching, volatilization and denitrification depending on the methods of application, soil types and weather conditions. For instance, the best timing of N-fertilizer application on Vertisols varied according to the moisture condition. In general, two split-applications of N, half at planting and the remaining half at tillering or booting stage, are recommended in order to increase the grain yield of tef (Tekalign *et al.*, 2001; Teklu, 2003). The amount of the intended rate of N fertilizer application also determines the time of N fertilizer application. For higher levels of N rates, split application is recommended. Conversely, when the rate of N fertilizer is low, applying once at the active tef growth stage can increase N use efficiency. The time of N fertilizer application is also affected by the soil moisture status, and generally both the excess and scarce soil moisture are not favorable conditions. For instance, Balesh *et al.* (2005a) indicated that the mean fertilizer N use efficiency (FNUE) of different tef varieties was 61% on Nitisols, whereas it was 28% on Vertisols. The low FNUE on Vertisols has a negative impact on the livelihood of the farmers since Vertisols are the dominant soils in the major tef growing regions of the country. Sulfur fertilization was also found to increase nitrogen-use efficiency by 36% (Habtegebrial and Singh, 2006). According to Alemayehu *et al.* (2006), identifying tef genotypes with high N-use efficiency is useful to develop varieties with high N uptake, use and utilization.

9.2.3. Type and Rate of Organic Fertilizers

The utilization of organic fertilizers for soil amendment can be constrained by the quantity and quality of organic materials needed to supply the required amount of plant nutrients. In most cases, large amount of organic materials are required to supply significant amount of nutrients to crops and this depends on the quality of the biomass. Hence, integrated uses of inorganic and organic fertilizers not only improve crop yield but also improve soil structure and water holding capacity. In order to obtain immediate benefits from organic fertilizers, decomposing the organic matter before application into soils improves the nutrient availability. This is important because not all the nutrients are released in the year of organic fertilizer application. A two-year study made at Debre Zeit indicated that 28% of N, 19% of P, and 90% of K were released into the soil after the first year of farmyard manure application (Lupwayi and Haque, 1999).

Various organic fertilizers such as farmyard manure (FYM), green manure, compost and agro-industrial by-products were investigated for their role in improving the tef grain yield (Table 2). The findings indicated that sole application of these organic fertilizers did not satisfy the nutrient requirement of tef particularly in nutrient depleted soils. As a result, almost all studies recommended the integrated use of both chemical and organic fertilizers for tef production. For instance, the combined application of 4.53 t ha^{-1} FYM and 37 kg ha^{-1} inorganic N were recommended for tef on Vertisols of the Central Highlands (Teklu and Hailemariam, 2009). However, FYM is widely used as a source of energy and cash in central part of Ethiopia. Hence, research and development interventions should be urgently made on the alternative cash and energy sources in order to assist farmers on proper use of FYM for soil amendment instead of selling and/or using it as a source of energy. The introduction of agroforesty systems, apiculture, high value crops and biogas to the farming communities can partly alleviate the shortage of cash and energy while improving the soil fertility.

Table 2. Effects of organic fertilizers on tef grain yield in different regions.

Description of the area		Organic Fertilizer		Grain yield (kg ha^{-1})	References
Region	Location	Type	Rate (ha^{-1})		
Tigray	Tahtai Maichew	Compost	6.4 t	1110	Halilu (2010)
Oromia	Holetta	Mustard meal	0.51 t	830	Balesh *et al.* (2005b)
	Debre Zeit	FYM + inorganic N	4.53 t FYM + 37 kg N	2200	Teklu and Hailemariam (2009)
Amhara	Adet	Lupine green manure	Rate not established	1610	Tadele *et al.* (2007)
	Adet	Vetch green manure	Rate not established	1720	Tadele *et al.* (2007)

Lupine and vetch green manures increased grain yield of tef by 15% and 23%, respectively, over the control at Adet in the Amhara Region (Tadele *et al.*, 2007). Green manure crops can first be grown and then incorporated into the soil during the period from the onset of rainfall to tef planting. In addition to protecting the soil from erosion, green manure crops could easily extract soil nutrients which otherwise lost by runoff and/or leaching.

Sources of composting materials significantly affected tef yield and yield components. The yield obtained from the application of compost derived from cereals was not better than the yield obtained without compost application. However, as the component of legumes increased in the composting materials, the dry biomass yield response showed a curvilinear increase up to 25% cereals materials plus 75% legume plant materials (Yihenew *et al.*, 2010). A linear increase of tef grain yield was obtained by increasing the composting time to 7.5 months, while there was a decline of tef grain yield when the composting period was extended beyond 8.5 months. However, the yield was increased as the time of composing extended beyond 8.5 months for 100% cereal composting materials. This clearly showed that the compositing period of easily decomposed plant materials which are rich in N and labile organic components are relatively short up to four months under favorable composting conditions. However, extending beyond four months can result in loss of essential elements from the compost as observed in reduction of tef grain yield. In general, increasing the proportion of legume plants in compost preparation increased the quality of compost and shortened period of compositing to use for immediate soil amendment.

'*Orga*' (containing mixture of manure, bone meal and blood meal) have been shown to significantly increase the grain yield of tef in the different parts of the country (Abay *et al.*, 2010; Niguse, 2010). However, since P in *Orga* and or bone meal is only partially available to the plant as compared to inorganic P fertilizer, the amount of organic P fertilizers to be applied should be double of that of the soluble P fertilizer (Wakene *et al.*, 2004).

Mustard meal is also a good source of N fertilizer. It increased tef grain yield up to 116% over the control (Balesh *et al.*, 2005b). However, the effects of mustard, FYM and compost applications showed variability on tef yield depending on soil types (Balesh *et al.*, 2007). Accordingly, tef was the most responsive to FYM on Vertisols and to compost on Nitosols, whereas mustard meal can be applied on both soil types. Other agricultural by-products from coffee, brewery, sugar, oil food cakes and sisal can also be potential fertilizer sources in Ethiopia (Wakene *et al.* 2010a, 2010b, 2012).

Hence, characterizing and evaluating agro-industrial by-products for soil amendments, and determining the rates and method of applications can help utilize the resources efficiently so that their contribution to environmental pollution could be alleviated.

9.2.4. Soil Test-Based Phosphorus Fertilizer Recommendation

Attempts have been made recently to provide phosphorus fertilizer recommendation based on the results of soil tests. Critical value and requirement factor are two important decision criteria whether to apply phosphorus or not and how much to apply if application is indispensable. Accordingly, the critical value and requirement factor of phosphorus for tef production were 6 ppm and 4.76 kg P ha^{-1}, respectively at Tahtay Koraro of Tigray Region (Abreha and Yesuf, 2008). The respective values for the whole country were 10 ppm and 6.72 kg P ha^{-1} (Yesuf *et al.*, 2009). Such a single P recommendation for the whole country with divergent types of soils, climates, crops and cropping histories does not reflect the realities. Before providing soil test-based P recommendations for different crops and soil types, standardizing the quality of soil testing laboratories is essential.

9.3. Conclusion and the Way Forward

The numbers of soil fertility management technologies are low for tef as compared to other cereals grown in Ethiopia. Most of these technologies also dealt with response of tef to NP fertilizers applications. Evaluation of different sources of organic and bio-fertilizers for tef-based farming system need immediate research and development interventions in the country. Revisiting the N and P-fertilizer rate recommendations given about a decade ago may help develop judicious chemical fertilizers recommendations for tef production.

The most yield-limiting element or nutrient is not yet known for diverse tef growing agro-ecosystems. N and P are the only chemical fertilizers currently used in Ethiopia. Assessing the requirement of the other macro- and micro-nutrients is, therefore, of paramount importance. Earlier greenhouse investigations indicated that tef genotypes differ in nutrient use efficiency. Finally, designing integrated soil fertility management research and development strategies may tackle the complex socio-economic problems that hinder the adoption of soil fertility management technologies in Ethiopia.

9.4. Abbreviations

CSA: Central Statistical Agency; **DAP**: di-ammonium phosphate; **FNUE**: fertilizer N use efficiency; **FYM**: farmyard manure; **N**: nitrogen; NFIU: National Fertilizer Input Agency; **P**: phosphorus; S: Sufur; Zn: Zinc.

9.5. References

Abay Ayalew, Shiferaw Boke and Wasie Haile. 2010. Review of soil and water technologies: case of Southern Nations Nationalities and Peoples Regional State (SNNPRS) (Unpublished).

Abay Ayalew. 2011. Application of NP Fertilizers for better production of Teff (*Eragrostis tef* (Zucc.) Trotter) on different types of soils in southern Ethiopia. Journal of Natural Sciences Research 1(1): 6-15.

Abedenna Deressa, Wakene Negassa, Fite Getaneh and Birhanu Dinsa. 2006. Response of tef to nitrogen and phosphorus fertilizers under farmers' conditions. *In*: Asfaw Zeleke, Hailu Tefera, Gemechu Keneni, Amsalu Ayana, Tesfaye Tefera, Solomon Assefa, Desalegn Debelo and Belay Simane (eds.). Proceedings of the Eleventh Conference of the Crop Science Society of Ethiopia, 26-28 April 2004, Addis Ababa, Ethiopia, pp 176-181.

Abreha Kidanemariam and Yesuf Assen. 2008. Recommendation of phosphorus fertilizer based on soil-test and response of tef to nitrogen and phosphorus fertilizers. Ethiopian Journal of Natural Resources 10(1): 103-122.

Alemayehu Assefa, Minale Liben and Tilahun Tadesse. 2010. Yield response of tef (*Eragrostis tef*) to nitrogen application in relation to precursor crops on Nitosols of Adet area, northwestern Ethiopia. *In*: Ermias Abate (ed.). Proceedings of the Third Annual Regional Conference on Completed Crop Research Activities, 1-4 September, 2008. Amhara Region Agricultural Research Institute. Bahir Dar, Ethiopia, pp 98-103.

Alemayehu Assefa, Minale Liben, Tilahun Tadesse and Abrham Mariye. 2007. Determination of optimum rates of nitrogen & phosphorus fertilization for tef (*Eragrostis tef*) production in different agro-ecological areas of northwestern Ethiopia. *In*: Ermias Abate., Akalu Teshome, Alemayehu, Asefa, Melaku Wale, Tadesse Dessalegn, and Tilahun Tadesse (eds.). Proceedings of the First Annual Regional Conference on Completed Crop Research Activities, 14- 17 August, 2006. Amhara Region Agricultural Research Institute. Bahir Dar, Ethiopia, pp 60-67.

Alemayehu Balcha, Gretzmacher R and Vollmann J. 2006. Genetic variation in nitrogen-use efficiency of tef. Journal of Plant Nutrition and Soil Science 169: 704-710.

Asnakew Woldab. 1989. Organic fertilisers, their use in crop production. Institute of Agricultural Research (IAR), Newsletter of Agricultural Research, Vol. 3, No. 3, Addis Ababa, Ethiopia.

Balesh Tulema, Zapata BF, Aune J and Sitaula B. 2005a. N fertilisation, soil type and cultivars effects on N use efficiency in tef [*Eragrostis tef* (Zucc.) Trotter]. Nutrient Cycling in Agroecosystems 71: 203-211.

Balesh Tulema, Zapata F and Aune JB. 2005b. Evaluation of mustard meal as organic fertiliser on tef (*Eragrostis tef* (Zucc) Trotter) under field and greenhouse conditions. Nutrient Cycling in Agroecosystems 73:49-57.

Balesh Tulema, Aune, J.B and Breland TA. 2007. Availability of organic nutrient sources and their effects on yield and nutrient recovery of tef [*Eragrostis tef* (Zucc.) Trotter] and on soil properties. Journal of Plant Nutrition and Soil Science 170: 543–550.

Balesh Tulema, Aune, J.B, Johnsen F.H. and Vanlauwe, B. 2008. The prospects of reduced tillage in tef (*Eragrostis tef* (Zucc) in Gare Arera, West Shawa Zone of Oromiya, Ethiopia. Soil and Tillage Research 99: 58–65.

Bereket Haileselassie, Stomph TJ and Hoffland E. 2011. Teff (*Eragrostis tef*) production constraints on Vertisols in Ethiopia: farmers' perceptions and evaluation of low soil zinc as yield-limiting factor. Soil Science and Plant Nutrition 57: 587-596.

CSA.2010 Central Statistical Agency. Agricultural Sample Survey Report on Farm Management Practices, September to December 2009, Statistical Bulletin No. 468, Addis Ababa, Ethiopia.

Habtegebrial K and Singh BR. 2006. Effects of timing of nitrogen and sulphur fertilizers on yield, nitrogen, and sulphur contents of Tef (*Eragrostis tef* (Zucc.) Trotter). Nutrient Cycling in Agroecosystems 75:213–222.

Hailu Araya. 2010. The effect of compost on soil fertility enhancement and yield increment under smallholder farming - a case of Tahtai Maichew district - Tigray region, Ethiopia. PhD dissertation submitted to the Faculty of Agricultural Science, University of Hohenheim, Germany. 186p.

Kelsa Kena. 1998. Effect of DAP and Urea fertilizers on grain yield of three tef varieties in Awassa and Areka. *In*: Tadele G/Selasssie and Sahlemedhin Sertsu (eds.). Proceedings of the Fourth

Conference of the Ethiopian Society of Soil Science. Feb. 26-28, 1998, Addis Ababa, Ethiopia, pp 122-127.

Lupwayi NZ and Haque I. 1999. Leucaena hedgerow intercropping and cattle manure application in the Ethiopian highlands. I. Decomposition and nutrient release. Biol. Fertil. Soils 28: 182–195.

Minale Liben, Alemayehu Assefa, Tilahun Tadesse and Abrham Marye. 2004. The response of tef to nitrogen and phosphorus applications at Bichena and Yilmana-Denssa areas, northwestern Ethiopia. *In*: Asfaw Zeleke, Getachew Belay, Belay Simane, Bulcha Weyessa and Nigussie Alemayehu (eds.). Proceedings of the Tenth Conference of the Crop Science Society of Ethiopia, 19-21 June 2001, Addis Ababa, Ethiopia, pp 135-144.

NFIU. 1993. National Fertilizer Input Unit, Wheat results of the FTS, ITS and DSFT, Addis Ababa, Ethiopia.

Niguse Hagazi. 2010. Soil and Water Management Research Achievements of Tigray Agricultural Research Institute (Unpublished).

Olani Nikus, Girma Abebe, Abuhay Takele, Hussen Harrun, Solomon Chanyalew, Abdel Rahman Al Tawaha and Tewodros Mefin. 2005. Yield response of tef (*Eragrostis tef* (Zucc.) Trotter) to NP fertilization in the Semi-arid zones of the central rift valley in Ethiopia. European Journal of Scientific Research 4: 49-59.

Sirinka Progress Report. 2007. Sirinka Agricultural Research Center Progress Report 2006/7, Sirinka.

Tadele Amare, Yihenew Gebreselassie, Enyew Adigo and Tesfaye Feyisa. 2007. Green manure: an option for replenishing soil fertility and its compatibility with the farming system of Gojam. *In*: Yihenew Gebreselassie, Enyew Adigo, Zewudu Ayalew, Abrham Abiyu and Belay Tseganeh (eds). Proceedings of the First Annual Regional Conference on Completed Research Activities on Natural Resources Management, 14-17 August 2006, ARARI, Bahir Dar, Ethiopia, pp 14-20.

Tekalign Mamo, Teklu Erkossa and Balesh Tulema. 2001. Soil Fertility and Plant Nutrtion Research on Tef in Ethiopia. *In*: Hailu Tefera, Getachew Belay and M. Sorrels (eds.). Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Addis Ababa, Ethiopia. Ethiopia Agricultural Research Organization, Addis Ababa, pp 191-200.

Teklu Erkosa. 2003. Some site-specific soil and water management technologies in the central highlands of Ethiopia. *In*: Betre Alemu and Asfaw Zeleke (eds.). GIS for Modeling Environments in Ethiopian Agriculture. Proceedings of a Workshop held at Debre Zeit, January 16, 2001, Debre Zeit, Ethiopia, pp 47-54.

Teklu Erkossa and Hailemariam Teklewold. 2009. Agronomic and economic efficiency of manure and Urea fertilizers use on Vertisols in Ethiopian highlands. Agricultural Sciences in China 8: 352-360.

Wakene Negassa, Kefalew Negisho, Tadesse Yohannes. 2004. Bone meal and rock phosphate as alternative sources of P fertilizer for maize production. *In*: Tilahun Amede and Eylachew Zewide (eds.). Challenges of Land Degradation to Agriculture in Ethiopia. Proceedings of the 6th Ethiopian Society of Soil Science Conference, 28 Feb-01 March, 2002, Addis Ababa, Ethiopia, pp 51-58.

Wakene Negassa, Baum C and Leinweber P. 2010a. Soil amendment with agro-industrial by-products: molecular-chemical compositions and effects on soil biochemical activities and phosphorus fractions. Journal of Plant Nutrition and Soil Science 174: 113-120.

Wakene Negassa, Kruse J, Michalik D, Appathurai N, Zuin L and Leinweber P. 2010b. Phosphorus speciation in agro-industrial by-products: sequential fractionation, solution ^{31}P NMR and P *K*- and $L_{2,3}$-edge XANES spectroscopy. Environmental Science and Technology 44: 2092-2097.

Wakene Negassa, Baum C and Leinweber P. 2012. Evaluation of agro-industrial by-products as sources of nutrient for plant growth. Archives of Agronomy and Soil Science 58 (4): 451-460.

Yesuf Assen, Kefyalew Girma and Taye Bekele. 2009. Phosphorus critical value and requirement factor determination for Tef (*Eragrostis tef*) production in Ethiopia. Paper presented on ASA-CSSA-SSSA International Annual Meetings, 1-5 November 2009, Pittsburgh, Pennsylvania, USA. http://a-c-s.confex.com/crops/2009am/webprogram/Paper53348.html

Yihenew Gebreselassie, Tadele Amare and Tesfaye Feyissa. 2010. Decomposition dynamics and inorganic fertilizer equivalency values of compost prepared from different plant Residues. *In*: Birru Yitaferu, Teshome Tesema and Zewudu Ayalew (eds.). Proceedings of the 3rd Annual Regional Conference on Completed Research Activities in Soil and Water management, Forestry, and Agricultural Mechanization. 1-4 September 2008, ARARI, Bahir Dar, Ethiopia, pp 91-104.

10. Boosting Tef Productivity Using Improved Agronomic Practices and Appropriate Fertilizer

Tareke Berhe[1,*], Zewdie Gebretsadik[2], Sue Edwards[3] and Hailu Araya[3]

[1]Tef Value Chain, Ethiopian Agriculture Transformation Agency, P.O. Box 708, Addis Ababa; [2]Sasakawa Global 2000/Ethiopia, P.O. Box 12771, Addis Ababa; [3]Institute for Sustainable Development (ISD), P.O. Box 171-1110, Addis Ababa, Ethiopia.

[*]Corresponding author: tbtareke@gmail.com

Tef is currently cultivated in Ethiopia on about 2.8 million hectares of land and produces about 3.4 million tons. This amount of production is extremely low comparing to the needs of the current 80 million population of the country of which over 60% depend on tef as staple food. To this date, tef has been classified as one of the orphan-, minor- or forgotten-crops not only due to its low productivity but also due to the little investment that has been made towards its improvement. The productivity of tef needs to be tremendously increased so that it competes with other more productive cereals and continue to be grown as a food crop. This was succinctly stated by His Excellency, Prime Minister Meles who said: "If a miracle is not created fast, tef will cease to be the food of the majority of Ethiopians". In the last two years, development partners such as Sasakawa Africa Association and the Institute for Sustainable Development supported by Oxfam America have showed that optimum agronomic practices would contribute to significant increase in productivity. By reducing the seed rate from the commonly used 25-30 kg ha^{-1} to only 2.5 kg ha^{-1}, by transplanting the seedlings in a row instead of sowing by broadcasting and by applying appropriate types of fertilizer, a three-fold increase in both the seed and straw yields were obtained. Nothing can be more exciting than to imagine doubling the 3.4 million tons of annual tef grain production to 6.8 million tons or tripling to 10.2 million tons. On the other hand, tef is no more going to be an orphan crop since it is already starting to get a lot of attention. Here, we show how the productivity of tef was remarkably raised by applying appropriate agronomic practices and fertilizers.

Key words: row sowing, transplanting, fertilizer, agronomic practice, *Eragrostis tef*, orphan crop

10.1. Introduction

Tef (*Eragrostis tef*) is one of the very important cereal crops in Ethiopia. It is cultivated in a wide range of environments and performs better than other cereals under adverse climatic and soil conditions. In Ethiopia, about 2.8 million hectares of land or nearly one-third of the cereal area is allocated to grow the crop (CSA, 2011). Tef is the staple food for over 50 million Ethiopians. Due to high demand, the price of tef has increased tremendously in the last several years. During 2007/08, the price of a ton of tef grains reached $1000, four-fold above the average price of 2000 to 2008. This elevated price created problems to dominantly resource-poor consumers and as result forced them to switch to other cereals as a substitute although tef is still the most preferred food crop in Ethiopia.

Despite its importance, the productivity of tef is much lower than that of the other cereals. The national average yield is about 1.2 t ha^{-1}, compared to 2.8 t ha^{-1} for maize and 1.9 t ha^{-1} for wheat (CSA, 2011). Lodging or the permanent displacement of the stem from the upright position is the major constraint limiting the productivity of the crop especially when it occurs during the grain-filling period. Lodging affects both the quality and quantity of the produce (Seyfu, 1993). Sub-optimum crop husbandry also contributes to reducing the yield of tef. For example, broadcasting the seeds at higher rate of 25 to 50 kg ha^{-1} results in increased plant density which renders the crop prone to lodging and subsequently lead to poor yields in terms of both quality and quantity.

Tef breeding in Ethiopia was focusing only on selection until the first of author of this article discovered in 1975 the possibility of using cross-breeding or hybridization (Tareke, 1975). Since then, eight cross-bred varieties have been released to the farming community (Hailu *et al.*, 2001; DZARC, 1995). It is estimated that over the past 20 years the yield of tef has increased by 25-30%. Three-fourths of this gain was attributed to the adoption of few improved varieties and application of fertilizers. Commonly recommended blanket fertilizer application in Ethiopia consists of 100 kg ha^{-1} DAP (18% N: 46% P_2O_5) and 100 kg ha^{-1} urea (46% N). Due to use of improved varieties and agronomic practices, the tef yields of 4 t ha^{-1} at the on-station fields and 2.5 t ha^{-1} on farmers' fields were obtained.

Tef is a survivor crop. Due to its poor yield, the former government of Ethiopia planned to substitute tef with more productive crops such as triticale. However, due to its high preference by the consumers and fetching high price for the farmers, the area under tef cultivation has even been increasing (Hailu *et al.*, 2001). Tef remains the favorite food crop for Ethiopians and is also becoming an important health crop in Europe and the USA especially due to the absence of gluten in its grain. Hence, the productivity of tef should be boosted in order that the crop competes with other more productive cereals.

Efforts were made in the past to implement different techniques and tools in order to improve tef. The status of some of the techniques is indicated below:

i) Inter-specific crossing was made between tef (*E. tef*) and *E. curvula* in an attempt to transfer the lodging tolerant trait of *E. curvula* to tef. However, so far, no viable hybrid was obtained from the crosses.
ii) Application of plant growth hormone in order to obtain semi-dwarf plant. A chemical known as CCC significantly reduced the height of tef plant but the panicles from these plants were also shorter. Hence, the use of this hormone did not increase the productivity of tef.
iii) Spray application of foliar fertilizers containing major and micronutrients one to three times in a season did not improve the productivity of tef.
iv) In attempts to develop doubled haploids using gynogenesis technique, some promising tef lines were obtained.

Contrary to the common belief that the tef yield has reached the ceiling, we show here that the yield could be increased several folds through intensification or precision agriculture. Our recent exploratory agronomic experiments in Ethiopia have shown that grain and straw yields of tef can be doubled or even tripled by: (i) drastically reducing the plant population; (ii) transplanting in a row instead of broadcasting the seeds; and (iii) application of fertilizers containing micronutrients such as zinc and copper. We present below some of the achievements from these studies.

10.2. Effect of Transplanting and Fertilizer Application

In order to investigate the effect of planting method, seeds of two tef varieties, namely *Tsedey* (DZ-Cr-37) and *Quncho* (DZ-Cr-387 RIL 355) were sown in a wooden box and grown for two weeks until transplanting to the field. Transplanting was done on a black clay soil at Debre Zeit Agricultural Research Center at 20 cm inter- and 20 cm intra-row spacing on 2 m x 5 m plots. This preliminary experiment indicated that transplanting in a row considerably increased the seed yield of both varieties compared to the broadcasting method (Fig. 1). Broadcasting the seeds is the only sowing method used for tef by farmers in Ethiopia.

The use of seed-coating fertilizer (indicated here as 'pelleting') further improved the yield of tef. The pellets were obtained by immersing tef seeds in a liquid fertilizer obtained from Yara, a fertilizer company in Norway, and contain nutrients such as nitrogen, phosphorus and zinc. Huge yield benefits were obtained due to transplanting combined with the use of pelleting with fertilizer. For *Tsedey* variety, however, about 50% increase in grain yield was obtained by using the pelleted fertilizer on the transplanted tef although inferior yield was recorded when pellets were applied to the broadcasted tef. The positive effect of transplanting on tef yield was mainly due to increases in the number of tillers, stem/culm strength, and number of seeds/panicle (Fig. 1).

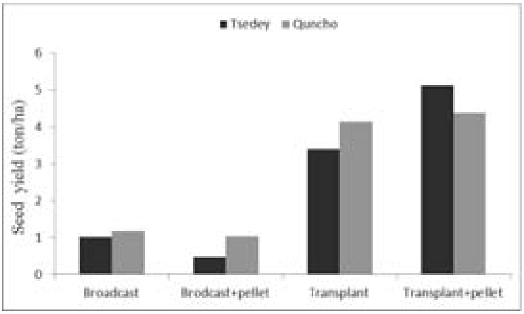

Fig. 1. Effect of transplanting and pelleted fertilizer on the seed yield of *Tsedey* (DZ-Cr-37) and *Quncho* (DZ-Cr-387 RIL 355) tef varieties at Debre Zeit. Transplanted plants were first sown in a box and transplanted 20 days later to soil at 20 cm x 15 cm spacing on a plot of 2 m x 5 m. The values were the average of three replications. Pelleting refers to the coating of tef seeds with fertilizer solution containing nitrogen, phosphorus and zinc.

10.3. Effect of Fertilizer on the Transplanted Tef

In order to investigate the effect of plant nutrients on tef productivity, fertilizers with different compositions were tested on transplanted tef in the lath-house. Fertilizers used in this study include DAP (18% N: 46% P_2O_5), Urea (46% N), Sucube (16% N: 26% P: 12% K: 4% S: 0.3% Zn) and DAP pelleted with zinc (Zn) alone, or with Zn and copper (Cu). DAP and urea are the most commonly applied fertilizers in Ethiopia while sucube is a granular fertilizer commonly used in West Africa for rice cultivation.

This preliminary experiment showed that fertilizer has tremendous impact in boosting the productivity of tef. Although DAP and urea are the most commonly recommended fertilizers in Ethiopia as nitrogen and phosphorus source, the application of zinc and copper also increased tef yield. The yield advantage due to these fertilizers was considerable for *Dukem* (DZ-01-974) variety where about 30 percent yield increase (from 6.7 t ha^{-1} to 8.7 t ha^{-1}) was obtained by sucube or DAP pelleted with zinc and copper (Fig. 2). This high productivity demonstrates that the potential yield for tef has not been yet sufficiently exploited. Although the application fertilizers increased the yield for the currently popular *Quncho* variety, the yied increase was more pronounced for the variety Dukem.

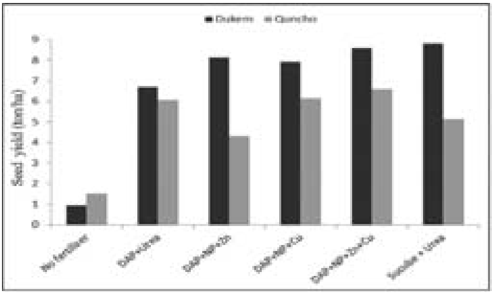

Fig. 2. Effect of different forms and types of fertilizer on the seed yield of *Dukem* (DZ-01-974) and *Quncho* (DZ-Cr-387 RIL 355) tef varieties in the lathhouse at Debre Zeit Agricultural Research Center. All plants in the experimental sample were transplanted. DAP (di-ammonium phosphate 18% N: 46% P_2O_5), Urea (46% N), Sucube (16% N: 26% P:12% K: 4% S: 0.3% Zn).

10.4. Performance of Transplanted Tef in the Field

The effect of fertilizers and transplanting were tested on three tef varieties; namely: *Dukem* (DZ-01-974): *Quncho* (DZ-01-Cr-387): and Gyno 8. The seedlings were first grown in pots for 20 days before transplanting to the field at 20 cm x 15 cm spacing and plot size of 20 m^2. The performance of transplanted tef at different growth stages is shown on Fig. 3. Tef appeared to responded positively to intensification or precision agriculture.

Both the seed and straw yields of *Dukem* variety were tremendously increased by transplanting and application of appropriate fertilizers (Fig. 4). Although sucube was found to be superior in the lathhouse experiment, the combination of DAP and another fertilizer called Buster Xtra (20% N: 20% P:20% K w/vol plus EDTA chelated trace elements ranging from 1.5% MgO to 0.0012% Mo) gave superior yield. This new fertilizer increased the seed yield to 6.6 t ha^{-1} which is equivalent to about 90% more than the yield obtained from the conventional/common application of DAP + urea fertilizers. DAP + buster mix also increased the straw yield to 25.8 t ha^{-1}

for same variety. This increase was about 75% over the amount obtained from DAP + urea. The straw of tef is a valuable feed for the livestock and a source of cash for smallholder farmers.

Fig. 3. The performance of transplanted tef in the field at Debre Zeit Agricultural Research Center. A) 20-day-old seedlings during transplanting; B) ten days after transplanting, C) three weeks after transplanting; D) five weeks after transplanting; E) at the grain filling stage; and F) tillering capacity of the transplanted (right) and non-transplanted (left) tef at the lathhouse.

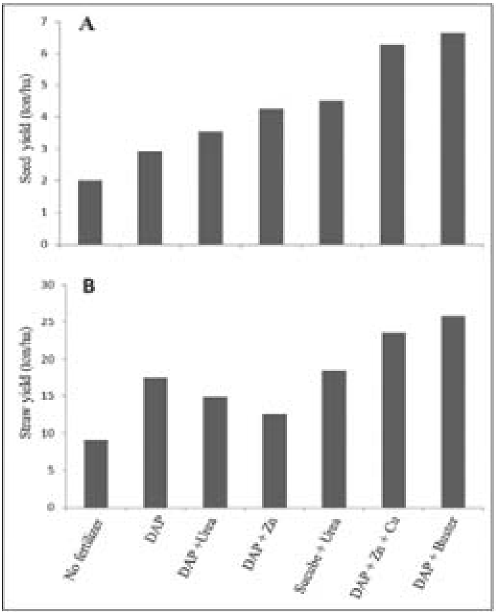

Fig. 4. Effect of different types and sources of fertilizer on seed (A), and straw (B) yield of *Dukem* tef variety. Tef plants were transplanted at the spacing of 20 cm x 15 cm. DAP (pho sphate Urea , Sucube (16N: 26P: 12K: 4S: 0.3Zn), Booster Xtra (20% N: 20% P:20% K wt/vol plus EDTA chelated trace elements ranging from 1.5% MgO to 0.0012% Mo) applied to the root zone four weeks after transplanting at the rate of 2-3 l ha^{-1}.

10.5. The Way Forward

In the year 2011, the Ethiopian government through its newly established Agricultural Transformation Agency (ATA) gave special focus to tef improvement. Plans have been put in place to demonstrate, along with improved varieties, several promising and productivity enhancing technologies including (i) reduced seeding rate, (ii) transplanting in a row instead of broadcasting, and (iii) the use of complex fertilizers that contain essential macro- and micro-nutrients. According to the plan, over 1500 demonstrations will be conducted in four tef producing regions, namely Amhara, Oromiya, SNNPR and Tigray. The demonstrations will be implemented at five levels by involving: (i) six MSc Students from Haramaya and Mekelle Universities, (ii) District Agricultural Officers (DAOs) at 90 Farmer Training Centers (FTCs), (iii) 1350 small scale farmers, (iv) 80 model farmers, and (v) six commercial farmers. In preparation for the season, trainings and briefings have been given at Federal, Regional and Woreda levels. Seeds of the popular *Quncho* variety will be provided free of charge by the Debre Zeit Agricultural Research Center while diverse types of fertilizers will be prepared by Ministry of Agriculture and Rural Development. The costs for conducting demonstrations at Farmer Training Centers will be covered by ATA. The ATA tef advisor will participate in the project in (i) deciding the types and numbers of demonstrations to be carried, (ii) quantifying the amount of inputs required, and (iii) preparing the overall plan of the activities including the publishing of the field manual.

In order to assess the performance of the project, several trials were conducted at Debre Zeit Agricultural Research Center during the off-season using irrigation. The trials investigated the effect of transplanting, row sowing and application of micro-nutrients such as zinc and copper. ATA was involved in the monitoring and supervision of the trials. Experience from these trials will be applied in planning demonstrations to be carried out during the main-season. In line with the Ethiopian Government's goal to double Agricultural Production within the coming five years, the tef value chain also aims towards fulfilling this objective.

10.6. Abbreviations

ATA: Agricultural Transformation Agency; **CSA**: Central Statistical Agency; **Cu**: Copper; **DAO**: District Agricultural Officers (DAOs); **DAP**: di-ammonium phosphate; **EIAR**: Ethiopian Institute of Agricultural Research; **FTC**: Farmer Training Center; **K**: Potassium; **Mg**: Magnesium; **Mo**: Molybdenum; **MoARD**: Ministry of Agriculture and Rural Development; **N**: Nitrogen; **P**: Phosphorus; **SAA**: Sasakawa Africa Association; **SAFE**: Sasakawa Fund for Extension Education; **SEP**: Supervised Enterprise Projects; **Zn**: Zinc.

10.7. References

Tareke Berhe.1975. Breakthrough in Teff breeding technique. FAO Inf. Bull., Cereal Improvement and Production, Near East Project xii (3)11-23. FAO, Rome.

CSA. 2011. Central Statistical Agency. Agricultural sample survey for 2010. Volume I. Addis Ababa, Ethiopia. Statistical Bulletin 505.

DZARC. 1995. Forty Years of Research Experience. 1955-1994. Agric. Exp. Station, Alemaya University.

Hailu Tefera, Getachew Belay and Sorrells M (eds.).2001. Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000. Addis Ababa, Ethiopia. Ethiopian Agricultural Research Organization (EARO), Addis Ababa, Ethiopia.

Seyfu Ketema. 1993. Tef (*Eragrostis tef*). Breeding, Genetic Resources, Agronomy, Utilization and Role in Ethiopian Agriculture. Ethiopian Agricultural Research Organization (EARO), Addis Ababa, Ethiopia.

11. Some Ecophysiological Characteristics of Tef, Including Mechanics of Lodging

J. Vos[1], S.H. van Delden[2], T.J. Stomph[1]
[1]Wageningen University, Center for Crop Systems Analysis, P.O. Box 430, 6700 AK Wageningen, the Netherlands; [2]University of Applied Sciences HAS Den Bosch, Green Business School, PO BOX 90108, 5200 MA 's-Hertogenbosch, the Netherlands. Corresponding author: jan.vos@wur.nl

The specific qualities of tef (i.e. the absence of gluten) inspired the start of a production and marketing chain of tef in the Netherlands. To be economically profitable, grain yields of at least 3000 kg ha^{-1} are needed, but the initial Dutch tef yields were below this threshold. Tef ripening takes place late in the season, this increased the risk of harvest failure due to unfavourable wet and windy weather conditions. Efforts were made to select early maturing genotypes that are better adapted to northern climates. In parallel, ecophysiological properties determining the performance of tef were assessed. These included: i) quantification of the response of germination rate to temperature and water potential; ii) phenology and agronomic yields; iii) effect of photoperiod on time to heading and plant structure; and iv) a study on the biomechanics of tef to identify the weakest point of the plant and assess tef's lodging sensitivity. This paper presents data on the performance of tef in the Netherlands and summarizes research on the afore-listed issues. As a preliminary approximation, the heat requirement of tef can be summarized with a base temperature of 11 ^{o}C and a heat sum of 18 ^{o}C d. As a result of a successful selection for early genotypes by breeders, we found large genetic variation in photoperiod sensitivity. At short-day lengths, tef headed earlier than at long-day lengths. Tiller numbers at short-day lengths were not significantly lower than that at long-day lengths. Biomechanical studies indicated that root failure is the primary cause of lodging on sandy soils, but on heavy clay soils breeding efforts for a stronger stem bases are equally important. Though progress has been made in enhancing the performance of tef, there is scope for further genetic improvement. Improved lodging resistance (through improved root anchorage and reduced stem length and thicker stems), reduced tillering, reduced variation in the

maturity of panicles and spikelets within a plant, reduced seed shattering and improved harvest index are seen as targets for breeding.

Key words: day length, photoperiod, thermal time, germination, tillering, lodging, grain yield

11.1. Introduction

Tef grains and flour do not contain gluten (Spaenij-Dekking *et al.*, 2005) and are rich in minerals, especially iron (Melak-Hail, 1966, Yewlsew *et al.*, 2007). These two characteristics make tef flour a desirable ingredient in health products particularly for celiac disease patients. Tef can replace gluten-containing cereals in products such as pasta, bread, beer, cookies and pancakes.

In view of anticipated economically feasible production, tef was recently introduced in north-western Europe (Hopman *et al.*, 2008). In the Netherlands, attempts were made to establish a tef value chain, including varietal development, production, processing and development and marketing of ingredients and products based on tef.

The initial experiences were positive, but successful adoption of the crop requires improvement on several aspects:

i) Yield measured in experiments and on farmers' fields varied, but was often in the order of 1500 kg ha^{-1}. A competitive value chain would require yields being doubled.
ii) Maturity was initially late in the season (i.e. September). Harvesting in September is too late for any cereal crop as the number of days on which crops get harvest-dry diminishes rapidly in autumn; hence, the risk of harvest failure, seed loss and poor seed quality (moulds, seed germination) is becoming too big.
iii) The crop is sensitive to lodging, aggravating the risk of crop failure at late harvest.
iv) There is large heterogeneity in terms of seed maturity within and between panicles, while seeds also too easily shatter from the panicle.
v) The minimum temperature for seed germination is in the order of 11 ^{o}C (common for C4 cereal species). Cool temperatures result in slow germination of tef, in contrast to common weeds which establish more quickly and present a problem.

Considering these experiences with tef, a research programme was initiated with the ultimate goal of underpinning an 'ideotype' of tef suitable for cultivation in temperate climates at relatively high latitudes.

11.2. Objectives of Research on Tef in the Netherlands

The research program conducted between 2004 and 2010 addressed the following issues:

i) Assessment of the yield level in relation to earliness and sowing date.
ii) Heat requirement of germination, and effects of water potential on the germination rate and the final germination percentage.
iii) The effect of photoperiod on plant development and heading (flowering) date.
iv) A biomechanical analysis of tef in order to identify the causes of lodging.

This paper summarizes the main findings. A more complete account is given in van Delden's PhD thesis (van Delden, 2011), and in van Delden *et al.* (2008, 2010, 2012). For details on the methods and techniques, the reader is referred to these publications (and to other forthcoming papers).

11.3. Tef Performance in the Netherlands

Since 2003 tef has been grown on several sites in the Netherlands. Not always dependable data were collected on yield. The performance of the crop varied from complete failure to over 3 ton ha^{-1}. By no means, the data presented here represent the average, but the data serve to i llustrate a number of important points. For a correct understanding we present some details. Cultivars Ayana and O4T19 were developed from Ethiopian germplasm by Dr. A. Mulder and Dr L. Turkensteen. Cultivars Ziquala (DZ-Cr-358) and Gibe (DZ-Cr-255) were obtained from Ethiopia. Seedbed preparation was done carefully: seeding was done on soil that was given time to achieve a natural compaction after ploughing (this ensured transport of water from depth to the soil surface *via* continuous water films). Seeding depth was 0.5 cm. Soil above the seed was slightly pressed so as to promote contact between seed and soil. Seed rate was 3 kg ha^{-1}. The distance between rows was 12.5 cm. Plot size was 10 m long by 4.5 m wide. There were two planting times in 2006: 28 April (S1; day number 118 in the year in Julian counting, (DOY)) and 16 May (S2; DOY 136). Time of heading was recorded and yield and biomass were recorded.

The time between planting and 50% emergence (50 % of emerged fraction) was 8 days in S1 and 11 days in S2 (Table 1). Across cultivars the average time between emergence and heading was 68 days in S1 and 58 days in S2. The time between emergence and heading was the shortest in cv. Ayana (56 d in S1 and 46 d in S2) and the longest in cv. Ziquala (84 d in S1 and 75 d in S2). This indicates a month difference in heading between the earliest and the latest cultivar. Harvesting was done when crops had reached the same stage of maturity. Hence, in S1 an early cultivar like Ayana was harvested on DOY 222 (August 10) and the latest harvest date was DOY 291 (October 18) for cv. Gibe in S2. The periods between heading and harvesting ranged from 41 d (cv. Ayana, S1, S2) to 68-70 d (cv. Ziquala, S1, S2).

Across cultivars, there was no difference in grain yield between S1 (1075 kg ha^{-1}) and S2 (1068 kg ha^{-1}) (Fig. 1). However, with 1370 kg ha^{-1} cv. Ayana yielded more than the other cultivars in S1, whereas in S2 cv. Ziquala out-yielded the other three cultivars (1322 kg ha^{-1}).

Table 1. Day numbers of the year of planting, emergence, heading and harvesting and duration from emergence to heading and from heading to harvest from a field experiment conducted in Wageningen, (51^{o} 59' N, 5^{o} 34' E) in 2006 for two sowing dates, i.e. day of the year (DOY) 118 (April 28) and DOY 136 (May 16) for four tef cultivars (Ayana and 04T19 are Dutch cultivars and Ziquala and Gibe are Ethiopian cultivars).

Days taken	Sowing date 1				Sowing date 2			
	Ayana	Ziquala	Gibe	04T19	Ayana	Ziquala	Gibe	04T19
Planting (DOY)	118	118	118	118	136	136	136	136
Emergence (DOY)	126	126	126	126	147	147	147	147
Heading (DOY)	181	209	191	193	192	221	197	205
Harvest (DOY)	222	277	226	241	233	291	247	247
Emergence-heading (d)	55	83	65	67	45	74	50	58
Heading-harvest (d)	41	68	35	48	41	70	50	42

The total aboveground biomass varied from near 8.5-10 ton ha^{-1} (cv. Ayana S1, S2) to near 15 ton ha^{-1} (cv. Ziquala S1, S2) (Fig. 2). Cultivar Ziquala, which had the longest crop cycle (Table 1) accumulated significantly more biomas than the cultivars with shorter growth cycle. Apparently, there was no relation between seed yield and total biomass production, or rather between vegetative mass and seed yield. The harvest index (per cent of total biomass allocated in seeds) was low, ranging between 7% and 13 % (average across cultivars and sowing dates = 9.5%).

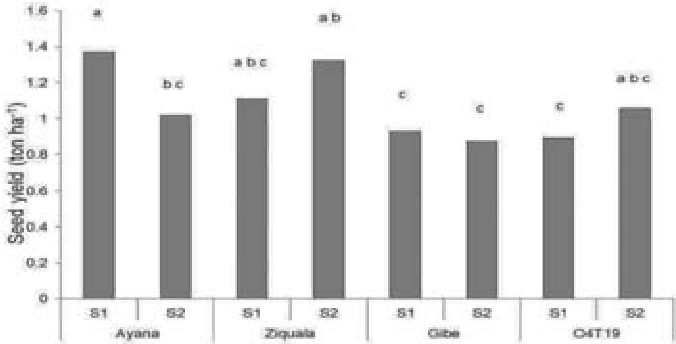

Fig. 1. Seed yield (ton ha^{-1}) from a field experiment, conducted in Wageningen, (51° 59’ N, 5° 34’ E) in 2006 for two sowing dates, S1 and S2, i.e. day of the year (DOY) 118 (= April 28) and DOY 136 (= May 16) for four cultivars. Ayana and 04T19 are Dutch cultivars and Ziquala and Gibe are Ethiopian cultivars. The standard error of the mean differences was 0.104 ton ha^{-1}. Bars with one or more letters in common do not differ statistically significantly as determined with Tukey's method of multiple comparison.

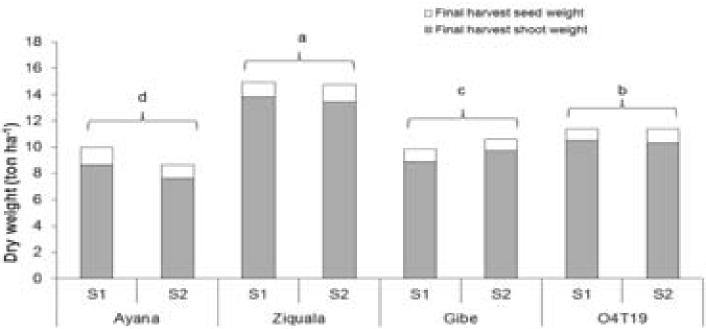

Fig 2. Dry weight of shoot biomass (i.e. straw + chaff) (hatched part of the bar) and seed yield (top part of the bars) from a field experiment, conducted in Wageningen, (51° 59’ N, 5° 34’ E) in 2006 for two sowing dates, i.e. day of the year (DOY) 118 (April 28) and DOY 136 (May 16) for four cultivars. Ayana and 04T19 are Dutch cultivars and Ziquala and Gibe are Ethiopian cultivars. The standard error of the mean differences was 0.54 ton ha^{-1} for shoot dry weight. There was no significant effect of sowing date on total biomass produced, but there were differences between cultivars as is indicated by the different letters (Tukey’s test).

11.3.1. The temperature response of the rate of germination of tef

Progression of developmental processes, such as germination or heading, are customarily analysed by relating the rate of development to the independent variable. The rate of development is the reciprocal of the amount of time till a particular state is r eached. For instance, if it takes 4 days between planting and germination then the rate of germination is ¼ = 0.25 d^{-1} (meaning ¼th of the process is completed in one day). Often the rate for 50% point of the population is quantified, i.e. r_{50} (ignoring the spread in the population). Fig. 3 presents some data on the rate of germination *versus* temperature. Two important properties can be derived from the data on Fig. 3, namely: the minimum temperature for any progress in the rate of development, T_b; and the reciprocal of the slope, i.e. Θ the heat sum (°C d). The T_b for germination of tef is ca. 11.4 °C; Θ is 17.9 °C d. Suppose the average daily temperature is 15 °C and minimum temperatures are above 11.4 °C, then the time to 50% germination equals Θ /(15 –Tb) = 17.9/(15-11.4) = 4.9 d.

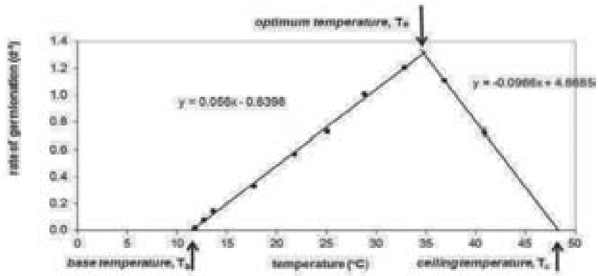

Fig 3. Germination rate (i.e. the reciprocal of the time to germination for 50% of the seeds) of tef *versus* temperature. From the linear regression, the 'cardinal temperatures can be deduced, i.e. the base temperature, T_b, below which the rate of development is zero (11.4 °C); the ceiling temperature, T_c, above which the rate of development is zero (48.3 °C); and the optimum rate of development, T_o (34.8 °C). The reciprocals of the slope represent the 'heat sum' or 'thermal constant', i.e. the number of degree days above the base temperature that need to be accumulated to reach 50% germination. For the sub-optimal temperature range, this is 17.9 °C d. The water potential of the germination medium was -0.4 MPa. Note: these are results of a pilot study; data from a more extensive study are still being analysed. Error bars indicate standard errors, when not visible they fall within the data point.

The interaction between water potential and temperature was extensively studied. Because we are still in the process of publishing these results only the highlights of the pilot studies are indicated here. It proved possible to describe the rate of germination (r_{50}) as a continuous function of both temperature and water potential. It appeared that the minimum temperature for germination and the minimum water potential allowing germination to proceed were dependent on each other. This means that when the soil is drier, a higher temperature is required to start germination and when the temperature is lower, more water is needed to trigger successful germination. Or one could say that the range of temperature allowing germination is narrower at the lower (more negative) water potential. The spread in the rate of germination could also be modelled. This means that the change in percentage germination as well as the final percentage germination can be predicted in relation to the prevailing temperature and water potential.

11.3.2. Effect of photoperiod on phenology and plant architecture

Tef is a short day plant. This means the progression through the life cycle is advanced under short days. Longer day-lengths retard the date of heading[1] and through this postpone harvest maturity. There are two experimental approaches to study day length sensitivity (note: synonymous to 'photoperiod sensitivity'). In the simplest approach, plants are subjected to constant length regimes, e.g. 9, 12, 15, 18 hours per day. Often researchers apply an equal daily number of hours of natural light (or: 'assimilation light' when working in growth chambers) plus a variable number of hours of low energy 'day length extending light', so as to avoid confounding effects of differences in assimilation energy between plants at the different regimes. In our cases we had 9 h of 'day light' (natural light when working in glasshouses and high energy lamps when working in growth chambers) plus variable duration of day length extending illumination as required by the treatment in question. In this experimental setup, one records the number of days to heading of 50% of the population of plants. In this approach, one gets no information on the developmental phases during which the plants are responsive to day length. The so-called 'reciprocal transfer experiments' (Ellis *et al.*, 1992) do provide information on differences in sensitivity. Commonly, an insensitive juvenile period (also called 'basal vegetative phase', BVP) is distinguished, followed by a photoperiod-sensitive phase, (PSP) and lastly a post photoperiod-sensitive phase (PPP). An example for tef is presented in van Delden *et al.* (2008).

In this paper, we present the summary of the photoperiod sensitivity of tef using the simple experimental approach, as published by van Delden *et al.* (2012). Fig. 4 (reproduced from van Delden *et al.*, 2012) shows the effect of day length regime on the time to heading. Average daily temperature was 19.8 ^{o}C. Across treatments and cultivars, the number of days to heading ranged from less than 30 to over 80 days. For a day length of 9 h, the time to heading was less than 40 days for all cultivars.

[1] In tef heading (the appearance of the panicle) coincides with flowering.

Cultivar Ayana was the least sensitive to day length; at 16.5 h day length, the time to heading was still around 40 days, whereas it was double that number for cv Gibe. These data clearly illustrate the quantitative short day response of tef, and, more importantly, tremendous genetic variation in day length sensitivity that can be exploited in breeding programs.

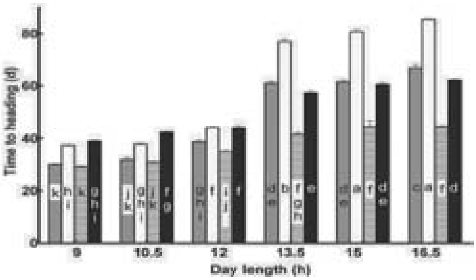

Fig. 4. The time from sowing to heading for the main stem of four cultivars: Gibe (grey bar), Ziquala (white bar), Ayana (hatched bar) and 04T19 (black bar), at six day lengths in the growth chamber experiment. Treatments with the same letter are not significantly different. Error bar represents the standard error (n = 6). (From van Delden *et al.*, 2012; courtesy European Journal of Agronomy).

Day- length sensitivity not only determines the date of flowering, but also the architecture of the plant. Cereal plants consist of conjugations of phytomers, i.e. basal units consisting of node, an internode, a leaf and an axillary bud. Once the parent phytomer is sufficiently matured, the bud can start growing to form a primary tiller. Primary tillers form (with some delay) secondary tillers, and so on. In wheat, the process of tillering stops at some stage. The decline in red to far red ratio of the light penetrating to the base of the plant is probably the environmental cue triggering cessation of outgrowth of buds into tillers (Evers *et al.*, 2006). The transition of the apex from the vegetative to the generative phase stops outgrowth of additional leaves; the buds differentiate into panicle structures, and therefore, the number of buds that can become a tiller is fixed at the transition to the generative phase. In principle, the earlier the life of the cereal plant, the apex becomes generative, the fewer the numbers of leaves on each shoot and the less the potential number of tillers. Tef is no exception in the sense that early heading leads to fewer leaves on the main stem.

We have collected data on leaf appearance *versus* time after sowing for different cultivars exposed to different day-length treatments. As shown on Fig. 5, intrinsically the rhythm of appearance of main stem leaves is the same for all the four cultivars and for all day- length treatments, indicating that leaf appearance rate is a robust property. The earlier in development, the apex becomes generative, the earlier progression along a common rhythm of leaf development is interrupted, and the earlier heading takes place.

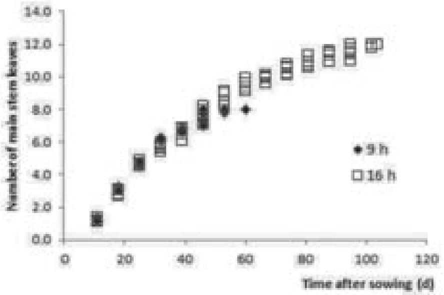

Fig. 5. Number of appeared main stem leaves *versus* time after sowing. Closed diamonds are treatments at 9 h day-length, while open squares represent treatments with 16 h day-length. Data points are from five cultivars, Gibe and DZ-Cr-37 (relatively early) and DZ-01-2053, DZ-01-354 and Ziquala (relatively late). The slope of the line is the leaf appearance rate (d^{-1}); the reciprocal of slope of the curve represents the phyllochron (d), i.e. the time required between the appearances of two successive leaves.

Long days increased not only time to heading of tef and the number of main stem leaves (i.e. vegetative phytomers), but also plant biomass, inter-plant variation, number of elongated internodes and crop height. In contrast to the shoot biomass, the grain biomass did not increase with day-length. Hence, longer days reduced the harvest index, reinforcing the same conclusion drawn from the sowing time experiments.

The day length response of plants is modified by the temperature regime (Roberts and Summerfield, 1987; Summerfield *et al.*, 1991, 1993; Ellis *et al.*, 1997; Yin *et al.*, 1997). We conducted research comparing treatments consisting of the combinations of two temperature regimes, i.e. 23 °C/16 °C (LT—lowest temperature) and 33 °C/26 °C (HT—highest temperature) and two day-lengths, i.e. 9 hours (SD—short day) and 18 hours (LD—long day). The full analysis of the data is beyond the scope of the paper, but Fig. 6 illustrates that both temperature and photoperiod exert an effect on the point of transition from producing leaves to producing an inflorescence (the point of plateauing of each response is the point of transition). Each treatment has a different number of main stem leaves (though the difference between 'SD HT' and 'LD LT' is only small). So, treatment combinations affected plant architecture in terms of the number of leaves per main stem. Within a temperature treatment, LD postponed the transition (levelling-off of the line at later time when more leaves had been initiated). Within photoperiod treatments more leaves were initiated at HT than at LT, but the time of levelling-off of the curves was relatively unaffected, especially for SD treatments. The latter finding hints at dominance of the photoperiod in determining the transition to th e generative phase. At higher temperature, more leaves can be produced within the time frame for vegetative development that is primarily determined by photoperiod.

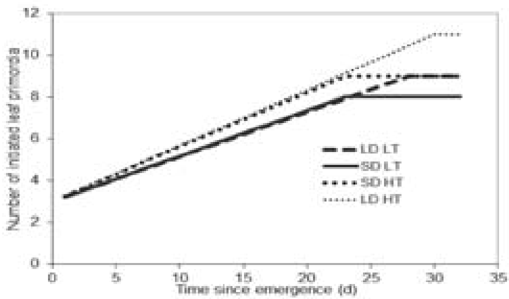

Fig. 6. Number of leaf primordia initiated over time since emergence at the apex of the main stem of tef for four treatments: LT = lowest temperature 23 ºC/16 ºC [day/night, i.e. 9/11 h and twice two hours to realize gradual temperature change]); HT= highest temperature 33 ºC/26 ºC in combination with two day lengths of SD (short day) = 9 hours and LD (long day) = 18 hours.

In principle, late heading provides the plant with more buds that can grow out to become a tiller. In our experiments, we recorded the number of tillers that were present at heading and at maturity and did not observe a clear effect of day-length on tillering dynamics within cvs. Ayana, Gibe and 04T19 (Fig. 7). In line with Doust (2007a, b), we distinguished basal tillers from axillary tillers. The former emerge from phytomers with non-extended internodes and can produce nodal roots; while the latter emerge from phytomers with extended internodes and are unlikely to produce their own nodal roots. The main findings as represented on Fig. 7 were: (i) tef is a profusely tillering plant species, (ii) most of the tillers are produced after heading of the main stem; and (iii) there is a clear genetic variation in tillering behaviour. In line with the latter,, at harvest, cv. Ayana showed the largest number of tillers per plant (mean = 23.6) and 04T19 the lowest number (mean = 7.8), and the number of basal tillers ranged from 10.2 in cvs Ayana and Gibe to 6.4 in cv. 04T19. The latter cultivar clearly produced fewer tillers per plant, especially fewer axillary ones. This result is somewhat counter intuitive since as argued, late maturing cultivars produce more leaves per stem, and hence, more buds from which tillers could emerge. This means, potentially more tillers can be formed the later the plant reaches heading. Clearly, more factors than the number of leaves per stem determine tillering. This opens options for breeding for less unproductive axillary tillers independent of leaf number. The number of basal panicle-bearing tillers that significantly contribute to plant yield is limited (supplementary material of van Delden *et al.*, 2012). In cv. Ziquala (the latest cultivar) the total number of tillers per plant (11-14; data not shown) was not affected by photoperiod, but the number of panicle-bearing, strong basal tillers increased from 3.1 to 4.1 per plant when photoperiod was extended from 12 to 18 h d^{-1}.

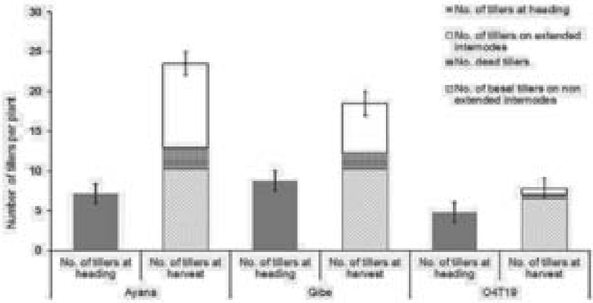

Fig. 7. Tillering of cultivars Ayana, Gibe and 04T19 measured in a glasshouse study (in 2006) in the Netherlands. Data are pooled over three day-length regimes of 12, 15 and 18 h d^{-1} because there was no significant effect of day length. At heading, the total number of tillers per plant is given (no distinction in type of tillers). At maturity a distinction is made between (i) axillary tillers which emerge from leaf axils on extended internodes (Doust, 2007a,b), (ii) the number of dead tillers, and (iii) the number of tillers emerging from non-extended internodes at the base of the plant. Error bars represent twice the standard deviation for the total number of tillers per plant.

11.3.3. The biomechanics of lodging

Lodging, defined as the permanent displacement of crop plants from their vertical position because of root or shoot failure, is a major yield reducing factor. Yifru and Hailu (2005) showed that over the years of breeding from 1960-1995, the yield potential of tef increased from about 3300 kg ha^{-1} to 4350 kg ha^{-1} when lodging was avoided. Though direct comparison with unsupported cultivation is lacking in that study, it is clear that prevention of lodging using netting boosts yield. In our study, we made a comparison of supported and unsupported growth in two seasons. Effects of prevention of lodging on grain yield were generally positive, but very variable ranging from zero to 65 per cent. The differences in grain quality were not measured.

In tef research, most attention has been devoted to relate the degree of lodging to shoot properties (Yu *et al.*, 2007; Kebebew *et al.*, 2011). However, roots can slide through the soil, making the plant fall over without the stems being bent or broken. Following earlier applications in cereals (Crook *et al.*, 1994), we measured the biomechanical properties of tef in order to distinguish whether the plant is more susceptible to root or shoot lodging. A full account of the findings is given in van Delden *et al.* (2010) (cf. Baker *et al.*, 1998; Berry *et al.*, 2004, 2006, 2007; Crook and Ennos 1993, 1994, 2000; Crook *et al.*, 1994). Here, summaries are given of the approach and main points. Two morphologically very different cultivars were included in the study (i.e. cv Ayana and 04T19). So-called 'safety factors' were determined, indicating how many times the root or shoot is stronger than is required to prevent root or shoot failure, respectively. The safety factor against anchorage failure ('root lodging') is given by:

$SF_A = S_A/M_P$ (Eqn. 1),

where S_A is the root anchorage strength (Nm; i.e. the maximum moment at θ° from the vertical that a root system can withstand before rotating further in the soil) and M_P, self weight moment (Nm) of the whole plant at θ° from the vertical. The safety factor against failure of an individual shoot, SF_S, is given by:

$SF_S = S_S/M_S$ (Eqn. 2),

where S_S is the maximum self-weight moment (Nm) which the individual shoot can support before it fails and M_S is the self weight moment (Nm) at θ° from the vertical of the shoot in question.

Self weight moments of whole plants (M_p, or individual shoots,M_s) can be calculated from the angle of inclination (θ), the height of the point of gravity (h), the mass/ 'weight' (m), and the acceleration due to gravity (g) as:

$M_p = \sin\theta \, h_p \, M_p \, g$ (Eqn. 3).

Self weight moments can also be determined experimentally using a device measuring forces i.e. a 'lodging meter', Mecmesin Ltd, Slinfold, UK (details in van Delden *et al.*, 2010). The root anchorage strength (S_A) can also be measured with the lodging meter by measuring the resistance when pushing over the plant (to express it somewhat simplified). The maximum moment a stem can withstand can be measured in a 'three- point bending test'. Basically the instrument consists of two supports and a blunt piston (or 'probe') in the middle between and above the supports. A stem section is fitted on the supports. The piston (probe) is travelling down, bending the stem section. A force/ displacement graph/ is simultaneously recorded. If the stem section breaks, the force at which this occurs is recorded. Material properties can be deduced from the force-displacement curve.

Initially, in the growing season the safety factors varied from 4 to 14 for both root and shoot, implying that between 4 and 14 times higher strength of the root and shoot, respectively was observed than minimally needed to withstand lodging forces. However, near heading the root safety factor already started to drop below unity (i.e.

insufficient root anchorage to keep the plant upright). The safety factor for shoots also dropped around heading but stayed larger than unity throughout the grain filling period. These results indicate that in both cultivars insufficient root anchorage is the prime cause of lodging. However, though the safely factor of the stems is above unity, it was concluded that shoot strength is a lso insufficient. Hence, simultaneously breeding for both improved root anchorage and shoot strength is advocated. Progress has been made in enhancing the lodging resistance of wheat and rice through breeding. Table 2 shows a comparison between tef, wheat and rice for some properties that are relevant for lodging resistance (van Delden *et al.*, 2010).

Compared to wheat and rice, the diameter of the tef stem base is small. The small diameter in combination with the long tef stems creates a fragile structure that is easily bent or broken. Moreover, the long tef stems create a large force on the roots. Therefore, the safety factors for root and shoot lodging are clearly much lower for tef than for wheat and rice. However, the Young's modulus, a measure for stiffness of material (i.e. tissue density) (Table 2), was higher for tef than for both wheat and rice. Therefore, stem rigidity of tef can be enhanced by merely increasing the stem diameter while preserving the current tissue density (van Delden *et al.*, 2010).

Table 2. Properties relevant for lodging resistance for tef cultivars Ayana and 04T19 as compared to values observed for wheat and rice (data from van Delden et al. 2010).

Variable	Tef cv. Ayana	Tef cv. 04T19	Wheat (*Triticum aestivum*)	Rice (*Oryza sativa*)
Young's modulus (N m^{-2})	3.8–4.2 ˜10^{-3}	2.4–2.7 10^{-3}	1.8–2.6 ˜10^{-3}	1.2–3.0 10^{-3}
Stem diameter (mm)	1.8	3.2	4.5	6.6
Bending strength (N m) [a]	0.02	0.07	0.16	2.5
Stem length (m)	1.3	1.7	0.8	1.0
Factor of safety shoot (-)	1.3	2.2	5	150
Factor of safety root (-)	< 1.0	< 1.0	3	5

[a] the maximum self-weight moment the stem base can support before it fails

11.4. Discussion and the Way Forward

Tef is the most important staple crop in Ethiopia. Because of the special properties of the grain, there is interest in growing tef in other parts of the world. The performance of tef in environments outside Ethiopia is strongly dependent on the effects of environmental factors on growth and development processes. Growth, the increase in mass and volume of the crop, depends primarily on solar radiation and temperature (apart from nutrients, water, pests and diseases). Leaf area index, leaf area duration (i.e. the integral of leaf area index over time, while ignoring leaf area in excess of LAI=3) and the production per unit radiation absorbed (i.e. the radiation use efficiency (g MJ^{-1})) are key factors in dry matter production. The rate of development (i.e. the progression through the successive stages of the life cycle) depends primarily on temperature and day-length sensitivity.

11.4.1. Interaction of temperature and day length on development

The initial experiences with tef in the Netherlands ignited research and development activities aiming at a shorter crop cycle and earlier harvest. Our research (van Delden *et al.*, 2008, 2012) verified that tef is a short day plant with large genetic variation in day-length sensitivity. This genetic variation means that there is scope to select and breed for earliness. Genetic differences in day length sensitivity become particularly apparent when civil day length exceeds 13.5 h (civil day length is the duration of the solar track from 6 ^{o} below the horizon east to 6 ^{o} below the horizon west). Day length sensitive cultivars that are planted early in the season in Ethiopia might even be retarded somewhat in their development.

The response to photoperiod is modified by the temperature regime (Summerfield *et al.*, 1991, 1993; Ellis *et al.*, 1997). Up to a maximum (which is probably beyond 25 ^{o}C average daily temperature) warmer temperatures shorten the plastochron (Fig. 6) and the phyllochron (Fig. 5). For tef, the current data indicate that photoperiod was the prime determinant of the transition to the generative phase (because the time when the initiation of leaves ceased was relatively insensitive to the temperature regime, but determined by day-length). Temperature affects the rate of leaf initiation, and hence, the number of leaves that can be initiated within the vegetative period the duration of which is primarily determined by the day length regime. Still, the data on the interaction between photoperiod and temperature that we collected need expansion before conclusions relevant to variable real-life conditions can be drawn.

11.4.2. Comparative yield potential of tef

Considering the need to increase plant production for food, feed, fibre and energy, it is important to determine realistic values for potential yield and biomass production for each crop species in a particular agro-ecological zone, and to make conscious choices on the types of crops to grow. Though we fully acknowledge the good reasons to grow tef, still important questions need to be answered like (i) what is the yield potential of tef and (ii) how does grain and biomass production of tef compare to alternative crops? Teshome and Verheye (1994) considered 4600 kg ha^{-1} of grain as the potential yield of tef for Ethiopia, and this is comparable to what Yifru and Hailu (2005) observed when avoiding lodging. For durum wheat (*Triticum turgidum* var. *durum*), Belay *et al.* (1994) calculated a yield potential of 6600 kg ha^{-1} for Ethiopia. Perhaps, it would be good to revisit the estimates for the potential and attainable yields of wheat and tef using all current knowledge and appropriate data and models. For the Netherlands, the cropping history of tef is too short to provide a dependable figure for attainable yield. As indicated, initially the yields were modest, around 1000 kg ha^{-1}, but progress is being made and 3000-3500 kg ha^{-1} seems a realistic target for grain yield.

We did not run an experiment directly comparing the performance of alternative crops including tef. However, Vos and van der Putten (2000) published data on wheat (*Triticum aestivum*), oats (*Hordeum vulgare*), potato (*Solanum tuberosum*) and sugar beet (*Beta vulgaris*) from an experiment conducted from 1990-1994 at Wageningen with basically similar management and experimental procedures as applied to the tef crops reported in this paper. Average data were 5.1 ton ha^{-1} of grain and 5.6 ton ha^{-1} of straw for wheat. Corresponding data for oats were 4.7 and 4.5 ton ha^{-1}. Potato yielded 12.1 to ha^{-1} dry tuber mass plus 2.4 ton ha^{-1} crop residues. Corresponding data for sugar beet were 16.1 plus 4.7 ton ha^{-1} (note: though this long-term experiment was managed with care, the yields attained cannot be called potential yields). The data on Figs. 1 and 2 (and other unpublished data) indicate that 9-10 ton ha^{-1} of shoot biomass of tef is not difficult to achieve, even for short-season and for early maturing cultivars. So, in terms of biomass production tef falls not much short compared to oats and wheat under Dutch conditions. There is a big gap between the biomass production of the summer cereal crops (wheat, oats) on the one hand and the long-season root crops like potato and especially sugar beet on the other hand. As also indicated on Fig. 2, day-length sensitive late cultivars like Ziquala can produce over 14 ton of biomass ha^{-1}, challenging the productivity of potato under similar conditions. So, if the biomass rather than seed yield were important the best choice is a late, photoperiod-sensitive genotype (higher biomass for the late cultivar is probably true for all production environments). Wheat and oats show a harvest index of 0.45 to 0.50 (ignoring stubbles). In tef, the harvest index is (at best) 0.25. The conclusion from this discussion seems that increasing biomass is not the prime target of breeding, but altering the distribution of biomass over vegetative parts and grain (i.e. in harvest index) certainly is. In cereals, a good deal of the increase in yield potential has also been accomplished by selection for less investment in vegetative material and more allocation of dry matter in grains (Foulkes *et al.*, 2011).

11.4.3. What degree of tillering is useful?

The tillering dynamics (as summarized on Fig. 7) underlines the inclination of tef to tiller profusely. Tillering dynamics of grasses and cereals differ between species (Doust, 2007 a, b). In wheat, there is a clear point of cessation of tillering during development (Evers *et al.*, 2006); tillering is supposed to stop when the red:far-red ratio of light reaching the base of the plant drops below a threshold value. Cessation of tillering in wheat usually coincides with the start of stem elongation (i.e. well before heading). In tef, such an environmental cue, inducing cessation of tillering, does not seem to exist as a large fraction of the tillers appeared after heading of the main stem. In this respect, tef perhaps resembles rice rather than wheat or sorghum (Dr. Tanguy Lafarge, pers. comm., 2012). Van Delden *et al.* (2012) analysed the contribution of tillers to grain yield (data in the supplementary material of that paper). These authors concluded that only the first three primary basal tillers contributed significantly to yield, whereas the other tillers did not. Investment of plant material in tillers that do not contribute to yield is a waste of plant resources. So, the question emerges as to whether or not the 'ideotypical' tef plant should show reduced inclination to tiller, while investing more energy in the panicles on the main tillers. The genetic variation to select for limited tillering is there. Of course, reduced tillering should not compromise plant plasticity since variable degree of tillering provides adaptation to growing conditions. In rice, the desired tillering dynamics (initiation and senescence, and ultimately surviving number) is a subject of much research on issues including genes coding for the degree of tillering, the contribution of early tillers to soil cover, and transfer of biomass of senescing tillers to surviving ones (e.g. Fujita *et al.*, 2010).

11.4.4. Intra-plant variation in seed maturity

In comparison to for example wheat, tef is characterised by much variation in the rate of development of the different tillers (some data in supplementary material of van Delden *et al.*, 2012). Also, within a panicle, florets and seeds mature at different times. In cereals like wheat or maize, maturity is more or less synchronized within and between shoots; hence, it is not difficult for a farmer to determine the point of maturity. Because of the variability within and between panicles, it is less obvious when to harvest tef. This would not be a big problem by itself if mature seeds stayed on the plant. However, this is not the case since mature tef seeds easily shatter. Seed shattering is a major shortcoming of tef. Selecting for reduced shattering is an important breeding goal, which we have not addressed. In addition, in agro-ecological zones with relatively wet conditions near maturity, the lack of seed dormancy (or at least short duration of dormancy) can lead to seed sprouting on the parent plant, whereas shattered seeds also easily germinate.

11.4.5. Lodging resistance

Improved lodging resistance is seen as a key objective of genetic improvement of tef (Kebebew *et al.*, 2011). Van Delden *et al.* (2010) advocated simultaneous breeding for both improved root anchorage and shoot strength. The self-weight moment of the plant (or an individual shoot) increases in proportion to the length of the stems. Hence, shortening stem length proportionally contributes to r educed lodging susceptibility. When the strength of the stems and roots remains unaltered, increased yield potential (i.e. increased panicle weight), reduces lodging resistance more than proportionally. This is because two factors determining the self-weight moment of the shoot (Eqn. 3) are increased, namely: the weight of the shoot and the point of gravity (which is moved upwards). Highly productive genotypes are more susceptible to lodging than poor performing types. Perhaps, progress in breeding for lodging resistance that may have been achieved may be masked by increased yield potential. Reducing stem length, while maintaining (or perhaps even increasing) green leaf area is one way to breed for improved lodging resistance. Leaving all other relevant stem properties unaltered, theoretically, a larger stem diameter must contribute to improved lodging resistance. The methodology to evaluate the mechanical and material properties of tef genotypes, as presented in van Delden *et al.* (2010), is probably too laborious to apply to select progenies. However, it may be sensible to apply the techniques to select parental materials in breeding programs, or to search for QTL's (e.g. Yu *et al.*, 2007). Especially, the 'three-point bending test' is quite straightforward to apply, and yields information on the strength and rigidity of the stems. The latter test seems comparable to the 'internode crushing test' applied by Yu *et al.* (2007).

Agronomic measures and new cultivation systems may help to reduce lodging. Row planting by hand (or machine) at row distances of 20 to 25 cm or transplanting at 10 to 15 cm between plants within the row seems to alleviate lodging (Tareke Berhe, pers. comm., 2012). Other ideas that have not materialized into established practices are: (i) earthing up in row cultivation since covering the base of the plant with soil would stimulate rooting, especially of tillers and improve the anchorage of the plant; and (ii) intercropping with a more rigid crop species (e.g. wheat or field beans).that mature at approximately the same time as that of tef.

11.5. Abbreviations

BVP: basal vegetative phase; **Cv**: cultivar; **DOY**: day of the year; **HT**: highest temperature; **LAI**: Leaf area index; **LD**: long day; **LT**: lowest temperature; $\mathbf{M_p}$: self-weight moments of whole plants; $\mathbf{M_s}$: self-weight moments of individual shoots; **Nm**: maximum self-weight moment; **PPP**: post-photoperiod sensitive phase; **PSP**: photoperiod sensitive phase; $\mathbf{S_A}$: root anchorage strength; **SD**: short day.

11.6. Acknowledgements

This research was supported by the Dutch Technology Foundation STW, which is the applied science division of NWO, and the Technology Programme of the Ministry of Agriculture, Economic Affairs and Innovation. Thanks are due to Nol Mulder and Lo Turkensteen of Millets Place for providing germplasm and for their continuous engagement in the research programme. Thanks are due to Gerard Brouwer, Ans Hofman, Ralph Post, Ton Blokzijl, Gezahegn Yadessa, Shuhang Wang and Unifarm for technical assistance, and to Dr Roland Ennos, Xinyou Yin and Paul Struik for their support.

11.7. References

Baker CJ, Berry PM, Spink JH, Sylvester-Bradley R, Griffin JM, Scott RK and Clare RW. 1998. A method for the assessment of the risk of wheat lodging. Journal of Theoretical Biology 194: 587-603.

Belay Simane, van Keulen H, Stol W and Struik PC. 1994. Application of a crop growth model (SUCROS-87) to assess the effect of moisture stress on yield potential of durum wheat in Ethiopia. Agricultural Systems 44: 337-353.

Berry PM, Sterling M and Mooney SJ. 2006. Development of a model of lodging for barley. Journal of Agronomy and Crop Science 192: 151-158.

Berry PM, Sterling M, Spink JH, Baker CJ, Sylvester-Bradley R, Mooney SJ, Tams AR, Ennos AR and Donald LS. 2004. Understanding and reducing lodging in cereals. Advances in Agronomy 84: 217-271.

Berry PM, Sylvester-Bradley R and Berry S. 2007. Ideotype design for lodging-resistant wheat. Euphytica 154:165-179.

Crook MJ, Ennos AR and Sellers EK. 1994. Structural development of the shoot and root systems of two winter wheat cultivars, *Triticum aestivum* L. Journal of Experimental Botany 45: 857-863.

Crook MJ and Ennos AR. 1993. The mechanics of root lodging in winter wheat, *Triticum aestivum* L. Journal of Experimental Botany 44: 1219-1224.

Crook MJ and Ennos AR. 1994. Stem and root characteristics associated with lodging resistance in four winter wheat cultivars. Journal of Agricultural Science 123: 167-174.

Crook MJ and Ennos AR. 2000. A field bases method of quantifying the lodging resistance of wheat cultivars. In: Spatz H-C, Speck T (eds). Plant biomechanics 2000. Stuttgart: Proceedings of the 3rd Plant Biomechanics Conference, Freiburg-Badenweiler, 315-320.

Doust A. 2007a. Architectural evolution and its implications for domestication in grasses. Annals of Botany 100: 941-950.

Doust AN. 2007b. Grass architecture: genetic and environmental control of branching. Current Opinion in Plant Biology 10: 21-25.

Ellis RH, Collinson ST, Hudson D and Patefield WM. 1992. The analysis of reciprocal transfer experiments to estimate the durations of the photoperiod-sensitive and photoperiod-insensitive phases of plant development: an example in soya bean. Annals of Botany 70: 87-92.

Ellis RH, Qi A, Crauford PQ, Summerfield RJ and Roberts EH. 1997. Effects of photoperiod, temperature and asynchrony between thermoperiod and photoperiod on development of panicle initiation in sorghum. Annals of Botany 79: 169-178.

Evers JB, Vos J, Andrieu B and Struik PC. 2006. Cessation of tillering in spring wheat in relation to light interception and red: far-red ratio. Annals of Botany 97: 649-658.

Foulkes MJ, Slafer GA, Davies WJ, Berry PM, Sylvester-Bradley R, Martre P, Calderin DF, Griffiths S and Reynolds MP. 2011. Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. Journal of Experimental Botany 62: 469-486.

Fujita D, Ebron, L, Araki E, Kato H, Khush G, Sheehy J, Lafarge T, Fukuta Y and Kobayashi N. 2010. Finemapping of a gene for low-tiller number, Ltn, in japonica rice (*Oryza sativa* L.) variety Aikawa 1. Theoretical and Applied Genetics 120: 1233-1240.

Hopman E, Dekking L, Blokland M-L, Wuisman M, Zuijderduin W, Koning F and Schweizer J. (2008). Tef in the diet of celiac patients in the Netherlands. Scandinavian Journal of Gastroenterology 43: 277-282.

Kebebew Assefa K, Yu J-K, Zeid M, Getachew Belay, Hailu Tefera and Sorrells ME. 2011. Breeding tef [*Eragrostis tef* (Zucc.) trotter]: conventional and molecular approaches. Plant Breeding 130: 1-9.

Melak-Hail Mengesha. 1966. Chemical composition of tef (*Eragrostis tef*) compared with that of wheat, barley and grain sorghum. Economic Botany 20: 268-273.

Roberts EH and Summerfield RJ. 1987. Measurement and prediction of flowering in annual crops. In Manipulation of Flowering (Ed. J. G. Atherton). Butterworths, London, pp. 17-50.

Spaenij-Dekking L, Kooy-Winkelaar Y and Koning F. 2005. The Ethiopian cereal tef in celiac disease. New England Journal of Medicine 353, 1748-1749.

Summerfield RJ, Law RJ, Qi A, Ellis RH, Roberts EH, Chay PM, Brouwer JB, Rose JL, Shanmugasundaram D, Yeates SJ and Sandover S. 1993. Towards reliable prediction time to flowering in six annual crops. II. Soybean (*Glycine max*). Experimental Agriculture 29: 253-289.

Summerfield RJ, Roberts EH, Ellis RH and Lawn RJ. 1991. Towards the reliable prediction of time to flowering in six annual crops. I. The development of simple models for fluctuating field environments. Experimental Agriculture 27: 11-31.

Teshome Yizengaw and Verheye W. 1994. Modelling production potential of tef (*Eragrostis tef*) in the central highlands of Ethiopia. Soil Technology 7: 269-277.

Van Delden SH. 2011. On seed physiology, biomechanics and plant phenology in *Eragrostis tef*. PhD thesis, Wageningen University, Wageningen, the Netherlands. 185 pp.

Van Delden SH, Brouwer G, Stomph TJ and Vos J. 2008. Towards an ideotype of tef for temperate climates. Italian Journal of Agronomy 3: 627-628.

Van Delden SH, Vos J, Ennos AR and Stomph TJ. 2010. Analysing lodging of the panicle bearing cereal tef (*Eragrostis tef*). New Phytologist 186: 696-707.

Van Delden SH, Vos J, Stomph TJ, Brouwer G and Struik PC. 2012. Photoperiodism in *Eragrostis tef*: Analysis of ontogeny and morphology in response to photoperiod. European Journal of Agronomy 37: 105-114.

Vos J and van der Putten PEL. 2000. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. I. Input and offtake of nitrogen, phosphorus and potassium. Nutrient Cycling in Agroecosystems 56: 87-97.

Yewlsew Abebe, Alemtsehay Bogale, Hambidge KM, Stoecker BJ, Bailey K and Gibson RS. 2007. Phytate, zinc, iron and calcium content of selected raw and prepared foods consumed in rural Sidama, Southern Ethiopia, and implications for bioavailability. Journal of Food Composition and Analysis 20: 161-168.

Yifru Teklu and Hailu Tefera. 2005. Genetic improvement in grain yield potential and associated agronomic traits of tef (*Eragrostis tef*). Euphytica International Journal of Plant Breeding 141: 247-254.

Yin X, Kropff MJ, Horie T, Nakagawa H, Centeno HGS, Zhu D and Goudriaan J. 1997. A model for photothermal responses of flowering in rice I. Model description and parameterization. Field Crops Research 51: 189-199.

Yu J-K, Graznak E, Breseghello F, Hailu Tefera and Sorrells ME. 2007. QTL mapping of agronomic traits in tef [*Eragrostis tef* (Zucc) Trotter]. BMC Plant Biology 7:30.

12. Some Experiences on Tef Mechanization

Friew Kelemu* **and Lake Kebede**
Ethiopian Institute of Agricultural Research, Melkassa Agricultural Research Center, Agricultural Mechanization Research Project, P.O.Box 436, Adama, Ethiopia.
*Corresponding author: friewkelemu@yahoo.com

In Ethiopia, tef cultivation starting from land preparation to harvesting and threshing of the crop is mainly based on traditional and unimproved implements. The Agricultural Mechanization Research group at Melkassa Agricultural Research Center in Ethiopia has been conducting some studies which led to the development of several improved implements for tef husbandry. Among these, a moldboard plow which minimizes repeated plowings has been developed and is currently being used by many farmers. A seed drill using a fluted type seed metering device was also developed and tested at the Center in 2010. A study on tef harvester has indicated that the loss from the modified pickup reel was about 6% while from the original harvester was about 18%. It was also shown that harvesting loss up to 28% was recorded from unleveled fields as compared to 13% from leveled fields. These studies show that the plow minimizes the drudgery of the farmer; the planter eases the weeding operation; and the combine harvester with the modified pick up reel minimizes the harvesting loss provided that the crop is planted on a leveled field.

Key words: Implements, plow, seed drill, harvester, thresher, tef mechanization

12.1. Introduction

Cultural practices and implements applied by tef farmers in Ethiopia are largely un-improved. These practices include activities from land preparation to harvesting and threshing of the crop. These indigenous practices are laborious and result in low productivity. Farmers prepare their land for tef by repeated and excessive plowings which sometimes reach up to ten times. These too many frequencies of plowings or pulverization enhance the loss of the upper and fertile soil by erosion. Optimum degree of soil pulverization was not yet studied for tef cultivation. In addition, the effect of surface configuration on the crop stand was not studied. Firming the soil by trampling of small animals before broadcasting is the usual farmers' practice of planting in many areas, though there is no adequate information whether this insures good soil-seed contact and enhance germination and emergence.

Weeding in tef is laborious as it involves at least one hand-weeding even in addition to herbicide application. The short period untimely late rains during tef harvesting also reduce the period of harvesting as they have negative impact both on the quantity and quality of the produce.

The Agricultural Mechanization Research group at the Melkassa Agricultural Research Center is mandated to develop agricultural implements for small-scale farmers in Ethiopia. Since tef is the dominant crop in the country, due attention has recently been given to introducing and developing implements to be used for various activities ranging from land preparation to harvesting and threshing. Major survey studies made in major tef growing areas and implements tested by the group are presented in the following sections.

12.2. Survey

The Agricultural Mechanization Research Center then called Appropriate Technology for Farmers (ATF) started its formal research work with a country wide survey conducted from 1985 to- 1986 in selected six administrative regions, eight Awrajas, and 24 Weredas. Altogether, 239 peasant farmers were included in the study whereby information on the resource base, types of implements used and constraints in crop production were gathered. According to the informant farmers, agricultural operations such as plowing, weeding, harvesting, and threshing were not efficiently applied in their traditional system. About 80% of the farmer associations reported overlap of several operations during the peak season. Regarding land preparation for tef, farmers plow their land from 2 to 10 times using a local *maresha* According to farmers, poor quality or less frequent plowing results in serious weed problem; hence, increases the labor required for weeding The study also indicated that the amount of labor required to weed a hectare of tef, wheat and maize were 235, 230 and 140 hours, respectively. Next to weeding, harvesting is the second operation that requires a lot of labor in tef husbandry as it is done by less efficient hand-held sickle. The time required to harvest a hectare of tef, sorghum and maize were 210, 200 and 100 hours, respectively (Pathak, 1986, unpublished). The subsequent research activities of the Agricultural Mechanization Research Division were, therefore, focused on developing and/or testing improved implements for tillage, harvesting, threshing and transport.

12.3. Implements for Land Preparation

The traditional method of land preparation using *maresha* is cumbersome. The frequency of plowing is so metimes more than five times especially in areas like Shirka (Arsi Zone) where grass weeds are predominant. In order to c ombat such problems and reduce repeated plowings, the Nazareth moldboard plow was developed by the Agricultural Mechanization Research group based at Melkassa Agricultural Research Center. The modified oxen-pulled moldboard plow reduces the tillage requirement by 50% due to its complete inversion or turning of the furrow slice that result in the inhibition of weed germination and growth. A yield increase of up to 12% was also observed due to use of the plow.

The efficiency of the plow was tested for various parameters both in the laboratory and field along with other prototypes imported from abroad or obtained locally. Results of field tests are summarized in Table 1. These tests led to the modification of the Nazareth and other plows in order to m eet both the technical and economic requirements of small-scale farmers.

Table 1. Summary of field tests of four plows at Melkassa Agricultura Research Center for various parameters.

Parameter	Local *Maresha*	ARDU plow	Nardi Plow	Nazareth Plow
Soil Moisture (%)	17.5	19.0	17.0	-
Weeding efficiency (%)	92.0	94.3	89.0	97.3
Average depth (cm)	6.6	20.8	9.8	9.9
Draft (kgf)	102.5	98.4	92.1	76.1
Time (h ha^{-1})	20.0	23.3	24.6	22.7

Despite improvements in some properties, the modified plows are heavier to transport by farmers. In addition, farmers encounter problem in adjusting the position of the handle and depth of the plow. A series of subsequent modifications on the plow led to th e development of the *erf* (handle) and *mofer* (beam) attached moldboard plow which was found to be not only superior in performance and but also commensurate with the technical knowhow of the farmer (Fig. 1A). This modified plow has been widely distributed to farmers across the country.

12.4. Implements for Sowing Tef

A seed drill using a fluted type seed metering device (Fig. 1B) was developed and tested on station in the year 2010. The experiment was conducted on a plot size of 5 m x 10 m with three replications using the conventional practice as a check. The experiments from the first year did not showsignificant difference in seed yield between the broadcasting and row-drilling. In the second year, comparisons were made in the field at Melkassa and Debre Zeit among row driller, and manual row sowing and broadcasting. Although the outcome of the latter experiment is not yet available, row sowing by the drill planter significantly reduces the amount of tef seed to be sown and operation time (Fig. 1C). Further experiments need to be done in order to reach at conclusions.

Fig 1. Implements developed or tested for various cultural practices involving tef. A) *Erf* and *Mofer* attached moldboard plow; B) Seed drill; C) Performance of tef plants sown by the seed drill indicated in B; D) Part of the modified pickup reel developed or tested for tef harvesting.

12.5. Implements for Harvesting Tef

Lodging substantially reduces the yield and quality of both the grain and staw of tef produced (Seifu, 1993). Modern harvesters have some provisions for harvesting severely lodged crops like tef provided that proper adjustments are made between the header and the pickup reel. This provision was considered to help the farmers in order to minimize the losses due to lodging which is mostly caused by rains, wind and inherent property of the plant.

The efficiency of harvesters was tested at Melkassa Agricultural Research Center using two tef varieties, namely: *Magna* (DZ-01-196); and *Tsedey* (DZ-Cr-37) using a Massey Ferguson combine harvester. In the first year, each variety was sown on 0.125 hectares of land using the conventional broadcasting method. Harvesting was done in early October by making some adjustment on the cutter and pick up clearance. Observations were made on the direction of lodging and harvesting, as well as on the amount of yield loss due to lodging and harvesting.

In the second year, a modified pick up reel (Fig. 1D) was developed using a round pipe attached with twice the number of the original picking fingers. A comparative test was made between the original picker and the modified version in the mornings and in the afternoons. A lower percentage of loss was recorded in the case of the modified version compared to the original one (Table 2). This could be attributed to the more efficient picking of the lodged crop by the modified version. A lower loss was recorded in the afternoons compared to the harvestings made in the mornings as shown in Table 2, which was easier to pick, when the crop has a lower moisture load. In addition to quantifying the amount of seed loss due to harvesting, correlations were made between the degree of lodging and loss due to harvesting.

Table 2. Yield losses of two improved tef varieties in the morning and afternoon due to two types of harvesters tested at Melkassa Agricultural Research Center in 2001.

Tef variety	Harvesting date	Normal pick up reel		Modified pick up reel	
		Morning	Afternoon	Morning	Afternoon
Magna (DZ-01-196)	19/10/2001	18.3	7.3	6.3	3.17
	31/10/2001	10.6	??	4.1	??
Tsedey (DZ-Cr-37)	23/10/2001	4.4	??	??	0
	24/10/2001	12.0	-	2.4	-
	31/10/2001	10.6	??	4.1	-

In the third year, the experiment was conducted at Melkassa and Debre Zeit using the two varieties indicated above but under two field conditions, namely leveled and unleveled. The field was leveled before planting using a scrapper as indicated in Table 3, a lower rate of harvesting loss was recorded on the leveled field in both types of the harvesters. Further more on these leveled fields a lower loss was recorded in the case of the modified version except in one case, which was attributed to clogging a rare occurrence on properly adjusted cutter bar. The loss on the unleveled field (Table 4) was higher compared to the loss on the leveled field in both cases (Table 3). The degree of lodging induced higher loss in case of the original picker than in the modified version (Table 4). The data generally indicate that tef should be planted on a leveled filed and be harvested with a combine harvester with many fingers on the pick-up reel for a better performance and minimal harvesting loss.

Table 3. The extent of lodging in two tef varieties and associated yield losses due to two types of harvesters for plants sown on leveled field.

Variety	Harvesting date	Normal Pick up reel		Modified pick up reel	
		Lodging (%)	Yield loss (%)	Lodging (%)	Yield loss (%)
Magna (DZ-01-196)	16/10/2002	69.2	26.6	51.0	0.0
	29/10/2002	54.0	0	64.4	8.2
Tsedey (DZ-Cr-37	18/10/2002	42.1	0	46.6	15.5
	19/10/2002	51.6	0	30.5	16.9 (Clogged)

Table 4. The extent of lodging in two tef varieties and associated yield losses due to two types of harvesters for plants sown on unleveled field

Variety	Harvesting date	Normal Pick-up reel		Modified pick up reel	
		Lodging (%)	Yield loss (%)	Lodging (%)	Yield loss (%)
Magna (DZ-01-196)	17/10/2002	24.7	16.6	71.8	8.6
	19/10/2002	57.2	0	71.3	0
Tsedey (DZ-Cr-37)	17/10/2002	55.7	40.2	64.4	22.7
	19/10/2002	60.6	17.3	48.6	0

12.6. Implements for Threshing

Threshing tef is a difficult job. Efforts were made to develop a threshing shelling machine at Melkassa Agricultural Research Center. The IAR threshing-shelling machine was tested on tef and a capacity of 0.1 ton h^{-1} was recorded (Table 5; Friew *et al.*, 1994). To get a better performance it was advised to re-thresh the crop. The low output is attributed to the small size of the crop, and the small travel distance within the threshing unit. This shows that a lot be done on this line to come up with a more efficient tef threshing machine. The Regional Rural Technology Centers, SELAM Vocational School and Sasakwa Global 2000 have developed some equipment which are now being popularized in the Arisi Negle Shasemene area.

Table 5. Test condition and performance of machine on tef threshing.

Description	Test condition and performance	
	Test 1	Test 2
Moisture Content		
Grain	14.74	16.11
Straw	9.87	10.30
Chaff	11.29	11.45
Grain/straw ratio	1:1.7	1:1.33
Grain losses (%)	2.55	1.91
Capacity (kg h^{-1})	122	88
Speed (rpm*)	1200	1200
Clearance (mm)	8	8

Source: Threshing-Shelling Machine of IAR (1994).

12.7. The Way Forward

Not only the crop itself but also implements used for various activities of tef husbandry are unimproved. Hence, farmers are largely using traditional and less efficient implements to plow their land and also for subsequent activities such as sowing, harvesting and threshing. The current method of land preparation pulverizes the soil so finely so that it exposes the field to soil erosion.

Some efforts are being made to introduce improved mechanization technologies in order to tackle these problems. Precision and efficiency of the implements used for various activities are given priority. In the future, in addition to training skilled personnel, strong research program on tef mechanization should be established since little or no technologies could be imported in order to be used not only for mechanization but also even in terms of improved implements for small-scale tef production.

12.8. Abbreviations

ATF: Appropriate Technology for Farmers; **ARDU**: Arsi Rural Development Unit; **RPM**: Revolution per minute.

12.9. References

Friew Kelemu, Muluken Tilahun and Awotahagne Tesfaye. 1994. Threshing and shelling machine of Institute of Agricultural Research (IAR). IAR Research Report No. 22, Addis Ababa, Ethiopia.

IAR. 1994. Threshing -Shelling Machine of IAR, Addis Ababa, Ethiopia

Seyfu Ketema. 1993. Tef (*Eragrostis tef*) Breeding genetic resources, agronomy, utilization and role in Ethiopian Agriculture. Institute of Agricultural Research Addis Ababa, Ethiopia.

IV. Pests, Diseases & Weeds

13. Insect Pest Management Research in Tef

Tebkew Damte
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O. Box 32, Debre Zeit, Ethiopia. Email: tebkew@yahoo.com

More than 40 insect pest species have been recorded on tef. Of these, tef grasshopper (Aiolopus longicornis), tef shoot fly (different species), tef red worm (Mentaxya ignicollis), Wello bush cricket (Decticoides brevipennis Rag.), termites (Macrotermes subhyalinus and Odontotermes sp.) and perhaps the tef black beetle (Erlangerius niger) are sporadically important insect pests in various tef growing areas. Hence, these insect pests cause different levels of yield losses in tef. The majority of research on insect pest management focused on identifying appropriate insecticides. Other aspects of pest management including cultural control (e.g. sowing date, seed rate, fertilizer rate, host plant resistance), natural enemies and ecological methods were not investigated. The current review presents major findings of entomological research related to tef and suggests future research directions.

Key Words: Ethiopia, *Eragrostis tef*, tef insects, tef entomology, pest control, insecticide

13.1. Introduction

Insect pests recorded on tef are many; however, the majority of these insect pests are merely on the recorded list (Table 1). Among these insect pests, the tef grasshopper (*Aiolopus longicornis*), which was once major pest of tef in central Ethiopia, had relegated to minor status. Other insect pests such as tef shoot fly (diverse species), tef red worm (*Mentaxya ignicollis*), Wello bush cricket (*Decticoides brevipennis* Rag.), termites (*Macrotermes subhyalinus* and *Odontotermes sp.*) and perhaps the tef black beetle (*Erlangerius niger*) are sporadically important in various tef growing localities. This sporadic nature of insect pests might be the probable reason why farmers in East Shewa do not include insect resistance as tef variety selection criteria

(Getachew *et al.*, 2006). Nonetheless, in order to devise control methods for these insect pests, entomological research have been carried out since the early 1970s. The goal of the current review is to compile the major outcomes of these studies and to indicate future researchable areas.

Table 1. Insect pests recorded on tef in Ethiopia.

Order	Scientific name	Common name	Pest status	Reference(s)
Diptera	*Atherigonia hyalinipennis* Reg	tef shoot fly	major	Sileshi (1997); Mekasha *et al.* (2001)
	Atherigonia sp.	shoot fly	minor	Mekasha *et al.* (2001)
	Delia aramburgi Seg	barely fly	minor	
	Hylemaya aramburgi	barely fly	minor	
	Thaumatomyia secunda	-	minor	Mekasha *et al.* (2001)
	Elachiptera simplicipes Beck.	shoot fly	minor	Sileshi (1994), Sileshi (1997)
	Melanochaeta vulgaris (Adams)	shoot fly	minor	
	Oscinella nartschukiana Bescho.	shoot fly	minor	
	Oscinella acuticornis Beck.	shoot fly	minor	Sileshi (1997)
	Rhopalopterum sp.	shoot fly	minor	Sileshi (1997)
Coleoptera	*Lasioderma serricorne*	cigarette beetle	minor	Tebkew & Getachew (2011)
	Tribolium confusum	confused flour beetle	minor	
	Epicauta albovitatta	striped blister beetle	uncertain	IAR (1981)
	Epilachna similes Thum.	tef epilachna	minor	Mekasha *et al.* (2001)
	Erlangerius niger Weise	tef black beetle	minor	
	Eysarcoris inconspicus (HS)	-	uncertain	Mekasha *et al.* (2001)
Isoptera	*Macrotermes subhyalinus*	Mendi termite	major	
	Odontotermes anceps (Sjos)	groundnut termite	major	Abdurahman (1992)
Hemiptera	*Carbula recurva*	carbula bug	minor	Mekasha *et al.* (2001)
	Diuraphis noxia	Russian wheat aphid	minor	
	Schizaphis graminum	greenbug	minor	
	Rhopalosiphum padi	oat aphid	minor	
	Rhopalosiphum maidis	maize aphid	minor	

Order	Scientific name	Common name	Pest status	Reference(s)
	-	mealybug	minor	
Orthoptera	*Aiolopus longicornis* Sjos	tef grasshopper	minor	Mekasha *et al.* 2001
	Aiolopus thalassinus Fab	grasshopper	minor	Tibebu & Landin (1992)
	Aiolopus simulatrics Walier	grasshopper	minor	
	Acrolytus spp	saddle grasshopper	minor	
	Acrolytus patruelis Her.	grasshopper	minor	
	Eyprepocnemis noxia Dirsh	grasshopper	minor	
	Triophidia contrubata Wal.	grasshopper	minor	
	Chrotogonus senegalensis abyssinicus Bolivar	grasshopper	minor	
Orthiptera	*Schistocera gregaria*	locust	sporadic	Mekasha *et al.* (2001)
	Decticoides brevipennis Rag	Wello bush cricket	major	
	Oedaleus senegalennis	sand grasshopper	minor	
	Medicogryllus spp	cricket	minor	
Thysanoptera	-	florate thrips	minor	Mekasha *et al.* (2001)
Lepidoptera	*Mentaxya ignicollis*	tef red worm	major	
	Spodoptera exempta	army worm	sporadic	
	Spodoptera exigua	lesser army worm	sporadic	
	Plusia acute	plusia worm	minor	
	Helicoverpa armigera	African boll worm	minor	

13.2. Tef Grasshoppers

13.2.1. Species composition

Tibebu and Landin (1992) studied the taxonomic composition of tef grasshoppers in tef and wheat fields in Denkaka, Godino, Debre Zeit and Dukum areas of East Shewa Zone where 29 taxa of short- and long-horned grasshoppers belonging to four families and nine subfamilies were recorded. Although *Aiolopus longicornis* is the dominant grasshopper species, it occurs together with *A. thalassinus* and attacks the seedlings of tef and wheat on both black and light soils. *Acrotylus patruelis* is active throughout the year and is the pest of tef and sorghum at the heading stage mainly on light sandy soil. On the other hand, *Eyprepocnemis noxia* Dirsh attacks both the seedlings and adult tef plants mostly on black soils.

13.2.2. Biology

Although the biology of this grasshopper was not yet investigated on tef, Tibebu *et al.* (1995) studied the same grasshopper by feeding the first and second instars to wheat seedlings and wheat bran and the third instar through adult stage to lettuce. Environmental conditions set for the study were 13 hours day and 9 hours night; a temperature of 25°C during the day and 15°C during the night; and a relative humidity of 55% during the day and 70% during the night. Under these environmental conditions, the eggs hatched after 23 days, and the first and the second instar lasted each for six days, the third instar for 11 days, the fourth through the six instars for 23 days and the adult lifespan was 61 days. The survival rate and the duration of each life stage were significantly reduced when the tef grasshopper was infected at the third instar stage with *Nosema locustae* Canning (Protozoa: Microsporidia: Nosematidae).

13.2.3. Seasonal abundance

A study at Denkaka and Godino indicates that the population of the tef grasshopper fluctuates within a season, between seasons and from location to location (DZARC, 1988; Tibebu, 1999). Abundant populations were observed during rainy season and on black soils than on light soils. This grasshopper also inhabits and increases in number in fallow fields during the short rains before shifting to the seedlings of crop plants at the beginning of the long rainy season. The tef grasshopper reproduces during the rainy period whereby two to three generations are completed in a single season. It overpasses the dry period as reproductively inactive adult and as an egg (DZARC, 1983; Tibebu, 1999).

13.2.4. Grasshopper density effect on tef

The effect of grasshopper density was assessed for *Enatit* (DZ-01-354) tef variety on the level of crop damage by introducing the grasshopper at four densities (0, 5, 10 and 15 grasshoppers per m^2) and at three tef growth stages (early seedling, early tillering and early heading). The increase in the extent of seedling loss or seedlings attacked commensurate with the increase in tef grasshopper density. But seedling loss and seedlings attacked decreased as the age of the crop increased (DZARC, 1991, 1994). According to the study, 15 grasshoppers per m^2 caused economic loss on tef cultivation.

13.2.5. Management of tef grasshopper

13.2.5.1. Effect of insecticide

The efficacy of several insecticides was investigated under field conditions based on the proportion of seedling loss, seedling attacked by tef grasshopper and grain yield of tef (DZARC, 1990, 1991). Among the insecticides tested, cypermetrin (cymbush 5ec), carbaryl 85wp and sumi-cumbi 30ec consistently reduced the seedling loss for three growing seasons (Table 2). However, carbaryl 85wp at 1.5 kg ha^{-1} is recommended to control this particular grasshopper. The insecticide is formulated in bait form using 136 kg ha^{-1} of wheat bran and 66 l ha^{-1} of molasses, and the bait is broadcast over the tef field.

Table 2. Effect of insecticides on tef grasshopper and yield of tef.

Insecticide	Rate (kg ha^{-1} or l ha^{-1})	Seedling loss (%)	Seedlings attacked (%)	Grain yield (kg ha^{-1})
Carbaryl 85wp	1.50	5.70	8.50	1314.20
Deltametrin 25ec	-	5.80	14.20	1731.05
Sumi-cumbi 30ec	0.029	2.65	9.00	1262.60
Cypermetrin 5ec	4.80	3.15	10.00	1395.10
Primiphos-methyl 50ec	1.00	7.40	14.30	954.20
Propoxur 70wp	0.32	4.00	7.60	924.60
Unsprayed check	-	29.40	15.75	768.45

Source: Data from DZARC (1990, 1991).

13.2.5.2. Effect of sowing date

The influence of sowing date on the incidence of tef grasshopper was evaluated at Denkaka (1870 m a.s.l.) and Akaki (2200 m a.s.l.) (DZARC, 1989, 1990, 1991). At both locations, planting tef early in the growing season exposed the crop to more damage by the tef grasshopper than planting late in the season. Thus, at Denkaka, about 6-10% of the seedlings were lost due to tef grasshopper when tef was sown in the fourth week of June, while the seedling loss was only 3% of those planted in the first week of August (DZARC, 1989). Despite higher infestation by the grasshopper, early sown tef yielded greater than the late sown ones. Due to similar grasshopper damages on early sown tef at Akaki, the third to fourth week of July is suggested as an optimum planting time for tef (DZARC, 1994).

13.2.5.3. Host plant resistance

The response of various tef genotypes to tef grasshopper infestation was tested in a cage experiment (Table 3). In a decreasing order the genotypes DZ-01-1681, DZ-01-176 and DZ-01-974 suffered less seedling loss whereas DZ-01-1868 and DZ-01-1281 were highly susceptible to tef grasshopper (DZARC, 2002). In another evaluation the tef genotype DZ-01-172 was least affected and gave the highest grain yield. DZ-01-134 and DZ-01-170 were intermediate in terms of seedling loss and seedling attack but yielded better than most genotypes (DZARC, unpublished report). Compared to tef grown under full sunlight, tef crops grown under mesh wire were tender and succulent, and as result most genotypes were ravaged by the grasshoppers.

13.3. Tef shoot fly

13.3.1. Species composition

According to Sileshi (1994, 1997) the species assemblage of tef shoot fly in Alemaya (Haramaya) area include *Elachiptera simplicipes* Becker, *Melanochaeta vulgaris* (Adams), *Oscinella nartschukiana* Beschovsky, *O. acuticornis* Becker and *Rhopalopterum* sp. in the family Chloropidae and *Atherigona hyalinipennis* and *Atherigona* sp. in the family Muscidae. The Chloropidae flies infest tef starting from crop germination and dominate up to the three leaf stage (but they occur in combination with Muscidae flies in the other crop stages), whereas the Muscidae flies occur starting from the three leaf stage and dominate between the heading and maturity of the crop. Sileshi (1997) asserted that *A. hyalinipennis* alone causes more than 90% of panicle damage. Although tef shoot flies were not identified to species level, in the East Shewa Zone at least two genus *viz. Atherigona* and *Delia* were identified, whereas in East Gojam only *Atherigona* spp. were reared on tef samples with dead heart (DZARC, 2003). According to several authors, *Delia arambourgi* (Seguy) is considered as insect pest of tef (Adugna and Kemal, 1986; Abraham and Adane, 1995; AARC, 2002; DZARC, 2003). But other investigators indicated that tef might not be the host for this particular fly as the stem of tef is too small to accommodate the larva of the insect (Sileshi, 1997; Tesfaye and Zenebe, 1998).

These different species of shoot flies also infest other cereal crops and grass weeds (Table 4). The period when the shoot flies are active is influenced by the type of the crop and weather condition. For instance, the adults of *A. hyalinipennis* are abundant in tef fields from August to September, whereas the adults of *E. simplicipes* and *M. vulgaris* are active in sorghum fields from August to October and June to September, respectively (Sileshi, 1994, 1997).

Table 3. The response of tef to grasshopper attack

Genotype	Seedling loss (%)		Seedling attacked (%)		Productive tillers (%)		Biomass (g/ m^2)		Grain yield (g/m^2)	
	Infested	Control	Infested	Control	Infested	Control	Infested	Control	Infested	Control
DZ-01-99	75.6	7.9	66.7	0	82.2	96.8	518.8	604.2	72.2	81.7
DZ-01-112	72.7	2.2	33.3	0	79.4	80.7	422.6	694.9	68.8	119.6
DZ-01-176	63.3	0.0	100	0	65.4	89.2	735.6	679.2	89.3	122.5
DZ-01-262	64.3	0.0	33.3	0	97.4	96.4	452.5	638	89.4	108.1
DZ-01-787	52.7	0.0	80.8	0	54.1	92.3		765	108.2	123.5
DZ-01-974	35.9	11.6	84	-	86.8	94.6	610.4	624.2	93.7	117.8
DZ-01-1281	100	0.0	100	0		69		611		125.0
DZ-01-1285	95.1	3.5	100	0	-	87.5	-	664.1	-	94.5
DZ-01-1681	23.1	0.0	40	0	66.7	97.4	461.6	531.5	68.6	86.4
DZ-01-1868	100	0.0	100	0	-	88.5	-	617.4	-	82.2
DZ-Cr-44	93.3	4.1	100	0	62.5	100	407	541.3	51.3	83.6
DZ-Cr-82	79.2	2.1	81.8	0	91.2	94.7	481.5	576.1	91.1	96.2
DZ-Cr-255	80.9	0.0	100	0	82.4	88.9	384.7	659.1	84.6	122.5
DZ-Cr-358	94.9	0.0	100	0	100	95.4	429.7	509.9	77.6	92.5

Source: DZARC unpublished repor

Table 4. Alternate hosts of various tef shoot flies at Alemaya

Shoot fly species	Alternate host
Atherigona hyalinipennis	Wheat, sorghum
Atherigona sp.	Wheat, *Cynodon dactylon, Setaria verticilata*
Elachiptera simplicipes	Barley, sorghum
Melanochaeta vulgaris	Barely, sorghum, wheat, *Digitaria sp,*
Oscinella nartschukiana	Barely, sorghum, wheat, *Eragrostis aspera, E. aulacosperma, E. braunii*
O. acuticornis	Wheat, *Brachiaria eruciformis*
Rhopalopterum sp.	Barely, sorghum, wheat, *Digitaria abyssinica*

Source: Sileshi (1997)

13.3.2. Biology of Atherigona hyalinipennis

Sileshi (1997) studied the biology of *A. hyalinipennis* under laboratory condition (at 22 ± 2°C and RH 60 ± 5%) at Alemaya (Table 5). Eggs are laid singly (rarely up to four) on the leaf sheath at the base of the seedling or on the soil. The larva, the destructive stage of shoot fly, requires about two weeks to reach pupal stage. After hatching, the larva bores into the stem, cut the growing shoot and feeds on the rotting tissue. Pupation site is in the soil and adults emerge after dawn until 0900 h.

Table 5. Duration of life stages of *A. hyalinipennis* under laboratory condition

Stage	Duration (days)	
	Range	Mean
Egg	2-4	3.0
Larva	10-15	12.7
Pupa	8-12	9.6
Pre-oviposition period	6-13	6.0
Adult life span - female	8-15	11.2
Adult life span - male	4-8	9.2

Source: Sileshi (1997)

13.3.3. Geographical distribution

Surveys conducted in Central Ethiopia (Debre Zeit, Mojo, Koka, AlemTena and Akaki), East Gojam (Yilmanadensa, Bahr Dar Zuria and Adet Zuria) and Tigray Region (Mekoni, Axum and Wukro) confirmed the wide occurrence of tef shoot fly (DZARC, 2002; Bayeh *et al.,* 2008). Depending on the season, the level of tef seedling infestation ranged from 2 to 4% in Central Ethiopia, 3 to 10% in East Gojam and 7 to 37% in Tigray. According to Bayeh *et al.* (2009), this fly is considered as a pest of tef in Asgori, Teji and Tulu Bolo areas of Southwest Shewa Zone and Ginchi area of West Shewa Zone, but not in Guder and Ambo areas of the same Zone. The incidence of shoot fly in Guba Lafto, Habru, Sirinka and Ziquala areas of North Wollo Zone ranged from 5 to 6% at seedling and 2 to 5% at heading stage (Bayeh, 2004). Within a field, tef shoot fly had aggregated type of distribution (DZARC, unpublished report).

13.3.4. Yield losses

The tef yield loss due to tef shoot fly in different areas of the country is indicated in Table 6. The yield losses reported in areas where the rainfall is abundant (eg. East and Southwest Shewa Zones) was negative or less than 5%. Similarly, in Gojam area tef shoot fly does not cause yield losses (AARC, 2002). On the other hand, in Tigray Region where precipitation is low and the soil is degraded (Tesfaye and Zenebe, 1998), the tef shoot fly causes greater yield losses than in the other tef growing areas. At Alemaya (Haramaya), tef is sown after sorghum and the shoot fly population that built-up on sorghum might have caused severe damage (378 to 522 kg ha^{-1}) (Sileshi, 1997).

Table 6. Yield loss caused by tef shoot fly in different tef growing areas in Ethiopia

Region/Zone	Location	Year	Variety	Yield loss (%)	Reference
East Shewa Zone	Debre Zeit	1971	DZ-01-238	13 to 24	Tareke (1972)
		1971	Asgori (DZ-01-99)	-2 to 13	
		1995	Tsedey (DZ-Cr-37)	0.52	DZARC (1998)
		1995	Magna (DZ-01-196)	0.43	
		1995	Enatite (DZ-01-354)	0.30	
Tigray Region	Dibdibo	1999	Not reported	19.9	Bayeh *et al.* (2008)
		2000	Not reported	18.9	
	Mekoni	1999	Not reported	16	
		2000	Not reported	24	
Southwest Shewa Zone	Asgori	2006	Not reported	-22.4 to 4.9	Bayeh *et al.* (2009)

13.3.5. Management of Tef Shoot Fly

13.3.5.1. Natural enemies

According to Sileshi (1997), 7 to 1 9% of *A. hyalinipennis* larvae are parasitized by *Neotrichoporoides nyemitawus* (Rohwer) (Hymenoptera: Eulophidae). Moreover, the parasitoid *Bobekia sp.* (Braconidae: Hymenoptera) parasitizes 3% of the pupae of this fly species.

13.3.5.2. Effect of sowing date and fertilizer

The incidence of tef shoot fly around Debre Zeit, in Central Ethiopia, is primarily governed by the rainfall distribution. During the normal growing season, late sown tef is infested by the tef shoot fly, while early sown tef is infested only if there is dry spell (DZARC, 1983). At Melko, Jima area in southwestern Ethiopia, planting in the first week of July gave better yield than late planting although the level of shoot fly incidence was not reported (IAR, 1976). On the contrary, in Mekele area, northern Ethiopia, sowing tef in early- to mid-July favors the incidence of tef shoot fly than sowing in August; however, grain yield of early sown tef was greater than late sown ones (Tesfaye and Zenebe, 1998; Bayeh *et al.*, 2008). In Anno area, western Ethiopia, tef was sown at ten days interval between the fourth week of June and the second week of August (Fig. 1). Both the damage due to tef shoot fly and grain yield of tef increased until third week of July and decreased thereafter (Abraham and Adane, 1995). Regarding control measures, except in Tigray Region where farmers use late planting, repeated plowing, soil compaction and insecticides, farmers in other part of the country do not apply any control measures against shoot fly (DZARC, 2002; Bayeh *et al.*, 2008).

According to Corbeels *et al.* (2000), the application of manure predisposes the crop to infestation by the tef shoot fly. In general, dead hearts were more prevalent in fertile parts than in the waterlogged or less fertile parts of the tef field (Tesfaye and Zenebe, 1998).

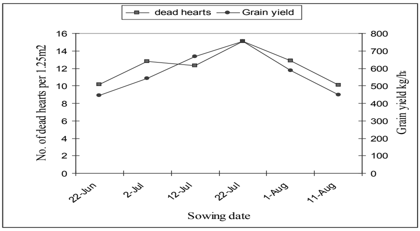

Fig. 1. Effect of sowing date on shoot fly incidence and yield of tef at Anno [Source: data from Abraham and Adane, (1995)].

13.3.5.3. Effect of insecticide

At Debre Zeit, Tareke (1972) evaluated three insecticides each at two rates for shoot fly control on tef (Table 7). Perfekthion at 1 l ha^{-1} killed 50% of the maggot population six days after spraying. However, nine days post-spraying, more survivors of shoot fly maggots were recorded on the insecticide treated plots. Grain yield was greater on tef sprayed with perfekthion at l l ha^{-1}, even though the within treatment variation was large. Dimecron sprayed at the rate of 1 l ha^{-1} has equal efficacy as perfekthion sprayed at 1 l ha^{-1} (Tareke, 1972). Seed dressing insecticides were also tested but they did not increase the grain yield of tef (Adugna and Kemal, 1986). The application of trichlorophos 50 wp, fenitrothion 50 ec and diazinon 60 ec reduced infestation by tef shoot fly and increased tef yield in Tigray Region (Bayeh*et al.*, 2008). However, in Southwest Shewa Zone, although insecticides reduced the shoot fly infestation level, the tef grain yield was greater in unsprayed tef than sprayed ones (Table 8) (Bayeh *et al.*, 2009). In general, the low shoot fly infestation in areas with adequate rainfall (eg. in Asgori area of Southwest Shewa), has stimulatory effect on the performance of the tef plant and grain yield. Also malathion reduces the damage by the tef shoot fly (DZARC, 1983).

Table 7. Effect of various insecticides on tef shoot fly and grain yield of two tef varieties.

Insecticide	Rate (l or kg ha^{-1})	Efficacy (%) days after spraying			Tef grain yield (kg ha^{-1})	
		Three	Six	Nine	DZ-01-238	Asgori (DZ-01-99)
Perfecthion (ec)	0.8	54.2	18.3	-1.7	1578.3	1681.7
	1.0	52.5	55.0	-1.7	1724.0	1883.3
Dipterex (sp)	0.4	45.8	8.3	0.0	1705.7	1647.0
	0.5	40.7	10.0	-1.7	1705.0	1891.3
Metasytox (ec)	0.8	35.6	13.3	-1.7	1712.0	1885.7
	1.0	40.7	18.3	-1.7	1628.7	1798.0
Unsprayed check	0	-	-	-	1391.7	1673.3

Source: Data from Tareke (1972)

Table 8. Effect of insecticides on the incidence of tef shoot fly and grain yield of tef at Asgori, Southwest Shewa Zone.

Insecticide		Panicle infestation (%)	Grain yield (kg ha^{-1})
Name	Rate (l ha^{-1})		
Chlorpyriphos 48 EC	1.0	0.51	2056
Dimethoate 40 EC	1.33	0.06	2520
Fenitrothion 50EC	2.0	0.43	2770
Malathion 50EC	2.0	0.22	2093
Untreated check	–	1.82	2640

Source: Bayeh *et al.* (2009)

Tef Black Beetle

13.3.6. Importance and host range

The tef black beetle, *Erlangerius niger* (Weise) is a pest during the heading stage of tef (DZARC, 1983). Although this beetle is not considered as major pest around Debre Zeit (DZARC, 1983), it causes significant tef yield loss in Berfeta (near Holetta) and Filiklik (in the Abay Gorge) (IAR, 1977; Tadesse and Kemal, 1984). Alternate hosts for tef black beetle include wheat, *Cyperus rotundus, Rumex* sp., *Elusine* spp., *Eragrostis* sp., and *Setaria spp*. (IAR, 1981; DZARC, 1983; Tadesse and Kemal, 1984). The beetle is more abundant in weedy tef fields than in weed free fields (IAR, 1981).

13.3.7. Seasonal abundance

At Debre Zeit, tef black beetle appears in mid-July, which is about three months earlier than its initial appearance in Holetta (IAR, 1981; Tadesse and Kemal, 1984). The oviposition site, the larval habitat, pupation site and the over-seasoning habit of this beetle are not known. Similar to most other insects, the population of the tef black beetle fluctuates from season to season. For instance, in 1978 there was no infestation (IAR, 1983), whereas in 1977 and 1979 the beetle population per m^2 was in the range of 180 to 300 and 131 to 238, respectively (Tadesse and Kemal, 1984).

13.3.8. Management of Tef Black Beetle

The preliminary experiment at Berfeta indicated that although fenitrothion and malathion completely killed the tef black beetle, carbaryl at 1.5 l ha^{-1} was economical to apply (Tadesse and Kemal, 1984).

13.4. Wello Bush Cricket (WBC)

13.4.1. Geographical distribution

WBC occurs in Wello (Wag, Lasta, Wadla Delanta, Wara Himanu, Wara Illu and Borena districts), north Shewa, east Gojam, south Gondar and Tigray (Stretch *et al.*, 1980; Bayeh and Tsedeke, 1996). The pest inhabits the hillsides between 1860 to 2516 m a.s.l. but prefers intensively cultivated areas (Stretch *et al.*, 1980).

13.4.2. Biology

Stretch *et al.* (1980) studied under field condition the biology of the WBC between Goha Tsion and Dejen in the Abay Gorge. WBC is a non-migratory and a univoltine insect i.e. it has a single generation per year. Eggs are laid singly in the soil from

October to December (Table 9). Hatching occurs from July to September in the following year. According to A dane *et al.* (2001), the time of egg hatching is dependent on the start of rainy season; when the rainy season begins in March and April, WBC population explodes and reaches outbreak level. WBC passes through seven instar stages and the interval between the two successive molts (stadium) is about 10 to 11 days. The adults have pink, turquoise, and green color particularly on the pronotum, and yellow band on the margin of the pronotum and on the wing. The early instars (instars I to III) occur in green and lush vegetation with an upright growth habit and as the season progresses they develop to older instars and adult during which the vegetation dries. It is a t this time that the WBC assumes pest status.

Table 9. The period of egg hatching and population peak for WBC in various districts representing five Zones in the Central and Northern Ethiopia.

Zone	District (Woreda)	Egg hatching begins in	Peak damage period
North Shewa	Wara Jarsso	August	September to October
East Gojam	Enese Sar Midir	August	September to October
	Dejen	August	September to October
North Wello	Dawnt	July	September to December
	Delanta	July	September to December
	Sekota	July	September to December
South Wello	Debre Sina	August	September to December
South Gondar	all Woredas	July	September to November

Source: Bayeh and Tsedeke (1996)

13.4.3. Yield losses

According to Bayeh and Tsedeke (1996), WBC causes a tef yield loss of 15 to 35%. The losses at specific districts in North Wello Zone were 19% at Bugna, 37% at Delanta-Dawnt and 19% at Meket district (Bayeh, 2004).

13.4.4. Management of WBC

13.4.4.1. Traditional control methods

Farmers apply the following techniques in order to control WBC: early tef planting, spray cow urine, dust ash, grow resistant cultivars, remove alternate hosts, and grow crops such chickpea or make furrows at the border (Girma *et al.*, 2000; Adane *et al.*, 2001).

13.4.4.2. Insecticidal control

Although studies were not so far made to identify the best insecticide against WBC, a number of insecticides are applied by farmers (Bayeh and Tsedeke, 1996; Adane *et al*., 2001). Some of the insecticides recommended to control WBC including lindane, DDT and gamma BHC (Stretch *et al*., 1980; Adugna and Kemal, 1986) were banned from use in agriculture. Since WBC is a univoltine and non-migratory insect, one well-timed application of insecticide provides complete control (Stretch *et al*., 1980). According to these authors, the insecticide should be applied after most of the eggs have hatched (Table 9) and before damage to the crop becomes serious. However, no insecticide should be applied during the peak flowering period of plant species that are sources of nectars for honeybees.

The insecticides diazinon, endosulfan, carbaryl, dimethoate, bendiocarb, fenitrothion (ec/ulv), ekatin, malathion, dimecron and phosphamidon can be used for WBC control (Bayeh and Tsedeke, 1996).

13.5. Tef Red Worm

13.5.1. Geographical distribution

The Tef Red Worm (*Mentaxya ignicollis*) infests tef grown on black clay soils in Southwest Shewa, Gojam (Achefer and Bichena), Gondar (Dembia and Forgera), Kefa, Tigray and Wellega (Tadesse, 1987a; AARC, 2002).

13.5.2. Yield losses

The tef yield loss due to the tef red worm ranged from 24 to 30% (Tadesse and Matthews, 1986; Tadesse, 1987a), while the yield increase due to the application of insecticide ranged from 16-80% (Tadesse, 1987b).

13.5.3. Biology

Tadesse (1987a, b) studied the biology of tef red worm under laboratory condition at a temperature of 14-24°C and relative humidity of 40-82%. Eggs are laid singly or in batch on the leaf and stem of the tef plant. The larvae, which are red, reddish brown or light green in color, have well developed green head and true legs. Larval developmental period ranges from 25 to 47 days, and during this period it passes through six instars. Although egg hatchability is high, natural mortality in the first and second instar stage is about 51-65% and 3-23%, respectively. Due to their small size, detecting early instars of the tef red worm is difficult. The first instar feeds on the bottom surface of the tef leaf, leaving the epidermis of the upper surface intact;

while the second instar feeds on the entire leaf. Older instars feed on the whole plant except on hard stem. Feeding time is limited to early morning and evening (Tadesse and Matthews, 1986; Tadesse, 1987a).

Pupation takes place in the soil within an earthen cell constructed by the last larval instar, and under laboratory condition pupation period ranges from 18 to 78 days. However, under field condition most pupae enter diapause at the end of the crop season. Hence, pupation period in the field might be longer than the one under laboratory condition. The survival rate of pupae is inversely related with the length of diapause period. The adult is grayish or brownish nocturnal moth. Under laboratory condition, the adult of each male and female tef red worm has life span of 17 days. It is believed that tef red worm has three to four generations in a year. Kravtchenko (1992) described the daily rhythms of tef red worm activity as follows: as the sun sets, the tef red worm moths begin and continue feeding for about 2 h; this feeding activity is followed by rest period which ended around 2:00 am. After the rest period, females call males and at this phase the number of active male moths are greater than that of active females. At dawn the moths feed for short period and the activity ceases until the next sun set.

13.5.4. Alternate hosts

The tef red worm is oligophagous, i.e., it feeds on a restricted or limited number of plant species. The alternate hosts of this pest include wild grasses such as *Digitaria scalarum* and *Phalaris pardoxa* which belong to the family of Gramineae (also known as Poaceae) (Tadesse and Matthews, 1986; Tadesse, 1987a).

13.5.5. Management of the Tef Red Worm

13.5.5.1. Cultural control

This pest survives the dry period by entering pupal diapause at the end of the cropping season. Plowing the field immediately after harvesting reduces the number of diapuasing pupae and, therefore, tef red worm population significantly diminishes in the following season (Tadesse, 1987b).

13.5.5.2. Natural enemies

Some of the potential natural control agents on tef red worm include diverse species of birds, the bacterium *Bacillus thuringiensis* that infects the larva, and the parasitoid *Enicospilus rudiensis* Bischoff (Hymenoptera: Ichneumonidae) that parasitizes the pupa (Tadesse, 1987a). Provision of perches might encourage birds to stay and prey in tef fields for longer period of time.

13.5.5.3. Insecticidal control

Malathion and DDT (although the latter is band from use in agriculture) controlled the tef red worm effectively (IAR, 1977). Later, Tadesse (1987a, b) evaluated for two years the performance of five insecticides and *Bacillus thuringiensis* (Bt) in Becho area in western Shewa (Table 10). In both years, the numbers of the tef red worm per m^2 were at most four for the insecticide treated tef, 11 for the Bt and 50 for the untreated tef. The grain yield of tef was also higher for insecticide or Bt treated tef than unsprayed one. Karate and selecron provide effective control when sprayed on the first to third instar of tef red worm. Two times spraying, the first at the initial appearance of the insect and the second three weeks after the first spray, are more effective than spraying only once (AARC, 2002).

Table 10. Effect of different insecticides on larval population (number/m^2) of the tef red worm and grain yield of tef.

Insecticide	Rate (l ha^{-1} or kg ha^{-1})	Days after spraying		Yield ($kg\ ha^{-1}$)
		two	three	
Diazinon 60ec	1.00	4.4	2.5	1904.2
Fenitrothion 50ec	1.25	5.8	2.4	2083.4
Trichlorophon 50ec	2.00	7.5	3.6	1704.2
Endosulfan 35ec	2.00	3.4	2.8	1987.5
Cypermethrin 25ec	0.75	1.5	0.4	2154.1
Bacillus thuringiensis 16000 ITU/ mg wp	(700ga.i./ha)	22.3	10.9	1650.0
unsprayed check		50.0	49.2	1287.5

Source: Tadesse (1987b)

13.6. Tef Epilachna

Tef epilachna [*Chnootriba similis* (Thunberg) synonym: *Epilachna similis*] infests tef in various localities including Gimbi and Nedjo (IAR, 1983), Debre Zeit (DZARC, 1983), Welkite (1776 m a.s.l.), Yem (2274 m a.s.l.), Sokoru (1810 m a.s.l.), Jima (1775 m a.s.l.), and Sheka (1217 m a.s.l.) but severe damage was observed only at May-megelti (2558 m a.s.l.) (Yibrah *et al.*, 2006). The entire life cycle of tef epilachna is completed on tef leaves. Grass weeds such as *Cynodon dactylon* grown around the tef field harbor this insect and serve as source of infestation (DZARC, 1983).

Although infestation and level of injury by tef epilachna appears to be severe, the crop usually recovers rapidly, which makes devising control measure unfeasible.

Moreover, the pupae of the insect are heavily parasitized by unidentified Hymnopterous parasitoid, which may provide some level of control (DZARC, 1983). However, when heavy infestation of the insect is accompanied by a dry period, spraying carbaryl 85wp or trichlofon 95 at the rate suggested by the manufacturer and 100 to 300 liters of water per hectare effectively controls tef epilachna (Seyfu, 1993).

13.7. Termites

The Mendi termite, *Macrotermes subhyalinus* (Rambur) and the groundnut termite *Odontotermes anceps* (Sjostedt) are other tef pests in Wellega and Assosa area (Abraham, 1986). The damage due to Mendi termite reaches 5% and 12% at vegetative and heading stage, respectively; while that of groundnut termite, which attacks stacked tef, is about 30% (Abdurahman, 1992). According to this author, fields plowed by tractors had less termite problem than those plowed by oxen. Aldrin was recommended for use in tef fields (Abraham, 1986), although this insecticide was banned from use in agriculture.

13.8. Storage Pests of Tef

Tef is known to b e resistant to storage insect pests; hence, the damage under traditional storage condition is vir tually nil (McFarlane and Dobie, 1972; Ousman, 2007). However, artificial infestation with eight species of storage insects indicated that red flour beetle (*Tribolium castaneum*), warehouse moth (*Cadra cautella* synonym: *Ephestia cautella* (Walk)), and false black flour beetle (*T. destructor*) were able to reproduce in the stored tef grain (McFarlane and Dobie, 1972).

Recently, Tebkew and Getachew (2011) reported that the cigarette beetle (*Lasioderma serricorne)* and confused flour beetle (*T. confusum)* naturally infest stored tef. The insects feed on only the embryo of the seed; hence, they significantly reduce germination. Since both species do not reproduce in clean tef, storing clean tef is recommended.

Some farmers use tef as grain protectant especially in storing sorghum and chickpea (Blum and Abate, 2001). The study by Abraham and Basedow (2005) showed that by increasing the proportion of tef mixed with maize from 50 to 70 % (w/w) the mortality of maize weevil (*Sitophilus zeamais)* increased from 7% to 21% after eight days of infestation. Under farmers' storage condition, tef mixed with maize at the rate of 33% (w/w) significantly reduced the damage by *S. zeamaiz*. Thus, 54 weeks after storage, damaged grain for pure maize and tef – maize mixture was 75% and 44%, respectively.

13.9. Conclusions and the Way Forward

In tef, only few insect pests are considered as a major threat to tef productivity. The tef grasshopper is no more a major pest. Since the tef shoot fly has aggregated pattern of dispersion in a field, large number of samples should be taken in order to assess the level of infestation. Moreover, the negative yield losses in tef due to tef shoot fly in East Shewa and Southwest Shewa Zones, where rainfall is abundant and tef is fertilized, suggest that either tef over-compensates for shoot fly damages or the insecticides tested were ineffective in controlling tef shoot flies. The best period of controlling tef shoot fly using insecticide is before the adults lay their eggs and/or before the larvae bore and enter into the stem of tef. However, determining these critical periods is difficult. Even if the critical period of application is known, it requires repeated applications of insecticide within short period of time. Moreover, the tillering capacity and the high population density (per unit area) of tef might contribute to over-compensation in grain yield of tef after damage by shoot fly. The number of tef shoot fly species recorded at Alemaya is an indicative of the need for replicating the species identification effort in other tef growing regions. The pest status of tef black beetle is not yet determined, even though it was considered as a major pest of tef.

It has been indicated that the time at which Wello Bush Cricket (WBC) egg begin to hatch and the subsequent build up of population is dependent on the onset of rainfall. The association between early onset of rainfall and outbreak of WBC can be explained by increased egg survival (because of reduced desiccation) and food supply. The efficacies of insecticides applied for and traditional control methods practiced by farmers for WBC have not been scientifically evaluated. Therefore, determining the efficacy of traditional WBC control methods will help to decide whether it is necessary to apply insecticides or not.

The bulk of the research work on tef insect pest management was on insecticides. Other aspects of pest management such as cultural control (sowing date, seed rate, fertilizer rate, host plant resistance and the likes), natural enemies and ecological areas were not investigated. The available yield loss estimates due to different tef insect pests is very old and seems inflated. Although investment on insect pest management research is based on the economic importance of insect pests, engaging some full time researchers on tef insect pest research is necessary.

In general, future research on tef entomology needs to focus on the following main areas: i) periodic monitoring and surveying of tef pests in order to determine shifts in pest status; ii) determining the species composition of tef shoot fly; iii) undertaking nationwide yield loss assessment for sporadically occurring insect pests; iv) exploration of indigenous farmers' insect pest management practices and knowledge; v) continuing screening and testing of new insecticides for major tef insect pests; vi) identifying and assessing the effectiveness of natural enemies of insect pests of tef; vii) evaluating cultural control methods; and viii) developing integrated insect pest management options.

13.10. Abbreviations

a.s.l.: above sea level; AARC: Adet Agricultural Research Center; **DZARC**: Debre Zeit Agricultural Research Center; **IAR**: Institute of Agricultural Research; **RH**: relative humidity; **WBC**: Wello Bush Cricket

13.11. Acknowledgments

I acknowledge Dr Bayeh Mulatu of Holetta Agricultural Research Center for kindly providing his unpublished data.

13.12. References

AARC. 2002. Adet Agricultural Research Center. Summary of research achievements (1987-2001), Amhara Regional Agricultural Research Institute, Bahir Dar, Ethiopia.

Abdurahman Abdulahi. 1992. Termites of agricultural importance in western Ethiopia. *Ethiop. J. Agric*. Sci. 13:21-29.

Abraham Tadesse. 1986. Method and rate of aldrin application on tef to control termite infestation at Bako area. IAR Proceedings of the 18th National Crop Improvement Conference, 24-26 April 1986, Nazret, Ethiopia.

Abraham Tadesse and Adane Kassa. 1995. The influence of sowing date on the damage by tef fly (*Delia arambourgi* (Seguy): Anthomyiidae) on tef at Anno. *In*: Proceedings of the Third Annual Conference of the Crop Protection Society of Ethiopia, 18-19 May 1995, Addis Ababa, Ethiopia, pp 87-91.

Abraham Tadesse and Basedow Th. 2005. Laboratory and field studies on the effect of natural control measures against insect pests in stored maize in Ethiopia. *Journal of Plant Diseases and Protection* 112: 156-172.

Adane Tesfaye, Eshetu Belete and Getaw Tadesse. 2001. Participatory analysis of Welo bush cricket (*Decticoides brevipennis*) problem in Wag-Himra zone. *Pest Mgt. J. Eth*. 5:81-84.

Adugna Haile and Kemal Ali. 1986. A review of research on the control of insect pest of small cereals in Ethiopia. *In*: Tsedeke Abate (ed). A Review of Protection Research in Ethiopia. 4-7 February, 1985, Institute of Agricultural Research, Addis Ababa, Ethiopia, pp 57-75.

Bayeh Mulatu, Biruk Wubshet, Gezahegne Getaneh and Belay Eshetu. 2009. The significance of tef shoot flies on tef and their control in western and southwestern zones of Shoa, central Ethiopia. Paper Presented at the 16th Annual Conference of Plant Protection Society of Ethiopia. August 13-14, 2009, Addis Ababa, Ethiopia.

Bayeh Mulatu, Mekasha Chichaybelu, Tafa Jobe, Tesfaye Belay, Yeshitela Merine, Asmare Dejen, Bayuh Belay, and Biruk Wubshet. 2008. Review of research outcomes on insect pests of economic importance to major small cereals. *In*: Abraham Tadesse (ed.) Increasing Crop Production through Improved Plant Protection Vol. 1. Proceedings of the 14th Annual Conference of the Plant Protection Society of Ethiopia (PPSE), 19-22 December 2006, Addis Ababa, Ethiopia, pp 325-374.

Bayeh Mulatu. 2004. Estimates of yield losses caused by major insect pests of main crops grown in north Wollo and Wag Himra Zones of the Amhara Regional State. Save the Children- UK/ Ethiopia. pp. 44.

Bayeh Mulatu and Tsedeke Abate. 1996. Survey results on the Wollo Bush Cricket (*Decticoides brevipennis* Ragge, Orthoptera: Tettigoniidae). Proceedings of the Third Annual Conference of the Crop Protection Society of Ethiopia, 18-19 May 1995, Addis Ababa.

Blum A and Abate Bekele. 2001. Ethiopian farmers' practice of on-farm grain storage. *Trop. Sci.* 41:23-30.

Corbeels, M., Abebe Shiferaw and Mitiku Haile. 2000. Farmers' knowledge of soil fertility and local management strategies in Tigray, Ethiopia. Managing Africa's Soils No. 10.

DZARC. 1983. Debre Zeit Agricultural Research Center . Crop Protection Annual Research Report for the Period 1977-1983. Addis Ababa University, Ethiopia.

DZARC. 1988. Debre Zeit Agricultural Research Center. Annual Research Report for the Period 1987/88. Debre Zeit, Ethiopia.

DZARC. 1989. Debre Zeit Agricultural Research Center. Annual Research report for the period 1988/89. Debre Zeit, Ethiopa.

DZARC. 1990. Debre Zeit Agricultural Research Center. Annual Research report for the period 1989/90. Debre Zeit, Ethiopia.

DZARC. 1991. Debre Zeit Agricultural Research Center. Annual Research report for the period 1990/91. Debre Zeit, Ethiopia.

DZARC. 1994. Debre Zeit Agricultural Research Center. Annual Research report for the period 1991/92. Debre Zeit, Ethiopia.

DZARC. 1998. Debre Zeit Agricultural Research Center. Annual Research report for the period 1995/96. Debre Zeit, Ethiopia.

DZARC. 2002. Debre Zeit Agricultural Research Center. Annual Research report for the period 2000/2001. Debre Zeit, Ethiopia.

DZARC. 2003. Debre Zeit Agricultural Research Center. Annual Research report for the period 2002/2003. Debre Zeit, Ethiopia.

Getachew Belay, Hailu Tefera, Birhanu Tadesse, Gizaw Metaferia, Daniel Jarra and Tadelle Tadesse. 2006. Participatory variety selection in the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter]. Experimental Agriculture 42: 91–101.

Girma Tesfahun, Wondimu Bayu and Adane Tesfaye. 2000. Indigenous crop pest management technique in Welo. *Pest Mgt. J. Eth.* 4: 97-100.

IAR. 1976. Institute of Agricultural Research. Annual Report –April 1973 to March 1974.

IAR. 1977. Institute of Agricultural Research. Results of the national crop trials and others for the period of 1975. National Crop Improvement Committee, Addis Ababa, Ethiopia.

IAR 1981. Institute of Agricultural Research. Pests of tef. pp. 185-186. In 13th National Crop Improvement Conference, Addis Ababa, Ethiopia.

IAR. 1983. Institute of Agricultural Research. Crop Protection Department Progress Report for the Period 1978/79, Addis Ababa, Ethiopia.

Kravtchenko VD. 1992. Imago activity rhythms of some pest species of Noctuidae in Ethiopia (Insecta: Lepidoptera). Tropical Pest Management 38: 75-76

McFarlane JA and Dobie P. 1972. The susceptibility of T'ef (*Eragrostis abyssinica* Schrad) to infestation by some insect pest of stored grain. *J. Stored Prod. Res.* 8:177-182.

Mekasha Chichaybelu, Tebkew Damte and Tadesse Gebremedhin. 2001. Entomological research in tef. *In*: HailuTefera, Getachew Belay and Sorrells M (eds). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia pp 223-235.

Ousman Srur Ousman. 2007. Effectiveness of agricultural development training programs. The case of tef and livestock farmers of Alaba Woreda, Southern Ethiopia. MSc Thesis, Haramaya University.

Seyfu Ketema. 1993. Tef (*Eragrostis tef*): breeding, genetic resource, agronomy, utilization and role in Ethiopian agriculture. Institute of Agricultural Research, Addis Ababa, Ethiopia.

Sileshi Gudeta. 1994. Management of the sorghum shoot fly, *Atherigonia soccata* Randani (Diptera: Muscidae) in the eastern Hararghe region. MSc Thesis, Alemaya University of Agriculture, Dire Dawa, Ethiopia

Sileshi Gudeta. 1997. Biology of the tef shootfly, *Atherigona hyalinipennis* van Emden in eastern Ethiopia. *Insect Sci. Applic.* 17: 349-355.

Stretch C., Tekleab Kebreab and Edwards SB. 1980. The biology and control of the Welo bush cricket, *Decticoides brevipennis* Ragge (Orthoptera: Tettigoniidae), a pest of cereals in Ethiopia. *SINET: Ethiop. J. Sci.* 3: 21-36.

Tadesse G/Medhin and Kemal Ali. 1984. Black tef beetle, *Erlangerius niger* (Weise) and its control. *Committee of the Ethiopian Entomologist* 4(2):18-22.

Tadesse G/Medhin and Matthews GA. 1986. The Biology of red tef worm, *Mentaxya ignicollis* (Walker) (Lepidoptera: Noctuidae). *Ethiop. J. Agric. Sci.* 8: 103-115.

Tadesse G/Medhin. 1987a. Red tef worm, *Mentaxya ignicollis* (Walker), a pest of tef. *Committee of the Ethiopian Entomologist* 1:4-8.

Tadesse G/Medhin. 1987b. The control of red tef worm, *Mentaxya ignicollis* (Walker) (Lepidoptera: Noctuidae) in Ethiopia. *Tropical Pest Management* 33: 170-172.

Tareke Berhe. 1972. Insecticide trial on tef. Proceedings of Annual Research Seminar, 22 to 24 Sept. 1971. Addis Ababa, Ethiopia.

Tesfaye Belay and Zenebe Woldu. 1998. Barley fly incidence on tef in Tigray. *In*: Beyene Seboka and Abera Deressa (eds). Agricultural research and technology transfer attempts and achievements in north Ethiopia. Proceedings of the Fourth Technology Generation, Transfer, and Gap Analysis Workshop, 18-21 March 1997, Bahir Dar, Ethiopia, pp 173-179.

Tebkew Damte and Getachew Belay. 2011. New record of insect pest infesting stored tef (*Eragrostis tef* (Zucc.) Trotter) grains. *Ethiopian Journal of Crop Science* 2: 109-113.

Tibebu Habtewold and Landin J. 1992. Composition and structure of Orthopteran faunas in cereal crops in Ethiopia. *Bulletin of Entomological Research* 82: 29-39.

Tibebu Habtewold, Landin L, Wennergen U and Bergman KO. 1995. Life table for the tef grasshopper, *Aiolopus longicornis*, under laboratory conditions and demographic effects of the pathogen *Nosema locustae*. *Biological Control* 5: 597-502.

Tibebu Habtewold. 1999. Seasonal abundance and breeding habits of *Aiolopus longicornis* Sjostedt (Orthoptera: Acrididae) in cereal crops in central Ethiopia. *Pest Mgt. J. Eth.* 3:1-12.

Yibrah Beyene, Hofsvang T, Ferdu Azerefegne and Berg T. 2006. Geographical distribution, population density and host plants of tef epilachna, *Chnootriba similis* (Coleoptera: Coccinellidae) in Ethiopia. *International Journal of Tropical Insect Science* 26:183-189.

14. Pathological Research in Tef

Ayele Badebo
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O.Box 32, Debre Zeit, Ethiopia. Email: ayele88@yahoo.com

This paper gives an overview of the pathological research made on tef after the first comprehensive reviews of research on tef made in 2001. Since then, only limited efforts were made to develop management methods for tef diseases and that was particularly for tef rust (Uromyces eragrostidis). In most cases, applying fungicides like propiconazole (Tilt® 250 EC or Bumper® 250 EC) and triadimefon (Bayleton® 25 WP or Nobel® 25 WP) against tef rust did not result in significant yield saving. Early planting of tef exposes the crop to relatively high tef rust, but early planted tef gave greater grain yield than late planted one. Several tef accessions were tested for resistance to tef rust and head smudge (Helminthosporium miyakei), but resistant accessions were not found. Tef rust survives and reproduces on wild relatives of tef and other grass species.

Key words: tef diseases, rust, *Uromyces eragrostidis,* head smudge, *Helminthosporium miyakei,* control measures

14.1. Introduction

Tef is a cereal crop primarily produced and used as human food in Ethiopia. In the past one decade (2000/01 to 2009/10) area coverage under and yield of tef increased at an annual average rate of 3.5% and 5.4%, respectively. Thus, in 2009/10 cropping season more than 2.5 million hectares of land was sown to tef, and this accounted 28% of the total area covered by cereals (CSA, 2010). Although the crop is dominantly cultivated as sole crop, it is also grown as an intercrop or mixed crop, relay crop or in rotation with several types of crops (Fufa *et al.*, 2001; Walelign, 2004). The crop is also grown both in *Belg* (short rainy season) and *Meher* (long rainy season). Despite the wide area coverage, the various cropping system and agro-ecologies where tef grows, it suffers less from epidemic damages from diseases and insect pests (Kebebew *et al.*, 2011).

14.2. Major Diseases and Geographical Distribution

The numbers of diseases recorded on tef are many. However, the majority of these diseases are merely on the record list. Among the diseases, tef rust (*Uromyces eragrostidis*), head smudge (*Helminthosporium miyakei*), damping-off (*Drechslera spp*) and helminthosporium leaf spot (*Helminthosporium spp)* are occasionally important (Sewalem *et al*., 2001; Ayele *et al*., 2008).

14.3. Research on Tef Disease Management

14.3.1. Fungicide against tef rust (Uromyces eragrostidis)

Using the tef variety Asgori (DZ-01-99), the efficacy of *propiconazole* (Tilt®250 EC or Bumper®250 EC) and *triadimefon* (Bayleton® 25 WP or Noble® 25WP) was evaluated for controlling tef rust at Debre Zeit (DZARC, 2002; Woubit and Yeshi, 2005; Ayele *et al*., 2008). The level of rust incidence on *propiconazole* treated tef was significantly lower than the one treated with *triadimefon*. Although it was not statistically significant, reduced rust infection was coupled with more grain yield production. In another experiment, however, agronomic traits of tef were not affected by tef rust; rather only crude protein content of the grain was affected (DZARC, 2002, 2003; Ayele *et al*., 2008). Thus, fungicide sprayed tef had the highest crude protein content than unsprayed tef.

14.3.2. Effect of sowing date on tef rust

At Debre Zeit, planting tef between the third week of July and first week of August exposes tef to relatively higher tef rust pressure than planting during mid-August (DZARC, 2002). However, in terms of grain yield earlier planted tef out yields late planted ones. Since yield is the ultimate measure of the effectiveness of a control measure, early planting is recommended to avoid yield penalty. Sowing early maturing tef varieties in the third week of July and first week of August will enable them to evade tef rust infection (Table 1) (Woubit and Yeshi, 2005).

14.3.3. Tef resistance to tef rust

About 2000 tef accessions and 5000 mutants developed by radiating the tef variety Magna (or DZ-01-196) with 700 gy gamma-ray were evaluated for resistance to tef rust at Debre Zeit Agricultural Research Center (DZARC, 2002; Woubit and Yeshi, 2005). In this evaluation, complete resistance to tef rust was not found. Moreover, the majority of the accessions and all mutant lines were susceptible to tef rust (had large uredia without chlorosis). However, there were quantitative differences among genotypes, and 22 tef genotypes exhibited relatively lower rust severity when compared to the rest. In 2007, 361 core tef germplasms obtained from the tef breeding program of Debre Zeit Agricultural Research Center were tested against tef leaf rust under field conditions at Debre Zeit (Ayele *et al.*, unpublished), and none of the entries showed complete resistance (Fig. 1). Out of these, 36 entries were evaluated further after raising them in pots and transplanted to the field. In general, rust severity showed increasing trend when tef is grown under optimum conditions (space planting), and only six entries showed severity below 30%. The highest rust severity was noted on Kaye*y Muri* (80S) followed by Magna (DZ-01-196, 60S). This result indicated that tef rust could be economically important under optimum management conditions.

Table 1. The severity of tef rust and yield of three tef varieties under different maturity classes at Debre Zeit.

Tef variety		Rust Score (Coefficient of infection)	Seed yield (kg ha^{-1})
Name	Maturity group		
Tsedey (DZ-Cr-37)	early	45.4	1071.2
Magna (DZ-01-196)	intermediate	52.3	885.0
Asgori (DZ-01-99)	late	47.5	959.2
LSD (1%)		4.7	92.7

Source: DZARC (2002)

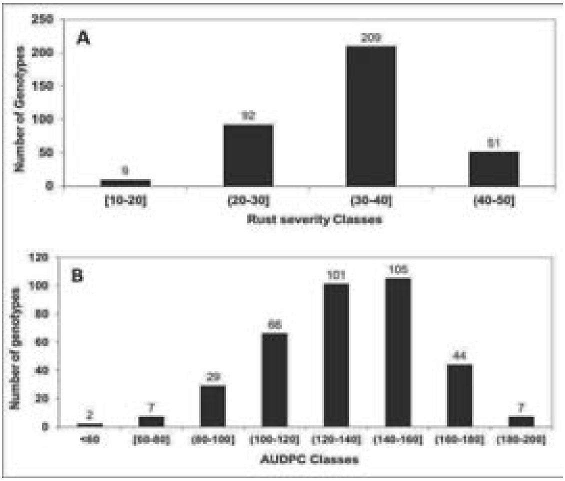

Fig. 1. The distribution of tef genotypes under different rust (A) severity classes, and (B) area under disease progress curve (AUDPC) classes at Debre Zeit in the year 2007.

The absence of complete resistance in tef to tef rust could be due to the co-evolution of the host and the pathogen. Since tef is a crop species native to Ethiopia, the major genes might have gradually been depleted through selection and probably tef varieties with minor genes (residual resistance) co-existed with the pathogen. It is interesting to raise a question that "if tef is susceptible to tef rust as revealed in many field screenings, why has the disease not reached epidemic level in tef fields under natural infection?" One assumption is that tef resistance to rust is conferred by poly-genes (Kebebew *et al.*, 2011), which is more durable than resistance conferred by mono- or oligo- genes. The second assumption is that the screening methodology followed to screen tef accessions to rust disease is unable to detect subtle differences among the test entries.

Tef accessions were also evaluated for head smudge resistance at Bako. As in the case of tef rust, complete resistance to head smudge was not found in the tested tef accessions (Ayele *et al.*, 2008). The lowest incidence of head smudge was recorded on a local tef cultivar Ijaji white.

14.3.4. Host range of tef rust

Wild relatives of tef, cultivated cereal crops, forage grasses and grass weeds were evaluated under glasshouse condition to determine if some of these plant species are hosts of tef rust (DZARC, 2002; Sewalem, 2004). *Eragrostis curvula,* among the wild relatives of tef, and wheat, sorghum and barley, among the tested cultivated cereal crops, were non-host for tef rust (Table 2). On the other hand, the perennial sedge, *Cynodon dactylon* was infected by tef rust, and because of its wider geographical distribution and abundance *C. dactylon* might serve as reservoir of this disease during dry seasons (Sewalem, 2004; Ayele *et al.*, 2008).

14.4. The Way Forward

Tef is reported to be less affected by diseases under the current farmers' practices in Ethiopia; however, diseases like tef rust and head smudge are considered to be relatively important. The importance of tef rust might increase with change of agronomic practices such as row planting. Since there was no complete resistance against the two diseases, emphasis on tef disease research should be given to integrated disease management (IDM) where two or more of the control measures could be integrated for sustainable disease management.

Table 2. Reaction of different grass species to tef rust.

Species	Response to tef rust*	Species	Response to tef rust*
Andropogon spp.	-	*E. octurtiana*	+
Avena sativa	-	*E. papposa*	+
Bracheria eruciformis	-	*E. patens*	+
Chloris gayana	-	*E. pilosa*	+
Cynodon dactylon	+	*E. shimbri*	+
Dinebra retroflexa	-	*E. sputehinephi*	+
Eleusine spp.	-	*E. unitoides*	+
Eragrostis banyodes	+	*E. utabchedecity*	+
E. burrelien	+	*Hordeum vulgare*	-
E. cilianensis	+	*Hyperhenia spp*	-
E. ciliaris	+	*Lolium temulentum*	-
E. curvula	-	Murei	+
E. dakota	+	*Pennisetum unisetum*	-
E. dielsa	+	*Sorghum bicolor*	-
E. kiwains	+	*Sorghum halepense*	-
E. mexicana	+	*Triticum durum*	-
E. minor	+		

* + = infection occurred, - = no infection. Source: DZARC (2002)

14.5. Abbreviations

AUDPC: area under disease progress curve; **CSA**: Central Statistical Agency; **DZARC**: Debre Zeit Agricultural Research Centre; **IDM**: Integrated Disease Management; **RTR**: Response to Tef Rust.

14.6. References

Ayele Badebo, Eshetu Bekele, Berhanu Bekele, Bekele Hundie, Melaku Degefu, Asnaketch Tekalign, Melkamu Ayalew, Amare Ayalew, Kiros Meles and Fekede Abebe. 2008. Review of two decades of research on diseases of small cereals crops.. *In*: Abraham Tadesse (ed.) Increasing Crop Production through Improved Plant Protection Vol. 1. Proceedings of the 14th Annual Conference of the Plant Protection Society of Ethiopia (PPSE), 19-22 December 2006, Addis Ababa, Ethiopia, pp. 375-429.

Central Statistical Agency (CSA). 2010. National Statistical Abstract. Accessed on internet at http://www.csa.gov.et/

DZARC. 2002. Debre Zeit Agricultural Research Center. Annual Research report for the period 2000/2001. Debre Zeit, Ethiopia.

DZARC (Debre Zeit Agricultural Research Center). 2003. Debre Zeit Agricultural Research

Fufa Hundera, Tesfa Bogale, Hailu Tefera, Kebebew Assefa, Tiruneh Kefyalew, Aberra Debelo and Seyfu Ketema. 2001. Agronomy research in tef. In: Hailu Tefera, Getachew Belay and Sorrells M (eds). Narrowing the Rift. Tef Research and Development. Proceedings of the International

Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia, pp. 167-176.

Kebebew Assefa, Yu, JK, Zeid M, Getachew Belay, Hailu Tefera and Sorrells ME. 2011. Breeding tef (*Eragrostis tef* (Zucc.) Trotter): conventional and molecular approaches. Plant Breeding 130: 1-9.

Sewalem Amogne, Zerihun Kassay, and Eshetu Bekele. 2001. Tef pathology research in Ethiopia. *In*: Hailu Tefera, Getachew Belay and Sorrells M (eds). Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia, pp. 215-222.

Sewalem Amogne. 2004. Host range of tef rust (*Uromyces eragrostidis*). Tropical Science 44: 177-179.

Walelign Worku. 2004. Maize-tef relay intercropping as affected by maize planting pattern and leaf removal in southern Ethiopia. African Crop Science Journal 12: 359-367.

Woubit Dawit and Yeshi Adnew. 2005. The study of fungicide application and sowing date, resistance, and maturity of *Eragrostis tef* for the management of teff rust (*Uromyces eragrostidis*). Canadian Journal of Plant Pathology 27: 521-527.

15. Weed Research in Tef

Kassahun Zewdie[1*] and Tebkew Damte[2]
[1]Ethiopian Institute of Agricultural Research (EIAR), Holetta Agricultural Research Center P. O. Box 2003, Addis Ababa; [2]EIAR, Debre Zeit Agricultural Research Center, P. O. Box 32, Ethiopia. *Corresponding author: kassahunzewdie@yahoo.com

Studies on loss assessment, critical period of weed competition and control methods including cultural, chemical and integrated weed management were made under rain-fed conditions. The critical period of weed competition for tef is three to four and six to seven weeks after crop emergence. A single application of post-emergence herbicides Starane M 64% EC, Derby 175 SC, Mustang, and 2, 4-D Amine Salt 72% SL 25-30 days after crop emergence was effective in controlling the dominant broad-leaf weeds, and resulted in a significant yield increase followed by twice hand weeding and standard check with a single 2, 4-D Amine Salt 72% SL application. To maximize the tef yield, one supplementary hand weeding in addition to the post-emergence herbicides may be needed depending on the weed flora and effectiveness of the herbicides. Integrated management of field bind weed (Convolvulus arvensis) i.e., five times plowing + 2,4-D application and continuous removal as it emerges until crop harvest substantially reduced the intensity of the target weed and increased the grain yield and biomass of tef.

Key words: tef , weeds, tillage, herbicides, control measures

15.1. Introduction

Effective weed management is one of many critical components of successful tef production. Weed control method in tef production remains to be one of the most expensive, time and energy consuming, and the least successful means of increasing yield. Weed control methods are limited by the level of technological advancement, the prevailing cropping systems, the climate and soil conditions, and by the resource base of small-scale farmers. Generally, the use of herbicides and information on the response of tef to various herbicides is sc anty. Thus, hand weeding and cultural methods of weed control remain the most common methods in dealing with weeds (Kassahun and Rungsit, 2005).

Tef is poor competitor with weeds; severe weed infestations particularly at its early growing stage reduce tef yields by at least 65% if left uncontrolled (Berhanu and Tessema, 1984; Kassahun and Likyelesh, 2001). Moreover, weeds reduce grain quality, harbor insect pests and make harvesting operation difficult. Nationwide estimates of the labor required for hand weeding of tef range from 40-138 man-days per hectare (Franzel *et al.,* 1989). The weed research conducted on tef before 2000 was reviewed by Rezene and Zerihun (2001) and published in the Proceedings of the First International Workshop on Tef Genetics and Improvement. The purpose of the present review is, therefore, to show the progresses made on different aspects of weed research on tef in Ethiopia since then. The review focuses on surveys on weed distribution and abundance, loss assessment due to weeds, critical period of weed competition, and a variety of control measures.

15.2. Composition and Geographical Distribution of Weeds in Tef

More than 39 weed species representing 18 families were collected, identified and documented from diverse tef growing areas in Ethiopia. In these species all groups of weeds including broad-leaf weeds, grassy weeds, parasitic weeds and sedges were present. Table 1 shows the list of these weeds and their relative abundance.

The dominant weeds are: *Argemone ochroleuca, Commelina benghalensis, Convolvulus arvensis, Echinocloa colona, Echinocloa crusgalli, Setaria pumila, Setaria verticillata, Oxalis corniculata, Parthenium hysterophorous, Plantago major, Polygonum nepalense, Raphanus raphanistrum, and Cyperus* spp.

15.3. Weed Competition in Tef

The competitive effect of nutsedge on tef was studied at Debre Zeit, Alem Tena and Tullu Bolo using three seed rates of tef (10, 30 and 50 kg ha^{-1}), three rates of phosphorus fertilizer (0, 10.5 and 21 kg ha^{-1}), three rates of nitrogen fertilizer (0, 10 and 20 kg ha^{-1}), and three densities of nutsedge (0, 30 and 60 plants m^{-2}) (Ahmed, 2004). The tef plant was aggressive competitor under low soil fertility, high crop density and low weed density conditions. Reduced tiller number and increased plant height are the mechanisms by which tef surpasses the competitive effect of nutsedge. On the other hand, under low crop density, high soil fertility and high weed density conditions nutsedge had more competitive advantage over tef. In another study, Ahmed (2004) and Juraimi *et al.* (2009) found that tef sown at Alem Tena in the second week of July was more competitive than tef sown one and two weeks later.

Table 1. Weeds growing in tef in Ethiopia.

Type of weed		Abundance
Family	Botanical name	
Asteracea	*Parthenium hysterophorous L*	*xx*
Chenopodiaceae	*Chenopodium album* L.	*x*
	Chenopodium ambrosoides L.	*x*
Commelinaceae	*Commelina Africana*	*x*
	Commelina benghalensis L.	*xxx*
Caryophyllaceae	*Corrigiola corniculata*	*xx*
Convolvulaceae	*Convolvulus arvensis*	*xxx*
Euphorbiaceae	*Euphorbia heterophylla*	*x*
	Euphorbia indica Lam.	*x*
Fabacea	*Prosopis juliflora*	*x*
Juncaceae	*Janicus* spp	*xx*
Nyctaginaceae	*Boerhavia coccinea*	*x*
	Boerhavia erecta L	*xx*
	Borehavia repens	*x*
Oxalidaceae	*Oxalis corniculata* L.	*xxx*
	Oxalis stricta	*xx*
Papaveraceae	*Argemone ochroleuca*	*xxx*
Plantignaceae	*Plantago major L.*	*xxx*
Poaceae	*Cenchrus ciliaris* L.	*xx*
	Diplachne caudata	*x*
	Echinocloa colona L.	*xxx*
	Echinocloa crusgalli	*xxx*
	Eragrostis aethopica	*xx*
	Eriochloa fatmensis	*x*
	Lolium temulentum	*x*
	Panicum repens	*xx*
	Pennisetum spp.	*x*
	Poa annua L.	*x*
	Setaria pumila (L.)	*xxx*
	Setaria verticillata (L.)	*xxx*
	Sorghum arundinaceum	*x*
Polygonaceae	*Polygonum aviculare* L.	*xx*
	Polygonum convolvulus L.	*x*
	Rumex abyssinicus L.	*xx*
Rubiacea	*Galium aparine* L.	*xx*
Solanaceae	*Solanum incanum*	*x*
Zygophyllaceae	*Tribulus terrestris*	*xx*

Note: xxx = major weed, xx= important weed, x=commonly occurring weed.

Sources: Compiled from Ahmed and Mohammed (1988), Chris (1989), Kassahun (1996, 1999); Kassahun et al. (1999, 2009); Mesfin (1989), Melaku (1988), Rezene (1991), and Taye and Yohannes (1999).

15.4. Control Measures

15.4.1. Effect of tillage on tef weeds

Tef is sown on fine seedbed prepared by plowing the field two to six times depending on the density of weed in the field (Fufa *et al.,* 2001; Adamu and Kemelew, 2011). In southern Tigray, the biomass of weed from the untilled plot was about three-fold of the amount obtained from the conventionally plowed plot (Tigist *et al.,* 2010). Similarly, the weed density in Adet area was significantly high in the conservation tillage with single plowing and pre-sowing spraying of non-selective herbicide than in the seven-time plowed plot (Alemayehu *et al.,* 2008) (Table 2). Although plots with conventional tillage gave 23% more tef grain yield than the conservation plot, seven times plowing was not economical. However, three-time plowings and one-time weeding at tillering stage were economical for small-scale tef production.

Table 2. Effect of plowing frequency on weed density at tillering (Number m^{-2}) of tef in Adet area.

Weed species	Plowing frequency			
	Seven times	Five times	Three times	One time + roundup
Corrigiola capensis	164	191	186	252
Polygonum nepalence	198	181	171	222
Commelina sabulata	69	68	66	79
Cyperus esculentus	58	68	84	31
Setaria pumila	50	56	65	31
Erucastrum arabicum	21	33	29	32
Guizotia scabra	23	16	15	22
Other minor weeds	102	119	104	133
Total weed number	685	732	720	802
Grain yield (kg ha^{-1})	1562	1415	1344	1272

Source: Alemayehu *et al.* (2008)

On the other hand, both the density and biomass of weed in the Rift-Valley were higher on conventionally tilled (four times plowing + two hand weeding) than on conservation (pre-sowing glyphosate + post-emergence 2,4-D) plots (Worku and Chinawong, 2005). The production of tef was also more profitable under the conservation tillage compared to the conventional plot (Table 3). However, the exact time of plowing was not indicated, and the year with poor tef yield was excluded from the economic analysis; hence, the profits were exaggerated. According to Teklu *et al.* (2006) and Juraimi *et al.* (2009) tef does not need fine seedbed but needs effective pre-sowing weed control method. The importance of effective weed control prior to tef sowing is well known in other countries such as Australia (Lacey, 2005).

Table 3. Effect of tillage method on tef yield and profitability of tef production. Values were the average of four years.

Tillage Systems	Treatment combination[a]	Grain yield (kg/ha)[b]	Straw yield (kg/ha)[c]	Gross return (Birr/ha)	Productio n cost (Birr/ha)	Net return (Birr/ha)
Conservation Tillage	No-tillage (3.0 l ha^{-1} glyphosate + 1.0 l ha^{-1} 2,4-D + 1 time HW)	1260	4030	3437	2568	869
	No-tillage (3.0 l ha^{-1} glyphosate + 1.0 l ha^{-1} 2,4-D)	1190	4230	3263	2539	724
	No-tillage (3.0 l ha^{-1} glyphosate + 1 time HW)	1010	4290	2798	2478	320
Conventional Tillage	Tilled (four times plowing + 1.0 l ha^{-1} 2,4-D + 1 time HW)	1060	4190	2924	2664	259
	Tilled (four times plowing + two times HW)	1000	4260	2770	2576	194

Source: Worku and Chinawong (2005). [a]HW= hand weeding; [b]price of grain = 2.6 Birr/kg; [c]price of straw = 0.04 Birr/kg.

15.4.2. Hand weeding

In four districts of Arsi zone (Asasa, Bekoji, Iteya, and Robe) only 30% of the farmers hand weed their tef field twice in which the first hand weeding is done by 59% of the farmers in August and by 27% of the farmers in September (Setotaw *et al.*, 2000). About 60% of the farmers perform the second hand weeding in September. In most areas, this period overlaps with weeding time for early sown crops and planting time for late sown crops. The estimated time for hand weeding of tef on Vertisols ranges from 32 to 40 working days ha^{-1} (Rezene, 2002). Weeding three and six-weeks after crop emergence effectively controls broad leaved and grass weeds (DZARC, 2004). According to Rezene (2002), the tef yield advantages from two hand weedings at three and six weeks after crop emergence (WACE) were 24% over single spraying with 2,4-D at 1 l ha^{-1}, 13% over single hand-weeding 3-weeks after crop emergence, and 10% over single spraying with 2,4-D at 1 l ha^{-1} supplemented with hand weeding at 6 weeks after crop emergence. Hand weeding 3-weeks after crop emergence was not effective because it is difficult to identify tef plants from grass weeds at this early stage. Two times hand weeding (at tillering and stem elongation) were more effective in suppressing weeds in Adet area than a single hand weeding at tillering or stem elongation (Alemayehu *et al.,* 2008). However, single hand weeding at tillering stage gave higher monetary return than un-weeded or twice hand weeded tef. In some areas where tef is intercropped either with sesame or safflower, application of 2,4-D kills the companion crop (Adamu and Kemelew, 2011). In Arsi zone, one-third of tef farmers apply 2,4-D in August or September at the rate of 0.33 to 0.63 l ha^{-1} (Setotaw *et al.,* 2000).

15.4.3. Chemical weed control

Field experiments were conducted in the central highlands of Ethiopia to evaluate the effectiveness of selected herbicides against dominant broad-leaf weeds which include *Raphanus raphanistrum, Polygonium nepalense, Guizotia scabra* and *Galium aparine*. The results revealed that visual assessment of general and individual weed control on Starane M, Derby and Mustang showed similar score and effective weed control (Table 4). Derby showed better performance in controlling wild radish (*Raphanus raphanistrum)* than the other herbicides and resulted in a significant tef yield increase followed by twice hand weeding and the standard herbicide 2,4-D. Hence, due to high efficacy and selectivity in controlling weeds and increase in tef seed yield, Derby is a promising herbicide that could replace 2,4-D, the current standard check.

Table 4. Effect of different herbicides and hand weeding on general weed control score (GWCS), and shoot biomass, plant height and seed yield of tef.

Treatment			GWCS[1]			Plant height (cm)	shoot biomass (kg ha^{-1})	Seed yield (kg ha^{-1})
Trade name & Formulation	Common name	Amount	1st	2nd	3rd			
rane M 64% EC	*Fluroxypyr +MCPA*	1.0 l ha^{-1}	5.0	2.5	1.5	102.7	6100.0b	1575.5bc[1]
Derby 175 SC	*Flurasulam +Flumetsulam*	80 ml ha^{-1}	5.0	1.1	1.0	101.0	6445.3c	1845.9ab
Mustang	*(XDE 6.25 G/L +2,4-D 300GL)*	0.75 l ha^{-1}	5.0	2.6	1.5	101.0	6100.0b	1534.3bc
2,4-D amine 720 AE	*Dichlopheno xy acetic acid*	1.0 l ha^{-1}	5.0	2.1	1.2	100.3	6233.3b	1469.6c
Twice hand weeding	-	-	5.0	2.5	1.8	103.0	6833.3a	1939.9a
Weedy check	-	-	5.0	5.0	5.0	101.0	2966.7c	418.9d
CV%			18.34	16.86	20.31	8.1	22.8	15.7

Source: EIAR, 2009. Holetta Research Center Progress Report.

1= GWCS is with 1 to 5 scales where 1 refers to weeds effectively controlled while 5 refers to no effect on weed control. For shoot biomass means followed by the same letter within the same column are not significantly different at $P_{<}$ 0.05.

15.5. Conclusions and the Way Forward

Since most studies carried out so far on tef weed management were not conclusive, detailed investigations need to be done in the future. For instance, it was claimed that tef has smothering effect on the invasive weed *Parthenium* which needs further proof.

In general, future weed research in tef should focus on the following points:

i) To monitor and survey regularly tef weeds to determine shifts in weed status;
ii) To perform a nationwide yield-loss studies before embarking on control measures;
iii) To develop tef cultivars which have ability to compete with weeds;
iv) To devise effective control measures especially against grass weeds which cause substantial damages to tef productivity;
v) Targeted research should also be done on selected weed species in order to tackle noxious grass and broad-leaved weeds;
vi) Chemical and cultural control studies should be performed at different agro-ecologies with diverse cropping systems, and levels of infestation and distribution of weed species;
vii) To implement integrated weed management in tef including cultural, chemical and biological control measures using locally available and affordable resources;
viii) To determine the impurity of tef seeds with weed seeds;
ix) To explore indigenous weed management practices by farmers; and
x) To assign full-time researcher(s) at major tef growing areas as this needs further investigations.

15.6. Abbreviations

2, 4-D: 2,4-dichlorophenoxy acetic acid; **DZARC**: Debre Zeit Agricultural Research Center; **EC**: Emulsifiable concentrate; **EIAR**: Ethiopian Institute of Agricultural research; **EWSS**: Ethiopian Weed Science Society; **GWCS**: General Weed Control Score;**EWSC:** Ethiopian Weed Science Committee; **HW**: hand weeding; **MCPA**: 2-methyl-4-chlorophenoxyacetic acid; **SL**: Soluble liquid; **WACE**: weeks after crop emergence.

15.7. References

Adamu Molla and Kemelew Muhie. 2011. Tef (*Eragrostis tef*) based cropping systems in the hot to warm moist valleys of North Shewa, Ethiopia. Scientific Research and Essays 6: 1411-1416.

Ahmed Mohammed Sheif. 2004. Competition effect of purple nutsedge (*Cyperus rotundus* L) on growth and yield of tef (*Eragrostits tef* (Zucc) Trotter) in Ethiopia. PhD Dissertation, University Putra Malaysia, Selangor, Malaysia. 232pp.

Ahmed Sherif and Mohammed Gelma. 1988. *Orobanche* control research in Nura Era Horticulture Enterprise. *In:* Rezene Fessehaie and Chris Parker (eds.) Proceedings of the 2nd Ethiopian Weed Science Workshop. Addis Ababa, Ethiopia, pp. 56-63.

Alemayehu Assefa, Minale Liben, Tilahun Tadesse and Belsti Yeshalem. 2008. The effect of tillage frequency and weed control on yield of tef (*Eragrostis tef*) in Yilmana-Densa area, northwestern Ethiopia. East African Journal of Sciences 2: 35-40.

Berhanu Kinfe and Tessem Megenassa. 1984. Frequency of hand weeding on weed control and yield of tef (*Eragrostis tef*). Ethiopian. J. Agri. Sci. 6: 88-101.

Chris P. 1989. Identification of some groups of Ethiopian Weeds. *In:* Chris Parker and Rezene Fessehaie (eds.) Proceedings of the 6th Annual Meeting of the Ethiopian Weed Science Committee (EWSC). Addis Ababa, Ethiopia, pp. 25-35.

DZARC. 2004. Debre Zeit Agricultural Research Center. Annual Research Report for the Period 2003/2004. Debre Zeit, Ethiopia

EIAR. 2009. Holetta Research Center Progress Report for the Year 2008/2009.

Franzel, S., Mulugeta M., and Chilot Y. 1989. Small holder weed problem and weed control practices in Ethiopia: Information from case studies. In: problems and priorities in weed science in Ethiopia. Proceedings of the Ethiopian Weed Science Committee Workshop, 14-15 May 1987, Addis Abeba, Ethiopia. (PP. 45-51).

Fufa Hundera, Tesfa Bogale, Hailu Tefera, Kebebew Assefa, Tiruneh Kefyalew, Aberra Debelo and Seyfu Ketema. 2001. Agronomy research in tef. *In*: Hailu Tefera, Getachew Belay and Sorrells M (eds). Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia, pp 167-176.

Juraimi AS, Begum M, Sherif AM and Rajan A. 2009. Effects of sowing date and nutsedge removal time on plant growth and yield of tef [*Eragrostis tef* (Zucc.) Trotter]. African Journal of Biotechnology 8: 6162-6167.

Kassahun Zewdie and Likyelesh Gugsa. 2001. Agronomy research on some cereal crops on Vertisols in the Central Highlands of Ethiopia. *In*: Advances in Vertisols Management in Ethiopian highlands. Paulos Dubale, Asgelil Dibabe, Asfaw Zeleke, Gezahegn Ayele and Abebe Kirub (eds.) Proceedings of the International Symposium on Vertisols Management. Addis Abeba, Ethiopia, pp185-195.

Kassahun Zewdie and Rungsit Suwanketnikom 2005. Relative Influence of Tillage, Fertilizer, and Weed Management on Weed Associations In Wheat Cropping Systems of Ethiopian highlands. Kasetsart Journal, Natural Science Volume 39 No 4 PP. 569-580.

Kassahun Zewdie, Olani N and Tefera Asamenew. 1999. Evaluation of pre-emergence herbicides for the control of *Parthenium hysterophorus* in sorghum. *In*: Fasil Reda and Tanner DG (eds.), Bulletin of the Ethiopian Weed Science Society (EWSS), Arem 5:130-137, Addis Ababa, Ethiopia.

Kassahun Zewdie, Tadelle Amde and Woldeyesus Sinebo. 2009. Review of weed research in oil crops in Ethiopia Pp 339-354 *In:* Abrham Tadesse (ed.) In increasing crop production through improved plant protection. V. II, 14th Annual Conference of the Plant Protection Society of Ethiopia (PPSE), ISBN 978-99944-53-44-3.

Kassahun Zewdie. 1996. *Prosopis juliflora:* A highly problematic weed in Eastern Ethiopia. Newsletter of Ethiopian Weed Science Society vol. No. 2. Page 3.

Lacey T. 2005. *Eragrostis tef* as a specialized niche crop. Government of west Australia. Department of Agriculture. Farm note No. 42/2005.

Melaku Wale. 1988. Weeds of sorghum and tef in Raya-Kobo Awraja, Welo Region, pp. 31-33 *In:* Rezene Fessehaie (eds.), Proceedings of the 7th Annual Meeting of Ethiopian Weed Science Committee (EWSC). Addis Ababa, Ethiopia.

Mesfin Tadesse. 1989. Identification of some plant families with weedy members. *In:* Chris Parker and Rezene Fessehaie (eds.), Proceedings of the 6th Annual Meeting of the Ethiopian Weed Science Committee (EWSC). Addis Ababa, Ethiopia, pp 5-24.

Rezene Fessehaie and Zerihun Tadele. 2001. Weed research in tef. *In*: Hailu Tefera, Getachew Belay and Sorrells M (eds). Narrowing the Rift. Tef Research and Development. Proceedings of the "International Workshop on Tef Genetics and Improvement", 16-19 October 2000, Debre Zeit, Ethiopia, pp. 201-213.

Rezene Fessehaie. 1991. Weed Science Research on Noug, Linseed and Rapeseed in Ethiopia In: Oilseeds Research and Development in Ethiopia. 3-5 Dec., 1991, Addis Abeba, Ethiopia. PP. 136-148.

Rezene Fessehaie. 2002. Evaluation of weed control methods in tef on Vertisol at Ginchi watershed site. *In*: Gemechu Keneni, Yohanes Gojjam, Kiflu Bedane, Chilot Yirga and Asgelil Dibabe (eds.). Towards farmers' participatory research: attempts and achievements in the central highlands of Ethiopia. Proceedings of Client- Oriented Research Workshop, 16-18 October 2001, Holetta Agricultural Research Center, Holetta, Ethiopia, pp 240-245.

Setotaw Ferede, Verkuijl, Tanner DG and Takele Gebre. 2000. Optimizing fertilizer use in Ethiopia. Results of a baseline survey of fertilizer adoption in Arsi Zone, Sasakawa-Global 200, Addis Ababa, Ethiopia.

Taye Tessema and Yohannes Lema. 1999. Qualitative and quantitative determination of weeds in tef in West Shoa. *In*: Fasil Reda and Tanner DG (eds.), Bulletin of Ethiopian Weed Science Society (EWSS), Arem 5: 46-60, Addis Ababa, Ethiopia.

Teklu Erkossa, Stahr K and Gaiser T. 2006. Soil tillage and crop productivity on a Ve rtisol in Ethiopian highlands. Soil & Tillage Research 85: 200-211.

Tigist Oicha, Cornelis WM, Verplancke H, Nyssen J, Govaerts B, Mintesinot Behailu, Mitiku Haile and Deckers J. 2010. Short-term effects of conservation agriculture on Vertisols under tef (*Eragrostis tef* (Zucc.) Trotter) in the northern Ethiopian highlands. Soil & Tillage Research 106: 294–302.

Worku Burayu and Chinawong S. 2005. Conservation tillage - alternative systems of tef (*Eragrostis tef*) production for a semi-arid Central Rift Valley of Ethiopia. Kamphaengsaen Academic Journal 3: 1-10.

V. Food & Feed Values

16. Food Science and Human Nutrition Research

Geremew Bultosa[1†*] and Melaku Umeta[2]
[1]Department of Food Science and Postharvest Technology, Haramaya University, Box 138, Dire Dawa, Ethiopia; [2]Department of Biochemistry, School of Medicine, Addis Ababa University, Box 9086, Addis Ababa, Ethiopia; [†]Present address: Department of Food Science and Technology, Botswana College of Agriculture, Private Bag 0027, Gaborone, Botswana. *Corresponding author: Bultosageremew@yahoo.com

In the past, tef grain utilization as human food is highly confined to Ethiopia. Tef grain is used as whole flour mostly for processing injera (a staple food for the majority of Ethiopians). Tef grain food products had attracted global consumers due to: i) the current global trend towards healthy whole grain products consumption; ii) gluten-free nature especially for people with allergenic to wheat glutens; iii) pre- and pro-biotic potentials due to dietary fiber and fermentation by lactic acid bacteria and yeast, respectively; iv) very small starch granules (2-6 µm, useful as fat mimetic), shear tolerant, slow retrogradation nature, and digestible "A" types; and v) rich composition in desirable type proteins with well-balanced amino acids except low lysine levels similar to most other cereals. In general, tef grain products can be regarded as a good source of protein, calories, vitamins (particularly the B vitamins of thiamine and riboflavin), and minerals such as iron, calcium and zinc as compared to the common cereal grains. Lactic acid and volatile fatty acids (C_2 - C_6) are the major organic acids produced during the fermentation of tef thereby contributing to the good aroma and sour taste. Tef grain bears phytates which inhibit mineral bioavailability. However, processes like fermentation and baking reduce this factor and contribute to the development of desirable products as well as flavor. This review describes tef grain in reference to the end utilization, tef grain and its common food product constituents, functionalities of grain components, and other relevant topics on the quality of the tef grain food products.

Keywords: *Eragrostis tef*, gluten free, *injera*, nutrients, physicochemical, whole grain

16.1. Introduction

Tef [*Eragrostis tef* (Zucc.) Trotter] cultivation and utilization as human foods are highly confined to Ethiopia where it is believed to have been first domesticated sometime between 4000 to 1000 BC (Melak-Hail, 1966; Tadesse, 1969; Costanza *et al*., 1979; Seyfu, 2007). In Ethiopia, the grain is used as whole flour mostly for processing *injera* (or *caabitaa*, *budeena*, *tayeta), a* staple food for the majority of Ethiopians. *Injera* is a fermented, pancake-like, soft, sour, circular flatbread with eyes of honeycomb-like structure on the top and shiny smooth pale brown underneath. The period at which dough fermentation and baking for *injera* started is unknown (Stewart and Getachew, 1962; Tadesse, 1969). However, one can speculate similar period like that of other traditional fermented foods and beverages to match the transition from hunter-gather economies to the beginnings of settled agriculture (Wood, 2004). Currently, in addition to traditional foods and beverages, tef grain is processed for gluten free markets, in infant foods and various snack bars as whole grain supplement to the diet.

In this paper, a review on tef grain physicochemical properties, tef *injera* compositions, nutrition potential, tef grain components functionalities, latest trend in tef grain food and beverage products developments as human food, and the highlights on limitation on grain productivity and tef postharvest grain quality factors impact on tef grain product qualities are presented.

16.2. Physicochemical Properties of the Tef Grain

Tef grain is the smallest grain among cereals in the world and is oval in shape of grain length 1.7-0.9 mm of width 1.0-0.7 mm (Tadesse,, 1975). Geremew (2007) described this (mm) 1.30-0.51 length and 0.67-0.10 width for 13 tef grain varieties. Recently, by Kreitschitz *et al*. (2009) length and width (mm) for 3 tef varieties was reported 1.1-1.2 and 0.60-0.63, respectively. Selection for large grain size (i.e., plumb grain) is important in improving the handling and processing features, provided grain quality is not compromised particularly the *injera* making features. The grain color ranges from milky white to dark brown. The white color is the most preferred by consumers and fetches high price. Seed quality is measured mostly using the 1000-kernel weight (TKW) and hectoliter weight (HLW). The TKW for the improved tef varieties ranged from 0.19 to 0.42 g (Kebebew *et al*., 2001; Geremew, 2007; Tewodros,, 2011) while HLW for the popular tef variety called *Quncho* (DZ-Cr-387 RIL355) was 86.42 kghl^{-1}. In addition to genetic influence, the differences in TKW could be contributed by moisture differences in the grain (Zewdu and Solomon, 2007). Eventhough it is traditionally believed that high values of TKW and HLW (i.e., plumb grain) provide good quality *injera*, no systematic study was yet made to confirm these correlations.

16.3. Anatomical Structures and Composition of the Tef Grain

For the proper understanding of the nutritional value of cereal grains and the changes they undergo during processing for human consumption, it is important to consider the structure of the grain and its composition.

16.3.1. Structure of the tef grain

The seeds of tef are very light, with mean individual kernel mass of 0.62 ± 0.05 mg and 0.83 ± 0.02 mg for white- and brown-seeded varieties, respectively. The anatomy of tef kernel was studied by different workers using scanning electron microscopy (SEM), transmission electron microscopy (TEM) and light microscopy (LM) (Parker *et al.*, 1989; Kreitschitz *et al.*, 2009). The cross-sectional view of the seed is shown on Fig. 1. The outer layer, pericarp, is comparatively thin and forms the bran envelope which protects the seed (Parker *et al.*, 1989). In the inner surface of the pericarp, the mesocarp and endocarp are fused to appear as a single layer where some starch granules are also observed. The pericarp is formed by epidermal cells that bear slime layer rich in pectins (Kreitschitz *et al.*, 2009). The seed coat (testa) is present in the pericarp. The light microscopy study showed that a pigmented material was observed around the testa of the brown-seeded tef (Fig. 1b) and this layer is reported to bear tannins or polyphenolic compounds that give the seed a brown color (Parker *et al.*, 1989). In white-seeded tef, however, no pigmented material was observed. Review (Geremew and Taylor, 2004a) indicate that tef grain bears insignificant level of condensed tannins. The total amount of phenolics in tef grain were in the range 0.09-0.15 mg/100 g of which ferulic, vanellic, cinnamic, coumaric and protocatechuic acids are dominant (Dykes and Roony, 2006, 2007). Today, the antioxidant and various degenerative disease-suppressing activities of phenolics derived from consumption of whole grain are widely investigated. However, limited information is available on the antioxidant nature of the tef grain and its products (Dykes and Roony, 2006; (Tewodros, 2011). Recent study for the popular *Quncho* variety indicated that the total phenolics (mg/100 g) and the ferric-ion reducing antioxidant power (FRAP, µmol/g) were 34 and 97 for the grain, and 28 and 34 for *injera*, respectively (Tewodros, 2011).

Tef grain resembles sorghum and pearl millet by having some very small starch granules in the pericarp. This probably would facilitate breakage of the bran into pieces during milling since such influence is known in sorghum (Kebakile *et al.*, 2007). Adjacent to the testa is the aleurone layer—a single cell envelope rich in enzyme-type proteins and lipid bodies. The germ (embryo) is rich in protein and lipids, and occupies relatively large proportion, similar to other small grain cereals (Fig. 1).

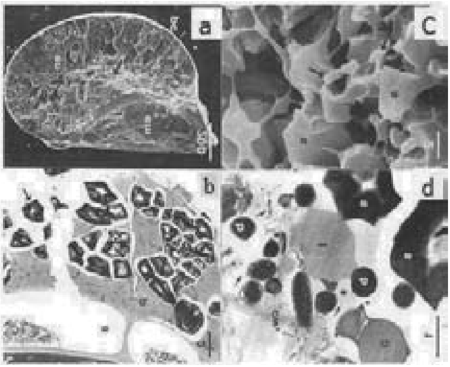

Fig. 1. **(a)** Scanning electron micrography of a halved tef grain showing the thin pericarp (pc), the starchy endosperm (en) with outer horny region and mealy center (arrowed), and relatively large embryo (em). **(b)** Fragment of flour of brown-seeded tef showing intact and broken endosperm cells attached to the bran. Starch granules are either within compound grains (cs) surrounded by protein bodies (p), or released singly (arrowed). The lipid-rich aleurone cell contents (a) are disrupted by milling. (**c**) Scanning electron micrograph of dough fermented for 48 h showing angular starch granules (s) with bacteria attached (arrows). **(d)** Dough fermented for 72 h showing numerous bacteria (b), protein bodies (p), starch granules (s), lipid (l) and cell wall materials (cw) (Parker *et al.*, 1989).

16.3.2. Chemical composition of the tef grain

The endosperm and starch: The largest component in the tef grain is the endosperm, which is below the aleurone layer, and is the main nutrient source of nourishment for the germinating embryo. The outer layer of the endosperm is vitreous (glassy or horny), rich in protein reserves and some starch granules, while the inner layer is floury due to richness in starch granules with few protein bodies.

Tef grain bears compound starch granules (Fig. 2) like rice, oats, amaranthus and quinoa from which many very small (2-6 μm) starch granules are released during milling (Fig. 3) (Melaku and Parker 1996; Geremew *et al.*, 2002).

Starch accounts for about 73% of the tef grain; hence, it plays a dominant role in influencing the end properties of various tef grain products. On tef fermentation process, the fermenting microorganisms were known to utilize about 9% of starches (Melaku and Faulks, 1988).

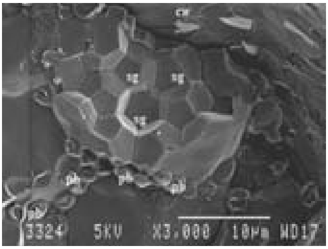

Fig. 2. Scanning electron microscopy (SEM) of tef compound starch granule (South African Brown), where: sg is individual starch granules; pb = protein bodies and cw = cell wall (Geremew and Taylor, 2004a).

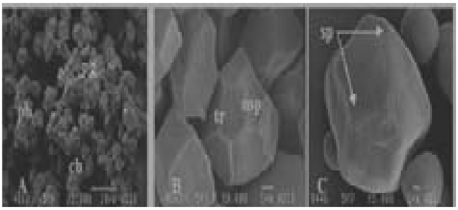

Fig. 3. A and B = SEM of individual tef starch granules (DZ-01-196) and C = normal maize starch granules with surface pores, where pg = polygonal, pb = protein bodies, cb = cubic, tr = tortoise–shell, nsp = no surface pores and sp = surface pores (Geremew, 2003).

Amylose was reported to range 25-32% from extracted starch granules (Geremew *et al.*, 2002) and 20-26% in flour starches (Geremew, 2007). Unlike in other cereals such as maize and rice, no *waxy*- or *amylo*- type starch traits were reported in tef. The X-ray diffraction study on tef starch granules indicated that it is A -type with similar crystallinity to rice (Geremew and Taylor, 2003). The A-type starches were noted for their good digestibility. The good digestibility and keeping quality of tef *injera* for example in *dirqoosha* (dried-form of *injera,* shelf stable) is related to the slow retrogradation nature of tef starches (Geremew *et al.*, 2008).

Tef starch pasting temperature is similar to maize starch, but cooking time for peak viscosity is longer (Geremew *et al.*, 2002). Peak, breakdown and setback viscosities are lower than that for maize starch (Fig. 4) (Geremew, 2007). The tef starch paste clarity is opaque and smooth with short gel texture (Geremew and Taylor, 2004b). Because tef starch granules are very small, and smooth with uniform size, they offer good functionality as fat substitute, flavor and aroma carrier similar to other small-granule starches. Tef starches application in high-shear processed foods looks promising because of its shear breakdown resistance.

Grain proteins*:* The average protein content in the tef grain is about 11% which is higher than in maize but comparable to that of wheat (Fufa, 1998; Geremew, 2007) (Table 1). This means that consumption of 469 g for female and 571 g for male of dried *injera* per day (Table 1) can meet the daily protein dietary reference intake (DRI) for adults (19-50 years old), provided that the protein is 100% digestible

(WHO, 2007). In Ethiopia, tef contributes upto two-third of the protein intake of the population consuming tef as staple food (NRC, 1996). Recent study with three tef varieties showed that prolamins (extraction by 60% tert-butanol, v/v containing 0.05% 4-dithiothreitol, w/v) constitute about 40% of tef grain storage proteins (Adebowale *et al.* 2011). According to these authors, the prolamins of tef are different from sorghum prolamins by being more hydrophobic and less polymerized with low thermal stability, and such high level of prolamins in tef were implicated as contributors for making superior semi-leavened flat bread as opposed to sorghum. Tef proteins are known to be rich in digestible type proteins of albumins and globulins (Endeshaw, 1995). Tef grain is regarded as excellent source of essential amino acids when compared to FAO reference pattern (FAO/WHO, 1973), except that is limited in lysine and somewhat also in threonine (Table 4). Tef contains more lysine than barley, millet and wheat and slightly less lysine than rice and oats.

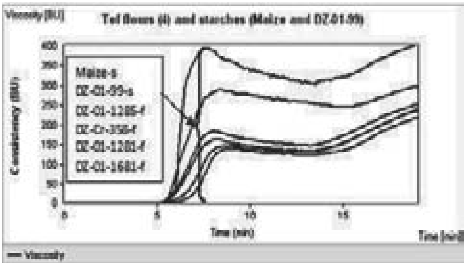

Fig. 4. Typical amylograph pasting curves of four tef flour starches (DZ-01-1285-f, DZ-Cr-358-f, DZ-01-1281-f and DZ-01-1681-f) and extracted starches (maize-s and DZ-01-99-s).

Fat: The crude fat in tef grain is comparable to that of wheat and is lower than in maize, sorghum and millets. The crude fat content in *injera* is lower than in the grain probably due to the loss during fermentation and baking. The limited available information (Fufa, 1998) indicates that the major fatty acids [linoleic (C18:2) > oleic (C18:1) > palmitic (C16:0)] were found similar to other small cereal grains. Eventhough it is cholesterol-free, tef is somewhat limited in offering essential fatty acids like omega-3 fatty acids. The product development study is virtually absent on whether the changes in the total fat content of tef grain affect the baking quality of injera or not.

Calorie**:** Tef is regarded as a good source of calorie, and contributes as much as 40-60% of the energy consumed by the body. Consumption of about 546 g of dried *injera* per day can meet the minimum dietary energy (2100 kcal) requirements recommended for food security.

Table 1. Tef (grain and *injera*) proximate composition and energy compared to sorghum, maize, bread wheat and millet grains (unless specifically mentioned, data is per 100 g) and some data on dietary reference intake (DRI).

Biochemical class	Tef grain[1](typical value[21])	Tef grain[19]	Tef grain[20]	Tef *injera* R (M)[19β]	Sorgh-um[20]	Maize white grain[20]	Bread wheat[20]	Millet[20]	DRI/ day[22]
Moisture (%)	8.8-11.0 (11)	10-11	8.8	52-64 (59)	9.2	10.91	10.7	10.7	
Protein (%) (N x 6.25)	9.4-13.3 (11)	10.5-11.0	13.3	3-5 (4=9.8db)	11.3	6.93	13.2	10.8	46g,56g
Carbohydrate (%) (virtually starch)	73.0 (73)	73-76	73.1	32-41 (35=85.4db)	74.6	76.9	72	73.1	130g
Starch (%)	78.5-78.7[£1]			69.6[£2]	-	-	57.8		
Fat (%)	2.00–3.09 (2.5)	2.4-2.7	2.4	0.6-1.0 (0.8=2.0db)	3.3	3.9	2.5	4.3	
Fiber (%)	1.98–3.50 (3)[ɸ]	3.0-3.5[ɸ]	8.0[&]	0.1-5.4 (2.0=4.9db)[ɸ]	6.3[&]	7.3[&]	10.7[&]	3.5[&]	25g, 38g
Ash (%)	2.66–3.00 (2.8)	2.5-3.1	2.8	0.7-1.7 (1.2=2.9db)	1.57	1.5	1.6	1.2	
Food energy (kcal/100 g)	336-367 (336)	336-339	367	145-169 (158=385db)	339	361	340	373	2100

Where: [1]data compiled from review 1-18 references; β is mean from EHNRI 1968-1997 and 1998 data for fermented tef *injera*; R=range and M =mean; £1 and £2 are from reference 9 at 0.00 h dough fermentation and in the baked *injera*, respectively; db = dry matter basis assuming 59% moisture in the fresh *injera*; [ɸ]Crude fiber; [&]total dietary fiber; DRI/day is for adolescent to elderly 19-50 years female and male, respectively.

Sources: [1]Jansen *et al.* (1962), [2]Rouk and Melak-Hail (1963), [3]Almgard (1963), [4]Mengesha (1966), [5]Mulugeta (1978), [6] Abraham *et al.* (1980), [7]Lester and Endeshaw (1981), [8]Tekalign and Parsons (1987), [9]Melaku and Faulks (1988), [10]Alemayehu (1990), [11]Alemayehu *et al.* (1993), [12]Alemayehu (1995), [13]Seyfu (1993), [14]NRC (1996), [15]Kelbesaa *et al.* (1997), [16]Fufa (1998), [17]Endeshaw (1995), [18]Geremew (2007), [19] ENHRI (1968-1997 and 1998), [20]USDA National Nutrient Database for Standard Reference, Release 24 (2011) accessed on 12 October 2011, [21]Geremew and Taylor (2004a), [22]National Academy of Science (2002), [23]Melaku *et al.* (2005), [24]Yewolsew *et al.* (2007).

Dietary fiber: Tef possesses high dietary fiber (DF) than millet, maize and sorghum (Table 1), although the fiber content frequently reported is crude fiber. In contrast to most common cereals, the amount of uronic acid in tef grain is high (Melaku, 1986). Tef bears relatively high β-glucans similar to oats and barley. It appeared that on *injera* making, the crude fiber is reduced than what is found in the grain.

Ash: The ash content of tef grain is high as compared to that of sorghum, maize, wheat and millet although in *injera* is reduced probably due to l osses during processing.

Mineral content: Both the grain and fermented products from tef are recognized to have high mineral contents compared to the grains of other cereals because tef is consumed as whole grain and often fermented as *injera*. Studies showed that fermented *injera* has more bio-available iron than the unfermented one. If the iron in *injera* is assumed 100% available, 30.78 g, 13.68 g and 46.15 g of dried *injera* can meet the DRI of iron for the adult (19-50 years old) female, male and pregnant women, respectively. However, in the developing countries where plant-based diets are the dominant ones, the iron from the food can be bio-available to the extent of 5-10% (WHO/FAO, 2004). Assuming a maximum of 10% availability, consumption of 307.8 g, 136.8 g and 461.5 g of dried *injera* can meet the iron DRI requirement of the adult (19-50 years old) female, male and pregnant women, respectively. The zinc content is high in tef grain than in maize grain (Table 2). Fermentation can improve the availability of zinc in *injera* (Melaku *et al.*, 2005). If this zinc is assumed 100% available, consumption of 250.0 g and 343.8 g of dried *injera* can meet the DRI for the adult male and female, respectively. But zinc availability is estimated to be 30% in plant-based diet (WHO/FAO, 2004), and when this is considered, consumption of 833 g and 1146 g of dried *injera* can meet the DRI for the adult male and female, respectively. The calcium contents in both the grain and *injera* made from tef are higher than those found in sorghum, maize, wheat and millet grains (Table 2). If this calcium is assumed 100% available, consumption of 662.3 g of dried *injera* can meet the DRI for the adult. However on intake of diet, gross and net calcium bio-availability is estimated at 25-30% and 10-12%, respectively (WHO/FAO, 2004). Based on 12% calcium availability, consumption of about 5519.2 g/day of dried *injera* can meet the calcium DRI required for adults between 19 and 50 years old. Both the grain and *injera* of tef contains high level of phosphorus, potassium and sodium as compared to the grains of maize, sorghum, wheat and millet (Table 2).

Table 2. Mineral elements composition of tef (grain and *injera*) compared to sorghum, maize, bread wheat and millet grains (unless specifically mentioned, data is per 100g) and some data on dietary reference intake (DRI).

Mineral elements (mg/100 g)	Tef grain[1](typical value[21])	Tef grain[19]	Tef grain[20]	Tef *injera* R, M[19β], (from[23])	Sorghum[20]	Maize white grain[20]	Bread wheat[20]	Millet[20]	DRI/ day[22]
Calcium (mg)	104–223 (165.2)	156-157	180	50-73, 62=151db (58-64, 61)	28	7	34	14	1000
Chloride (mg)	13 (13)				-				
Chromium (μg)	250 (250)				-				
Copper (mg)	0.7–5.3 (2.6)		0.8	0.57-0.67, 0.61=1.5db	-	0.2	0.4		
Iron (mg)	4.73–19.60 (5.7[a], 15.7[b])	18.9-58.9	7.6	7-56, 24=58.5db (30-39,35)	4.4	2.4	3.6	3.9	18[$], 8, 27[£]
Magnesium (mg)	138–190 (169.8)		184		-	93	137	119	
Manganese (mg)	1.6– 6.4 (3.8)		9.2		-	0.5	4.1	1	
Phosphorus (mg)	378–480 (425.4)	348-366	429	100-214, 143=348.8db (156-168,164)	287	272	357	285	700
Zinc (mg)	2.0– 6.7 (4.8)		3.6	1.0-1.8, 1.3=3.2db (1.00-1.40, 1.16)		1.7	2.6	2.6	8, 11
Potassium (mg)	330–570 (380)		427	185-235, 218=531.7db	350	315	363	224	4700
Sodium (mg)	11.8–47.0 (15.9)		12	7.7-25.0, 4.7=11.5db	6	5	2	4	1500
Selenium (μg)			4.4			15.4	61.8	32.7	

Source and abbreviations are as indicated in the Table 1; $ for female; [£]for pregnancy time; "a" is mean of iron from cleaned (acid and/or water washed) samples and "b" is from samples not received such treatments; R =range and M=Mean.

According to some studies, the phosphorus is more bio-available in the fermented *injera* than in the unfermented *injera* due to the destruction of phytates and other inhibitors on fermentation and baking (Melaku *et al.*, 2005; Yewulsew *et al.*, 2007). Eventhough, iron deficiency disorders are a recognized global challenge, the improved bio-availability of iron on fermentation and the less prevalence of iron deficiency related anemia among Ethiopian population consuming tef *injera* as staples indicates that fermented tef *injera* has substantial potential for reducing such problems. Since, tef *injera* is limited in offering calcium and zinc requirements (Melaku *et al.*, 2005), consumption of animal products along with tef *injera* should be encouraged.

Vitamins: The B-vitamin (thiamine and niacin) contents in tef grain are high as compared to other whole cereal grains (sorghum and maize). The riboflavin level is greater than that of sorghum, maize, wheat and millet (Table 3). In the *injera*, somewhat an increase in the riboflavin and a decrease in the niacin levels are observed as compared to th e content in the tef grain. Since the B-vitamins are concentrated in the bran portion of the grain and tef is consumed as a whole grain, it makes this cereal superior in B-vitamins than cereals such as wheat and maize in which the bran is removed during processing. In order to fulfill the daily thiamine requirement, 344 g and 377 g of dry *injera* should be consumed by an adult female and male, respectively while about 100 g of dry *injera* satisfies the daily DRI for riboflavin. The respective figures for niacin for an adult female and male are respectively 1077 g and 1231 g of dry *injera*.

Anti-nutritional factors: tef grain contains less than 1% (528-842mg/100g) phytic acid and other inositol phosphates, which are strong inhibitors of Fe and Zn absorption. The amount of phytates in *injera* is considerably reduced to 35-76 mg/100 g (91-93% destruction) due to fermentation and the acidity nature of *injera* (Melaku *et al.*, 2005; Yewulsew *et al.*, 2007). The brown-colored tef grain was reported to contain tannins although the type of tannin was not described (Melaku *et al.*, 2005). Trypsin inhibitor, a chemical that affects the availability of trypsin enzyme, was recorded in the tef dough at the start of fermentation. But this can be destroyed during steam heat baking of *injera* since these inhibitors are heat sensitive (Belitz *et al.*, 2009).

16.4. Grain Processing and Food Products of Tef Grain

In Ethiopia, tef is used to make a variety of food items like *injera,* sweet unleavened bread, opaque beer, local spirit, porridge, soups and gruels. However, *injera* is the single most important food item prepared from tef (Fig. 5), and consumed with spicy stew made from meat, beans, dairy products or cabbage. Various works have shown that in its *injera* making features (rollability, evenness of *injera* eyes, resilience, attractive flavor, freshness and slow staling over storage), tef grain flours are superior than any other cereal grain flours (Adamu, 1997; Senayit *et al*., 2004). The Ethiopian diaspora are using *injera* from rice or blend of rice and wheat flour, although rice or wheat *injera* suffers from staling and losses resilience and plasticity after a day. The rice flour *injera* making ability is similar to tef probably because of somewhat similar starches in both grains.

Injera made from tef is sour and can have good keeping quality. The degree of sourness depends on the length of the fermentation. Short fermentation for about a day produces sweet *injera* with good flavor. Mixing of tef four to that of fenugreek *(Trigonella foenumgraecum*) legume improved the nutrition, appearance and texture of the *injera* (Beyene, 1965).

The processing of *injera* involves both the lactic acid and yeast fermentation and is known to last from about 24 to 72 hours (Chaltu and Abraham, 1982; Birhanu, 1985; Lealem and Birhanu, 1994). Fermentation is initiated by the bacteria from the *Enterobacteriaceae* family that reduce dough pH to 5.8. Then, a group of lactic acid bacteria take over and further reduce the pH to about 3.8. During the later fermentation phase, a variety of yeasts and *Bacillus* bacteria are involved.

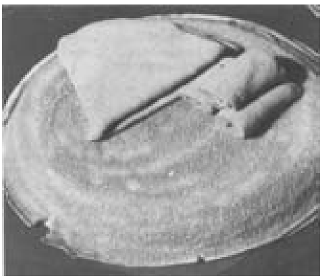

Fig. 5. Freshly prepared *injera*, showing “eyes” perforating the surface.

Table 3. Tef grain vitamins, fatty acids and anti-nutrients compositions and *injera* vitamins (unless specifically mentioned, the data are per 100g).

Vitamins	Tef [14](typical value[21])	Tef grain[19]	Tef grain[20]	Tef *injera* R, M[19β], (from[23])	Sorghum[20]	Maize white grain[20]	Bread wheat[20]	Millet[20]	DRI/ day[22]
Vitamin A (RE)	8 (8)								
Thiamin (mg)	0.30 (0.3)	0.3-0.6	0.39	0.03-0.21, 0.13=0.32db	0.24	0.25	0.5	0.41	1.1, 1.2
Riboflavin (mg)	0.18 (0.2)	0.13-0.14	0.27	0.01-1.16, 0.5=1.2db	0.14	0.08	0.17	0.07	1.1, 1.3
Niacin (mg)[Ꞩ]	2.50 (2.5)	1.7-1.8	3.4	0.5-0.6, 0.53=1.3db	2.9	1.9	5.0	6.0	14,16
Vitamin C (mg)	88 (88)	1		1					
Fatty acids (%)	Tef [16]								
Palmitic (C16:0)	13.95-16.40 (15.9)								
Palmitoleic (C16:1)	0.10-0.60 (0.3)								
Stearic (C18:0)	3.00-3.70 (3.3)								
Oleic (C18:1)	23.30-23.45 (24.0)								
Linoleic (C18:2)	41.25-46.45 (44.2)								
Linolenic (C18:3)	6.85-9.90 (7.9)								
Arachidic (C20:0)	0.60-0.90 (0.7)								
Arachidonic (C20:1)	0.50-1.15 (0.8)								
Behenic (C22:0)	0.25-1.05 (0.5)								
Erucic (C22:1)	0.00-0.85 (0.4)								
Antinutrients	Tef[15]								
Phytate (mg/100g)	707 (707) [#]	528-842[24]		118-134,126[23]; 35-76					
Tannin (mg/100 g)	881[#]			45-52, 50 [23]					
Trypsin inhibitor activity (TIU/g)	5584 (5584)[#]								

Source and abbreviations are as indicated in the Table 1; # At 0:00 h. tef flour dough fermentation (Urga et al. 1997), RE is retinol equivalent; Ꞩ is as niacin equivalent, 1 mg niacin = 60 mg tryptophan

Table 4. Tef grain amino acid compositions (whole grain).

Amino acid	g/100 g of protein recovered+	Tef grain (typical value)[21]	FAO/WHO (1973) pattern g/100g	Amino acid score (%)	mg/kg body mass per day
Aspartic acid*1	5.8–7.2	6.4			
Threonine	2.4– 4.4	3.6	4.0	90	15
Serine	2.8–5.6	4.1			
Glutamic acid*2	18.7–24.9	21.8			
Proline	5.1–11.4	8.2			
Glycine	1.7–4.1	3.1			
Alanine	5.5–14.7	10.1			
Cysteine	0.5–2.5	1.8			4
Valine	4.1–9.9	5.9	5.0	118	26
Methionine	2.0–4.6	3.3			10
Isoleucine	3.2–5.4	4.0	4.0	100	20
Leucine	6.0–9.7	8.1	7.0	116	39
Tyrosine	1.7–4.0	3.0			
Phenylalanine	2.7–5.9	5.0			
Histidine	2.1–3.7	2.8			10
Lysine	1.4–4.0	3.0	5.5	55	30
Arginine	2.9–6.2	4.5			
Tryptophan	1.2–1.3	1.3			4
Methionine + Cysteine		5.1	3.5	146	15
Phenylalanine + Tyrosine		8.0	6.0	133	25

Source and abbreviations are as indicated in the Table 1*1 is Aspartic acid + Aspargine; *2 is Glutamic acid + Glutamine;+is data compiled from 1, 7, 10, 13, 14 and 17; & amino acid requirements for adults (WHO, 2007) and FAO/WHO (1973).

Fermented products from tef including *injera* are noted for their probiotic potentials. Although the lactic acid bacteria and yeast involved in the fermentation are killed during baking, their dead cells and metabolic products are consumed as part of the diet and these were implicated as promoters of gut health (Poutanen *et al.*, 2009). Indeed, the lactic acid and volatile fatty acids (C_2 - C_6) were reported as the major organic acids produced during fermentation and contributing to good aroma and sour taste of *injera* (Melaku and Faulks, 1989).

Outside Ethiopia, tef is being promoted as a healthy food especially as an alternative non-gluten cereal (Roosjen, 2007). Supplementing tef flour to th at of wheat improved the iron and antioxidant potential of the bread (Mohammed *et al.*, 2009; Alaunyte *et al.*, 2012).

Although extensive studies were made in the area of fermentation and baking of *injera*, limited investigations have been done on the determination of the optimum processing method particularly on the particle size of the milling, blending, fortification, supplementation, fermentation and baking conditions. The Food Science Department of Haramaya University is at the present working on the various aspects of grain tef processing. Recent works using tef alone (Laike *et al.*, 2010), or blending with soybean (Sadik, 2010), rice (Mahilet, 2010), flaxseed (Tewodros, 2011), and maize and sorghum (on progress) are part of these efforts in order to improve the nutrient content, to introduce gluten-free products, and to mitigate the current tef grain premium price by replacing some portions of tef grains with other grains.

16.5. Health Benefits of Tef Grain Food Products

16.5.1. Tef and Anemia

Tef injera is known as good source of iron and has potential in reducing iron deficient anemia diseases (Kelbessa *et al.*, 1998; Melaku *et al.*, 2005; Yewulsew *et al.*, 2007). Molineaux and Mengesha (1965) reported that non-tef consumers have a lower level of hemoglobin, and hookworm anaemia develops in non-tef consumers if they are infested with hookworm. On the other hand, since tef consumers have higher levels of hemoglobin in their blood, they do not suffer from hookworm anaemia. In persons living in areas of the country where consumption of red tef is most prevalent, hemoglobin levels were found to be higher with a decreased risk of anemia related to p arasitic infection. As studies of the increased health benefits associated with high iron contents in brown tef become elucidated, there is more acceptance of this grain in the society. Today, in Ethiopia, brown tef is b ecoming more popular related to its increased iron content.

16.5.2. Tef and Diabetes

The other health related benefit of tef is the high fiber content of the grain. This is particularly important in dealing with diabetes and assisting with blood sugar control. Related to its small size, the grain cannot be separated into germ, bran and endosperm to create a variety of other products. Although this creates some disadvantages for the grain, it allows tef to yield much higher fiber content than the flour of the other grains. Tef *injera* can be regarded as diet with low glycemic index

(GI), even though systematic study is limited (Magaletta *et al.*, 2010). There have been some studies that look at the rates of diabetes for certain populations in Ethiopia. However, as in most developing countries the data for establishing reliable estimates does not exist. Some researchers have looked at diabetes in the Ethiopian Jewish immigrants to Israel, a subset of the Ethiopian population. Most these studies concluded that the prevalence is increasing for Ethiopians both at home and abroad as their lifestyles and diet change. As a whole grain and being high in dietary fiber (DF), tef can offer beneficial roles as pre-biotic and for health benefit (reduction in the risk of chronic diseases) (Seal and Brownlee, 2010). The slow release of glucose to blood on consumption of tef *injera* is probably influenced by the surface erosion of *endo*-corrosion nature of amylase enzymes' attacks to tef starches (Geremew and Taylor, 2004b). In part, digestibility is also modulated by the influence of high dietary fiber since tef is consumed as whole grain flour, and whole grain products are very well known for such action.

16.5.3. Tef and Celiac Disease

The products of tef grain are becoming popular globally mainly due to the absence of gluten, the cause for celiac disease (CD) (Dekking *et al.*, 2005; Hopman *et al.*, 2008; Bergamo *et al.*, 2011) which is affecting about 1% of the USA and Europe population (Engleson and Atwell, 2008; See and Murray, 2006). In the patients of CD, ingestion of gluten (from wheat, barley and rye) damages the lining of the small intestine and prevents normal digestion and nutrient absorption, thereby leading to chronic disorders of nutrient deficiency diseases like anemia, diarrhea and weight loss (See and Murray, 2006). There is a global move towards tef grain based gluten free recipe developments. Patent has already been granted for baked tef products including a variety of bread, cookies and cake (Roosjen, 2007). With popularization of consumption of tef *injera* and other tef products around many global restaurants, tef consumption will become culture as that of bread. Global effort is required to boost tef grain production, so that tef grain can be fetched at affordable price, since at present it commands premium prices among cereal grains.

16.6. Postharvest Tef Grain Handling

Little improvement has been made in the harvesting and post-harvesting operations of tef including transporting, stacking, threshing and cleaning. Considerable amount of loss in grain quantity and quality occurs due to untimely harvesting. Stacking harvested tef plants in the field allows further ripening.

Threshing using trampling with domestic animals does not only reduce the seed yield but also affects the quality of the produce especially due to the nature of the threshing ground. The grain cleaning at the threshing yard is not effective to remove the impurities to the level required by the grain industry. Although storage pests are not considered as the major problem for tef, studies need to be made to investigate the extent of damage from sprouting, and its impact on grain quality. On contrary, the high iron level in tef might in part have been contributed by nature of agronomic practice used in Ethiopia (Abraham *et al.*, 1980), and whether this high iron content that tef grain products are enjoying is going to be compromised by the grain post-harvest handling improvement will remain uncertain at this moment. Apart from yield potential of a given tef grain variety, all these factors will also contribute to the low tef grain productivity and grain quality challenges. It is hoped that with collaboration among Breeders, agronomists, food science and technologists, nutritionists, engineers and other allied professionals will take us to productive futures.

16.7. Conclusions and the Way Forward

The nutritive and health benefit of tef grain as human food is high and in many respects better than that of the other cereal grains. With the current cultural practices, the losses on the total grain yield and quality are considerable during harvesting and post-harvesting activities. Technologies that minimize the losses during threshing and cleaning especially for small-scale farmers are required. Research towards improving the *injera* processing particularly with regard to equipment and recipes is important. Information on tef starch granules damage levels on milling and optimum flour particle size range and their influence on *injera* processing and quality deserve to be addressed by research. Information on the amino acid profile of *injera* is limited. Research on various ready-to-eat food products, grain components (like starch) and innovative utilizations of tef grain by-products are important since this would add value to the tef crop and would help improve the living conditions of farmers. On the breeding aspects for new character in tef, early characterization on the starch traits and *injera* making feature are important. Complete information on nutrients, anti-nutrients and digestibility when tef is used as part of various innovative food and beverage products is also required.

Although tef grain possesses high nutritional and health benefits its production could not satisfy the ever-increasing national and global demands. Hence, efforts should be made to alleviate the production constraints to boost the productivity of this vital crop.

16.8. Abbreviations

CD: celiac disease; **DF**: dietary fiber; **DRI**: dietary reference intake; **ENHRI**: Ethiopian Health and Nutrition Research Institute; **FAO**: Food and Agriculture Organization of the United Nations; **FRAP**: ferric-ion reducing antioxidant power; **HLW**: hectolitre weight; **LM**: light microscopy; **NRC** National Research Council, USA; **pb** = protein bodies; **SEM**: scanning electron microscopy; **TEM**: transmission electron microscopy; **TIU**: Trypsin inhibitor activity; **TKW**: 1000 kernel weight; **WHO**: World Health Organization.

16.9. Acknowledgements

The organizers of the conference are indebted for inviting us to produce this review paper. Haramaya University and Addis Ababa University are acknowledged for granting leave permit to attend the workshop. The project Development of Functional Foods (NARF/CR/01/004/09) of Agricultural Research Fund (ARF) of the Ethiopian Institute of Agricultural Research (EIAR) is acknowledged for partially covering the travel expense for Dr. Geremew Bultosa.

16.10. References

Abraham Besrat, Admasu A and Mebratu Ogbai. 1980. Critical study of the iron content of tef (*Eragrostis tef*). *Ethiopian Medical Journal* 18: 45-52.

Adamu Zegeye 1997. Acceptability of *injera* with stewed chicken. *Food Quality and Preference* 8:293-295.

Adebowale AA, Emmambux MN, Beukes M and Taylor JRN. 2011. Fractionation and characterization of tef proteins. *Journal of Cereal Science* 30:1-7.

Alaunyte I, Stojceska V, Plunkett A, Ainsworth P and Derbyshire E. 2012. Improving the quality of nutrient-rich teff (*Eragrostis tef*) breads by combination of enzymes in straight dough and sourdough bread making. *Journal of Cereal Science* 55:22-30.

Alemayehu Areda. 1990. Studies on the nutrient composition of tef [*Eragrostis tef* (Zucc. Trotter] and the interactive influence of environment and genotype. Ph.D Thesis, University of London, London, U.K.

Alemayehu Areda. 1995. Protein contents of twelve tef genotypes. *SINET: An Ethiopian Journal of Science* 18:221-233.

Alemayehu Areda, Seyfu Ketema, Ingram J and Davis RHD. 1993. The iron content of tef [*Eragrostis tef* (Zucc.) Trotter]. *SINET: An Ethiopian Journal of Science* 16: 5-13.

Almgard G. 1963. High content of iron in teff, *Eragrostis abyssinica* Link. and some other crop species from Ethiopia–a result of contamination. *Lantbrukshogskolans Annaler*. 29:215-220.

Belitz HD, Grosch W and Schieberle P. 2009. Food Chemistry. Springer, 4th revised and extended ed., Berlin, Germany.

Bergamo P, Maurano F, Mazzarella G, Iaquinto G, Vocca I, Rivelli AR, Enrica Falco D, Gianfrani C and Rossi M. 2011. Immunological evaluation of the alcohol-soluble protein fraction from gluten-free grains in relation to celiac disease. *Molecular Nutrition and Food Research* 55:1266-1270.

Beyene Chichaibelu. 1965. Studies on the biological evaluation of the protein quality of tef *(E. abyssinica)* and *abish (Trigonella foenum-graecum)* and the supplementary value of *abish* when added to tef. M.Sc. Thesis, Cornell University, USA.Birhanu Abegaz Gashe. 1985. Involvement of lactic acid bacteria in the fermentation of tef (*Eragrostis tef*), an Ethiopian fermented food. *Journal of Food Science* 50:800-801.

Chaltu Gifawesen and Abraham Besrat. 1982 Yeast flora of fermenting tef (*Eragrostis tef*) dough. *SINET: An Ethiopian Journal of Science* 5:21-25.

Costanza SH, DeWet JMJ and Harlan JR. 1979. Literature review and numerical taxonomy of *Eragrostis tef* (Tef). *Economic Botany* 33:413–424.

Dekking LS, Winkelaar YK and Koning F. 2005. The Ethiopian cereal tef in celiac disease. *The New England Journal of Medicine* 353:1748-1749.

Dykes L and Rooney LW. 2006. Sorghum and millet phenols and antioxidants. *Journal of Cereal Science* 44:236-251.

Dykes L and Rooney LW. 2007. Phenolic compounds in cereal grains and their health benefits. *Cereal Foods World* 52:105-111.

EHNRI. 1998. Ethiopian Health and Nutrition Research Institute. Food composition table for use in Ethiopia, part IV. Addis Ababa, Ethiopia.

EHNRI.1968-1997. Ethiopian Health and Nutrition Research Institute. Food composition table for use in Ethiopia, part III. Addis Ababa, Ethiopia.

Endeshaw Bekele. 1995. Essential and non–essential amino acids in a free state and in the major protein fractions of teff seeds. *SINET: An Ethiopian Journal of Science* 18:79-99.

Engleson J and Atwell B. 2008. Gluten free product development. *Cereal Foods World* 53:180-184.

FAO/WHO. 1973. Energy and protein requirements. Report of a Joint FAO/WHO Ad-Hoc Expert Committee. Geneva: World Health Organization Technical Report, Series 522.

Fufa Hundera. 1998. Variations of morpho–agronomic characters and grain chemical composition of released varieties of tef [*Eragrostis tef* (Zucc.) Trotter]. *Journal of Genetics and Breeding* 52:307-311.

Geremew Bultosa. 2003. Physicochemical and functional properties of grain tef [*Eragrostis tef* (Zucc.) Trotter] starch. Ph.D Thesis, University of Pretoria, Pretoria, South Africa.

Geremew Bultosa.2007. Physicochemical characteristics of grain and flour in 13 tef [*Eragrostis tef* (Zucc.) Trotter] grain varieties. *Journal of Applied Sciences Research* 3:2042-2051.

Geremew Bultosa, Hall AN and Taylor JRN. 2002. Physico-chemical characterization of grain tef [*Eragrostis tef* (Zucc.) Trotter] starch. *Starch/Stärke* 54: 461–468.

Geremew Bultosa, Hamaker BR and BeMiller JN. 2008. An SEC-MALLS study of molecular features of water-soluble amylopectin and amylose of tef [*Eragrostis tef* (Zucc.) Trotter] starches. *Starch/Stärke* 60:8-22.

Geremew Bultosa and Taylor JRN. 2003. Chemical and physical characterization of grain tef [*Eragrostis tef* (Zucc.) Trotter] starch granule composition. *Starch/Stärke* 55: 304-312.

Geremew Bultosa and Taylor JRN. 2004a. Teff. *In*: Wrigley C, Corke H, Walker CE. (eds). Encyclopedia of Grain Science, Vol. 3, Elsevier Ltd. UK. Oxford. pp: 281-290.

Geremew Bultosa and Taylor JRN. 2004b. Paste and gel properties and *in vitro* digestibility of tef [*Eragrostis tef* (Zucc.) Trotter] starch. *Starch/Stärke*. 56: 20–28.

Hopman GD, Dekking EHA, Blokland MLJ, Wuisman MC, Zuijderduin WM, Koning F and Schweizer JJ. 2008. Tef in the diet of celiac patients in the Netherlands. *Scandinavian Journal of Gastroenterology* 43:277-282.

Jansen GR, Dimaio LR, Hause NL. 1962. Amino acid composition and lysine supplementation of tef. *Journal of Agricultural and Food Chemistry* 10:62-64.

Kebakile MM, Rooney, LW and Taylor JRN. 2007. Effect of hand pounding, abrasive decortication-hammer milling, roller milling, and sorghum type on sorghum meal extraction and quality. *Cereal Foods World*. 52(3): 129-137

Kebebew Assefa, Seyfu Ketema, Hailu Tefera, Fufa Hundera and Tiruneh Kefyalew.2001. Genetic diversity for agronomic traits in tef. *In*: Hailu Tefera, Getachew Belay and Sorrells M. (eds) Narrowing the Rift: Tef Research and Development, Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000. Ethiopia. EARO, Debre Zeit. pp: 33-47.

Kelbessa Urga, Alemu Fite and Eskinder Biratu. 1997. Effect of natural fermentation on nutritional and antinutritional factors of tef (*Eragrostis tef*). *Ethiopian Journal of Health Development* 11:61-66.

Kelbessa Urga, Narasimha HV, Sasikala BV and Vishwantha S. 1998. Bioavailability of iron and zinc from tef in rats. *Bulletin of the Chemical Society of Ethiopia* 12:95-103.

Kreitschitz A, Zerihun Tadele and Gola EM. 2009. Slime cells on the surface of *Eragrostis* seeds maintain a level of moisture around the grain to enhance germination. *Seed Science Research* 19: 27-35.

Laike Kebede, Solomon Worku, Geremew Bultosa and Senayit Yetneberek S. 2010. Effect of extrusion operating conditions on the physical and sensory properties of tef (*Eragrostis tef* [Zucc.] Trotter) flour extrudates. *Ethiopian Journal of Applied Sciences and Technology*. 1(1): 27-38

Lealem F and Birhanu Abegaz Gashe. 1994. Amylase production by a gram–positive bacterium isolated from fermenting tef (*Eragrostis tef*). *Journal of Applied Bacteriology* 77:348-352.

Lester RN and Endeshaw Bekele. 1981. Amino acid composition of the cereal tef and related species of *Eragrostis (Gramineae*). *Cereal Chemistry* 58:113-115.

Magaletta RL, DiCataldo SN, Liu D, Li HL, Borwankar RP and Martini MC. 2010. *In vitro* method for predicting glycemic index of foods using simulated digestion and an artificial neural network. *Cereal Chemistry* 87:363-369.

Mahilet Menwyelet.2010. Effect of extrusion operating conditions and blending proportion on the physicochemical and sensory properties of tef-rice blend extruded products. M.Sc. Thesis, Haramaya University, Ethiopia.

Melak-Hail Mengesha .1966. Chemical composition of teff (*Eragrostis tef*) compared with that of wheat, barley and grain sorghum. *Economic Botany* 20:268-273.

Melaku Umeta. 1986. Studies on the fermentation of tef *(Eragrostis ref)* and its nutritional Significance, M.Sc. Thesis, University of East Anglia, UK.

Melaku Umeta and Faulks RM. 1989. Lactic acid and volatile (C_2–C_6) fatty acid production in the fermentation and baking of tef (*Eragrostis tef*). *Journal of Cereal Science* 9:91-95.

Melaku Umeta and Faulks RM. 1988. The effect of fermentation on the carbohydrates in tef (*Eragrostis tef*). *Food Chemistry* 27:181-189.

Melaku Umeta and Parker ML. 1996. Microscopic studies of the major macro–components of seeds, dough and *injera* from tef (*Eragrostis tef*). *SINET: An Ethiopian Journal of Science* 19:141-148.

Melaku Umeta, West CE and Habtamu Fufa. 2005. Content of zinc, iron, calcium and their absorption inhibitors in foods commonly consumed in Ethiopia. *Journal of Food Composition and Analysis* 18:803-817.

Mohammed MIO, Mustafa AI and Osman GAM. 2009. Evaluation of wheat breads supplemented with teff (*Eragrostis tef* (Zucc.) Trotter) grain flour. *Australian Journal of Crop Science* 3:207-212.

Molineaux L and Mengesha B. 1965. Tef consumption, hookworm infestation, and hemoglobin levels: a preliminary report. *Journal of Health* 51:1-5.

Mulugeta Assefa. 1978. Floral morphogenesis, temperature effect on growth, development and variation in nutritional composition and distribution among cultivars in *Eragrostis tef* (Zucc.) Trotter. Ph.D Thesis, University of Wisconsin–Madison, Wisconsin.

National Academy of Science. 2002. Dietary reference intakes (DRI), Washington, DC, USA.

NRC. 1996. National Research Council of the USA. Lost crops of Africa. Volume 1: Grains. National Academy Press, Washington, D.C. pp 215-234.

Parker ML, Umeta M and Faulks RM. 1989 The contribution of flour components to the structure of *injera*, Ethiopian fermented bread made from tef (*Eragrostis tef*). *Journal of Cereal Science* 10:93-104.

Poutanen K, Flander L and Katina K. 2009. Sourdough and cereal fermentation in a nat ural perspective. *Food Microbiology* 26:693-699.

Roosjen J. 2007. Processing of teff flour: European patent specification (EP 1 646287 B1, grant of the patent 10-01-2007 Bulletin 2007/02), Publication Number: WO 2005/025319 (24.03.2005 Gazette 2005/12), European Patent Office. (http://www.abs-africa.info/uploads/media/Teff-Patent EP_1_646_287_B1_01.pdf) accessed on 1 October 20011.

Rouk HF and Melak-Hail Mengesha. 1963. An introduction to tef (*Eragrostis abyssinica Schard*). A nutritious cereal grain of Ethiopia. Debre Zeit Agricultural Research Centre. *Research Bulletin*. No. 26. College of Agriculture, Dire Dawa, Ethiopia.

Sadik Jemal. 2010. Effect of blending ratio and operating conditions on the physicochemical and sensory properties of extruded product from teff-soybean blend. M.Sc. Thesis, Haramaya University, Ethiopia.

Seal CJ and Brownlee IA. 2010. Whole grains and health, evidence from observational and intervention studies. *Cereal Chemistry* 87:167-174.

See J and Murray JA. 2006. Gluten-free diet: the medical and nutrition management of celiac disease. *Nutrition in Clinical Practice* 21:1-15.

Senayit Yetneberk, de Kock HL, Rooney LW and Taylor JRN. 2004. Effects of sorghum cultivar on *injera* quality. *Cereal Chemistry* 81:314-321.

Seyfu Ketema.1993. Tef (*Eragrostis tef*): breeding, genetic resources, agronomy, utilization and role in Ethiopian agriculture, Institute of Agricultural Research, Addis Ababa, Ethiopia.

Seyfu Ketema. 1997. Tef. *Eragrostis tef (Zucc.)* Trotter. Promoting the conservation and use of underutilized and neglected crops. 12. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy, pp. 7–10.

Stewart RB and Getachew A. 1962. Investigations of the nature of *Injera*. *Economic Botany* 16:127-130.

Tadesse Ebba.1969. Tef (*Eragrostis tef*): the cultivation, usage and some of the known diseases and insect pests. Part I. Debre Zeit Agricultural Experiment Station. Addis Ababa University, College of Agriculture, Dire Dawa, Ethiopia.

Tadesse Ebba.1975. Tef (*Eragrostis tef*) cultivars: morphology and classification. Experimental Station Bulletin. No. 66. Addis Ababa University, College of Agriculture, Dire Dawa, Ethiopia.

Tekalign Mamo and Parsons JW. 1987. Iron nutrition of *Eragrostis tef* (teff). *Tropical Agriculture* (Trinidad) 64:313-317.

Tewdros Girma. 2011. Fortification of grain tef [*Eragrositis tef* (Zucc.) Trotter] flour with flaxseed for *injera* for use as functional food. M.Sc. Thesis, Haramaya University, Ethiopia.

USDA. 2011. United States Department of Agriculture, National Nutrient Database for Standard Reference, Release 24. Available at http://www.nal.usda.gov/fnic/foodcomp/cgibin/list-nut-edit.pl - accessed on 12 October 2011.

WHO. 2007. Protein and amino acid requirements in human nutrition: report of a j oint FAO/WHO/UNU expert consultation. WHO technical report series; no. 935, Geneva, Switzerland.

WHO/FAO. 2004. Vitamin and mineral requirements in human nutrition, 2nd ed., Geneva, Switzerland.

Wood BJB. 2004. Fermentation: origins and applications. *In*: Wrigley C, Corke H, Walker CE. (eds). Encyclopedia of Grain Science. Vol. 1., Elsevier Ltd. UK. Oxford. pp 373–380

Yewulsew Abebe, Bogale A, Hambidge KM, Stoecker BJ, Bailey K, Gibson RS. (2007) Phytate, zinc, iron and calcium content of selected raw and prepared foods consumed in rural Sidama, Southern Ethiopia, and implications for bioavailability. *Journal of Food Composition and Analysis* 20:161-168.

Zewdu Abdi and Solomon Worku. (2007) Moisture dependent physical properties of tef seed. *Biosystems Engineering* 96:57-63.

17. Tef Straw: a Valuable Feed Resource to Improve Animal Production and Productivity

Alemu Yami
Ethiopia Sheep and Goat productivity Improvement Program (ESGPIP), Addis Ababa, Ethiopia. Email: alemuyami@yahoo.com

In Ethiopia, tef straw is a cereal crop residue produced in the largest quantities amounting to about a quarter of the total quantity of cereal crop residues produced in the country. It is also the highest valued cereal crop residue. The limited information available on the feeding value of tef straw indicates that it is a residue with the highest nutritive value, and as such it is among the crop residues that form the basis of the roughage supply to livestock especially in the mixed crop-livestock production system. Available information regarding the availability of tef straw as feed and other alternative uses is explored in this paper. Research and development effort to foster tef straw and enhancing its feeding value to improve animal production and productivity is also assessed in this paper. Furthermore, recommendations to further enhance the effective utilization of tef straw as animal feed including implications for the genetic improvement effort are forwarded.

Key words: tef straw, crop residue, feeding value, nutritive value, animal production, animal productivity

17.1. Introduction

Inadequate feed supply, both in terms of quantity and quality, is t he major constraint affecting livestock production in Ethiopia especially during the dry season. A survey in the central highlands of Ethiopia showed that the available feed resources at the smallholder farmer level could only support maintenance requirements (Zinash and Seyoum, 1991). According to the CSA (2006), the sources of livestock feed in Ethiopia are grazing (61.48%), crop residue (27.71%), hay (6.35%), by-products (0.82%), improved or sown fodder (0.8%) and others (3.47%). This shows that crop residues are the second most important sources of animal feed. The share would be much higher for the crop livestock system in the highlands (i.e. if the pastoral areas are excluded from the calculation).

The integration of livestock with crop production is a means of establishing sustainable production system that aims at optimizing resource use. Livestock greatly influence the ability of farmers to produce food and cash crops through draft power, cash availability and manure. On the other hand, crop residues play a crucial role in livestock nutrition. In such areas of Ethiopia like in the highlands, crop residues are the major feed resources for ruminants particularly during the dry season when the biomass of the natural grazing lands is very low. The tendency of increased acreage of cropping land is always at the expense of decreased available grazing lands, thus, boosting the importance of crop residues as animal feed resources. Cereal straws form the bulk of the residues available for feeding since cereals dominate Ethiopia's crop production covering 81.9% of the total area cultivated during the year 2010/11 (CSA, 2011). Tef accounts for 28.5% of total cereal area and 19.6% of total production. The area cultivated with tef has, in recent years, been increasing at the rate of 6.7% annually (Alemayehu *et al.*, 2011). This shows that the role played by tef straw as animal feed will not only continue but will increase as a result of the ever-increasing pressure on grazing land.

Farmers have been using tef straw as feed since the start of tef cropping with all the limitations associated with its use. This paper explores available information regarding the availability of tef straw as feed, its feeding value, limitations in its use as feed, and work done to improve its utilization and feeding value. Besidesa, recommendation for future action are also made. The information on tef straw utilization as feed is limited to work done in Ethiopia since the crop is not used elsewhere as a staple food crop, eventhough this seems to be changing in recent years. The very little information available on the value of tef as a forage crop in other countries like South Africa is not included since the prospects of the crop being used as forage in Ethiopia is remote.

Farmers highly value tef straw. It is stored and used as a very important source of animal feed especially during the dry season. For example, more than 99% of households in east Shoa collect and store their tef straw in stacks to minimize wastage (Tesfaye, 2006). Farmers have their own priority among livestock categories in the utilization of crop residues as feed. Among classes of animals, milking cows and oxen are given priority when there is feed scarcity (Zinash and Seyoum, 1991).

Owen and Aboud (1988) found the bulky nature of crop residues and lack of means of transport to be among the factors that constrain use of crop residues as feed. Tef straw with its lower bulk is the easiest to transport among the crop residues.

17.2. Availability of Tef Straw

17.2.1. Total tef straw available

The total amount of tef straw production is estimated based on harvest indices since there is no data from actual measurements. Based on crop production data of the Central Statistical Agency (CSA, 2011), the annual production of crop residues from tef, barley and wheat in the 2009/10 cropping season is estimated to be 20.32 million tons (Table 1).

Table 1. Total tef, barley and wheat straws produced nationally and the four major producing regions

Type of straw	Total straw available (million tons)*					
	National	Amhara	Oromia	SNNPR†	Tigray	Other regions
Tef straw	9.54	3.86	4.32	0.62	0.70	0.04
Barley straw	4.26	1.22	2.35	0.35	0.30	0.04
Wheat straw	6.52	1.91	3.55	0.37	0.66	0.03
Total	20.32	6.99	10.22	1.34	1.66	0.11
% of total	100	34.40	50.30	6.60	8.17	0.54

*Calculated from grain yields using conversion factors of 3.0 (Seyoum and Dereje, 2000); 2.12 based on a harvest index of 47% for wheat and 2.44 based on a harvest index of 41% for barley (Nordblom, 1988). †SNNPR: Southern Nations, Nationalities, and People's Region.

The four major regions, namely, Oromia, Amhara, Tigray and the SNNPR produce the largest share of the three types of straw with Oromia and Amhara taking the largest (84.7%) share. The other regions contribute less than one percent. A study by Tesfaye (2006) in east Shoa showed that 36.3% of total cultivated land in the 2004/2005 cropping season was allocated to tef and that 6.47 tons of crop residues were produced.

At the household level, tef straw (33%) followed by maize stover (31.6%) and wheat straw (6.97%) contributed to the total annual crop residue production by households (Table 2).

17.2.2. Tef straw available for animal feeding

The actual quantities of crop residues available for livestock feeding is reduced by the costs of collection, transport, storage and processing, other alternative uses and wastage. According to Zinash and Seyoum (1991), about 70% of the tef straw produced at the farm is allocated for livestock feeding while the remaining 30% is used for other purposes. An estimate of the amount of tef straw available for livestock feeding calculated based on these results is presented on Table 3.

Table 2. Contribution of different crop residues to the total annual crop residue production of each household at three agro-ecological zones (AEZ) in 2004 and 2005.

Agro-ecological zone (AEZ)	Share of residue (%)					
	Tef straw	Wheat straw	Barley straw	Maize stover	Sorghum stover	Haricot bean haulms
Tepid to cool sub moist mid highlands (SM2)	50.6	10.0	3.2	2.5	8.2	4.5
Tepid to cool sub humid mid highlands (SH2)	23.8	16.4	3.2	39.0	10.9	6.7
Tepid to cool semi-arid mid highlands (SA2)	24.6	2.6	6.6	53.3	1.8	11.2
Average	33.0	9.7	4.3	31.6	7.0	7.5

Source: Tesfaye (2006)

Table 3. Total amount of tef straw available for animal feeding nationally and at the regional level.

Type of straw	Straw available for feeding (million tons)*					
	National	Amhara	Oromia	SNNPR	Tigray	Others
Total tef straw available	9.54	3.86	4.32	0.62	0.70	0.04
Conversion factor	0.70	0.70	0.70	0.70	0.70	0.70
Tef straw available for animal feeding	6.68	2.70	3.02	0.43	0.49	0.03

*Calculated from total straw available by using the factor of 70% of the total available tef straw based on the survey work by Zinash and Seyoum (1991).

The amount of tef straw available for livestock feeding is again dominated by Oromia and Amhara having 45% and 40.4% of the national share, respectively.

Wastage represents a major loss of total tef straw produced that could potentially go for livestock feeding. According to percentage scores of causes of wastage by farmers in east Shoa, improper storage was the most important (35.8%) followed by inability to collect the residue (30.7%) (Tesfaye 2006). Inability to collect is largely due to the long distances between crop fields and homesteads, and accompanying unavailability of transport. By virtue of being soft and fine, tef straw was the most preferred and the least wasted.

17.3. The Feeding and Nutritional Value of Tef Straw

17.3.1. The feeding value of tef straw

The feeding value of crop residues including tef straw is variable depending on the crop variety, content of anti-nutritional factors (tannins, lignin, silica etc.), stage of harvest, length of storage, leaf to stem ratio, soil fertility and fertilizer application as well as the effects of agronomic practices such as irrigation. For example, Kernan *et al.* (1984) reported that straw from irrigated wheat had a 41% *in vitro* digestibility compared to 34% for non-irrigated wheat straw.

17.3.2. Chemical composition (Organic nutrients)

The chemical composition of tef straw and other selected crop residues are presented on Table 4. The composition of tef straw shares the general limitations of other straws in terms of being low in crude protein (CP) content of less than the 7.5% CP required for appropriate rumen function to s upport reasonable digestibility, feed intake and utilization. Compared with similar straws, tef straw is a better feed resource than wheat and barley straws in that it contains lower lignin content and higher *in vitro* dry matter digestibility (IVDMD) and energy composition. The nutrient supply of tef straw is close to the nutrient supply of a medium quality native grass hay.

Table 4. Chemical composition of selected crop residues and native hay

Feed type	DM	Composition % of DM*				Energy Mcal/kg DM		
		CP	NDF	Lignin	IVDMD	ME	NEm	NEg
Tef straw	91.9	6.0	72.3	5.4	53.2	1.97	1.12	0.57
Wheat straw	91.8	3.1	74.7	6.2	51.3	1.74	0.90	0.36
Barley straw	91.4	6.2	74.4	6.9	50.4	1.82	0.98	0.43
Native hay	92.3	6.4	73.2	7.5	57.2	1.98	1.13	0.57

Abbreviations: *DM dry matter; CP: crude protein; NDF: Neutral Detergent Fiber; IVDMD: *In Vitro* Dry Matter Digestibility; ME: metabolizable energy; NEm: Net energy maintenance; NEg: Net energy gain. Source: Adugna (2008), and Seyoum and Zinash (1989).

Energy deficiency is another important factor limiting animal production from cereal crop residues. For instance, the metabolizable energy (ME) requirement for maintenance of a 20 kg sheep kept in a thermo-neutral environment is 3.4 Megajoules (MJ)/day (ARC, 1980). The ME consumed by sheep fed various cereal crop residues ranges from 2.8 to 4.1 MJ/day. This shows that cereal crop residues may provide no more than maintenance rations unless adequately supplemented.

The limitations of the amino acid precursors of the branched (isobutyric, isovaleric and 2-methylbutyric) and straight chained volatile fatty acids (VFAs) may exist since these VFAs are essential nutrients for the growth of the principal cellulolytic and some non-cellulolytic rumen bacteria (Russell and Sniffen, 1983). Their deficiency may contribute to poor animal performance from un-supplemented or inadequately supplemented cereal crop residues.

17.3.3. Minerals in tef straw

In absolute terms, cattle diets based on crop residues are unlikely to supply adequate Na, and are marginal to deficient in P, Cu, and possibly Zn. But these problems, except for Na, seem rectifiable by the inclusion of appropriate proportions of by-products in the ration (Kabaija and Little, 1989) (Table 5).

Table 5. Mineral content of cereal crop residues.

Feedstuff	Ca	P	Na	K	Mg	Ca:P	Na:K	Fe	Mn	Zn	Cu
	g/kg					Ratios		mg/kg			
Tef straw	4.3	1.6	0.3	11.7	1.9	2.7:1	1:39	170	59	26	6.5
Wheat straw	4.1	1.3	0.3	14.8	1.5	3.2:1	1:49	325	78	11	3.0
Barley straw	4.6	1.9	0.5	10.7	1.4	2.4:1	1:21	1175	90	12	5.0
Oats straw	3.9	1.7	2.0	17.7	1.8	2.3:1	1:9	196	191	17	14

Source: Kabaija and Little (1989), and DZARC (1989).

Balance trials have shown that roughages may contain high percentages of a certain mineral; yet, the animal is in negative balance when fed such a diet. This indicates the poor availability of the mineral irrespective of its high concentration in the feed.

The apparent availabilities of Ca from tef and wheat straws *in vivo* when fed to sheep are very similar to the values obtained *in sacco*, much more so than for other minerals. It was noted that roughage diets with low apparent mineral availability had much of their intrinsic minerals in association with faecal fiber. These could not be removed by water. It may, thus, be useful to pay close attention to the balance of minerals in diets based on fibrous crop residues whose utilization may have been improved through chemical treatment or non-protein nitrogen (NPN) supplementation.

Low Mg content was observed in tef, wheat and barley straws. In addition, low Na and high Ca, Fe and Mn contents were observed in these straws (DZARC, 1989). The evaluation of feeds as sources of minerals depends not only on what the feed contains, but on how much can be absorbed and used. The Ca:P ratios of the straws including that of tef straw was wide. The mineral deficiencies and the Ca:P balance can be partially corrected by supplementation of grain and oil seed by-products which are higher in the deficient minerals compared to the straws. Supplementation of Na would still be necessary (Lema and Smit, 2005).

Percentage mineral disappearance from most feeds *in sacco* was high for K, Na, and Mg (Table 6). This is probably due to these elements existing in readily soluble ionic forms.

Table 6. Mineral disappearance from cereal crop residues incubated *in sacco* in the rumen of an ox

Feedstuff	% disappearance							
	K	Na	Ca	Mg	Fe	Mn	Zn	Cu
Tef straw	72	86	29	68	39	32	25	51
Wheat straw	81	80	22	67	35	49	32	54
Barley straw	68	87	36	79	35	49	41	49
Oats straw	84	73	28	83	39	52	19	62

Source: Kabaija and Little (1989).

17.3.4. Inherent and management factors that influence the feeding value of tef straw

Management and genetic makeup of the crop influences the quality of tef straw. The following are some of these factors:

i) **Effect of genotype:** Varietal differences were reported to be important determinants of nutritive value and yield of tef straw. The differences in nutritive value emanate largely from differences in leaf to stem ratios (Seyoum *et al.*, 1996; DZARC, 1989; Seyoum and Dereje, 2000).

ii) **Effect of location:** Variability among locations in terms of growth conditions also results in differences in straw quality and quantity. This has been shown between Holetta and Ginchi (Seyoum *et al.*, 1996) and between Debre Zeit and Akaki (DZARC, 1989).

iii) **Seeding rate:** Increasing seeding rate was reported to result in higher straw yield (DZARC, 1989).

iv) **Stage of harvest:** Early harvesting and sun drying of both grain and stover has been shown to have a potential of improving the yield and nutritive value of maize stover without significant effects on grain yield and quality (Adugna, 2001).

v) **Effect of fertilization:** Fertilization, especially nitrogen, has a positive effect on straw yield, crude protein content and digestibility.

vi) **Harvesting and post-harvest storage conditions:** Harvesting, transport and storage conditions contribute to the loss of the leaf fraction, and inappropriate storage that results in too much exposure to the sun with the ultimate loss in nutritive value. Molding caused by unsuitable storage results in loss of palatability.

17.3.5. Improvement of the feeding value of tef straw

Major achievements made in the improved utilization of tef straw as animal feed are presented here-under. Since feeding of these low protein roughages hardly support the maintenance requirement thereby leading to low production and reproduction of farm animals. Various options to alleviate the constraints of poor feeding value of crop residues including tef straw, have been the focus of work both locally and globally. These revolve around the following.

i) Nitrogen (N) fertilization;
ii) N-supplementation with some of its beneficial effects including increased digestion, higher intake of low quality roughages and body weight gain, while the materials used for supplementation included egume crop residues, browse legumes (e.g. sesbania, leucaena, etc.), forage legumes, (e.g. lablab and others that may be appropriate in the mixed farming system), supplementation with by-product protein sources like oil seed cakes/meals, and supplementation with NPN sources like urea.
iii) Supplementation with energy sources and pre-formed carbon skeleton sources (e.g. molasses, bran);
iv) Mineral supplements;
v) Physical treatment;
vi) Urea treatment; and
vii) A combination of these methods.

Low nitrogen feeds like straw ferment slowly and yield low levels of rumen ammonia nitrogen that does not promote an efficient digestion process. Un-supplemented tef straw when fed to Menz sheep provided rumen NH_3-N concentrations of 21 mg^{-1}

(Bonsi *et al.*, 1994), and this is substantially lower than required concentration of 50-80 mg^{-1} for optimal microbial growth and function (Satter and Slyter, 1974).

Urea supplementation: The addition of urea to tef straw increased N-digestibility, intake, DM and NDF digestibilities by 3.7%, 8.3% and 7.3%, respectively over tef straw alone (Nuwanyakpa and Butterworth, 1987). Supplementation with molasses alone depressed digestibilities and intake. This could be reversed by adding urea, indicating that N- is the major limitation and that a combination of urea–molasses is the best supplement. Urea is administered more beneficially as part of molasses-urea mixture rather than being dissolved in water and sprinkled on to tef straw.

Supplementation with forage legumes (FLs): Supplementing straw diets with FLs is beneficial in terms of intake, microbial N synthesis and yield. These benefits correlate positively with the degradability of FLs, and are further improved by a complementary high energy substrate (Nsahlai *et al.*, 1998).

Supplementation with multi-purpose trees (MPTs): The MPTs also raise the supply of protein, which is limited in fibrous feeds, and thus, raise animal productivity through improving the utilization of carbohydrate energy and other nutrients from fibrous feeds (Leng, 1990). Supplementation with either *Leucaena* or *Sesbania* species resulted in positive live weight gain, DM intake, feed digestibility, nitrogen balance and improved rumen function in different species of animals (Reed *et al.*, 1990; Abdurazak *et al.*, 1997; Zewdu *et al.*, 2006). Daily live weight gain of sheep on a basal diet of tef straw was significantly higher in *Sesbania sesban* supplemented than in *Leucaena pallida* or *L. purpureus* supplemented sheep (Solomon *et al.*, 2003). Solomon *et al.* (2005) studied the supplementary values of different MPTs to tef straw separately and in combination. They concluded that the limitations imposed on N digestibility by high content of soluble phenolics in *Acacia angustisima* and condensed tannins in *L. pallida* can be alleviated by supplementing them as mixtures with *S. sesban*. They concluded that all the MPTs and their mixtures have desirable characteristics as potential feed supplements to tef straw compared with wheat bran or *L. purpureus*. Within the MPTs, *A. angustissima* 15132 and *L. pallida* 14203 could be inferior supplements to tef straw compared to *S. sesban* 1198 or *S. sesban* 15019. However, mixing *S. Sesban* either with *A. angustissima* or with *L. pallida* has the potential of improving the utilization of the latter MPTs. *L. leucocephala* supplementation increased the total feed intakes, total water turnover of tef straw. Sheep supplemented with 180 g/head/day consumed

49% more dry matter and turned over 54% more water compared to sheep on tef straw alone (Table 7). Given the strong relationship between feed and water intake, any feed improvement/supplementation strategy should also consider the availability of water, or supplementation would rather exacerbate dehydration and physiological stress at times of water scarcity (Zewdu *et al.*, 2006**)**.

Table 7. Mean daily straw intakes of sheep fed tef straw supplemented with graded levels of *Leucaena leucocephala*.

Components	Level of *L.leucocephala* supplementation (g as-fed /head/day)			
	0	60	120	180
Dry matter intake(g)	338.1	505.8	515.6	507.1
NDF intake (g)	276.2	413.1	421.1	414.2
Crude Protein Intake (g)	9.3	13.9	14.2	14.0
Total ash Intake (g)	26.7	40.0	40.7	40.1

Source: Zewdu *et al.* (2006)

Home-grown *Leucaena* supplements can improve the productivity of small ruminants during dry periods when feed supplies are limited. Weight gains of 79 g/day wewr obtained by supplementing 238 g dry *leucaena* to lambs fed on a tef straw-based diet compared to only 10 g/day for lambs on tef straw alone (Lema and Alemu, 1992).

Wheat bran supplementation: Wheat bran supplementation to highland zebu cattle had a significant effect ($p<0.001$) on tef straw and total dry matter (DMI) and organic matter intakes (OMI). Both DMI and OMI increased with increasing level of supplementation. However, tef straw intake increased from low (0.75 kg/head/day) to medium (2.75 kg/head/day) and then decreased because of substitution. Supplementation increased body weight gain. The average body weight gains (BWG) were 68, 459, and 477 g/day for the low, medium, and high (4.75 kg/head/day) levels of wheat bran supplementation, respectively. The medium level performed best in terms of feed conversion efficiency and cost per kg body weight gain (Tesfaye *et al.*, 2002).

Urea treatment of tef straw: Treatment of straw with urea is a promising alternative solution to enhance straw utilization by ruminants. Urea, an important non-protein nitrogen source, is available to farmers at low cost. Effects of urea treatment in improving nutritive value of crop residues in general indicate that it increases digestibility (by 8-12 points), N- content (more than doubled) and intake (increased by 25-50%). The effects of urea treatment are generally a combination of these effects. Results of an on-farm treatment of tef straw with urea (Table 8) in the north Shoa zone showed that urea treatment increased the CP content of the straw from 4.3% to 8.9 % (a 105% increase) and *in vitro* organic matter digestibility (IVOMD) by 7.1 % (from 53.2% to 57.4 %). The NDF and hemicellulose contents of tef straw were reduced by 6.04% and 26.69%, respectively (Mesfin *et al.*, 2009). The feeding value of the straw is thus substantially increased. This was supported by the opinion of participant farmers who indicated that the intervention diet improved roughage intake, milk yield and body condition of the cows during the dry season. Urea treatment of straw is a technically effective and feasible on-farm technology to improve the nutritive value of fibrous crop residues. The feeding of urea-treated straw alone will lead to some increase in production, but the full potential will only be realized when the correct supplements are added. A supplement of bypass protein is the most important.

Table 8. Composition, IVOMD and estimated ME of treated and untreated tef straw

Parameter	Untreated tef straw	Treated tef straw	Change	% Change
DM (%)	92.0	43.0	-49.0	-53.3
OM (% of DM)	92.9	93.9	1.0	1.08
CP (% of DM)	4.3	8.9	4.5	105.0
IVOMD(% of DM)	53.2	57.4	3.8	7.14
EME (MJ/kg)	8.51	9.18	0.67	7.9

Source: Calculated based on Mesfin *et a*l. (2009)

Livestock excreta: In developing countries, only poultry litter has found ready acceptance as a component of livestock feeds. It appears to play a particularly appropriate role in high molasses diets, where it complements the readily fermentable sugars and the low levels of fermentable N and P. There appears to be a particularly beneficial effect of poultry litter on rumen propionate production in cattle fed on a molasses-based diet (Fernandez and Hughs-Jones, 1981). It is well documented that this is reflected in higher levels of animal performance (Meyreles and Preston 1982; Myereles *et al.*, 1982). Poultry litter is less effective than fishmeal or an oil cake meal for supplementing cattle given a molasses or pasture-based diet, and from this it can be inferred that it provides little or no bypass protein. This is expected in view of its chemical characteristics.

Legume forages and foliages from food crops: The role of a legume must be to increase the efficiency of utilization of the basal diet (crop residue) at low levels of supplementation (usually <20%) and used “catalytically”. In situations where the fermentable N requirement can be met from other sources (e.g. Urea or animal excreta), the need is to reduce the degradability of the legume protein to increase its bypass characteristics. This has been shown to occur when a forage is artificially dried and more so when pelleted. It is likely that legume forages rich in tannins will be superior as sources of bypass protein since tannins link with proteins during mastication and appear to reduce microbial degradation of plant proteins (Reid *et al.*, 1974).

17.3.6. Genotype versus straw quantity and quality

Continuous efforts have been made to develop improved varieties of tef for grain production. However, the breeding programs are basically aimed at improvement of grain yield with little consideration for yield and quality of the straw. On the other hand, tef straw is commonly used as an important source of feed for livestock, a scenario likely to increase as more grazing land is put under cultivation due to rapidly increasing population pressure, thus reducing available grazing land. Under such circumstances, it is desirable to produce a higher yield of better quality straw without sacrificing grain yield. This will benefit both animal production and crop production and consequently the farmer. Farmers may reject high yielding varieties because of their low straw yield or poor quality of straw. Attention must, thus, be paid to residue yields and quality in crop improvement programs. Surveys to understand farmer perceptions that involve agricultural economists and animal nutritionists are needed.

Eight tef varieties were ranked based on their grain yield and in vitro organic matter digestibility (IVOMD) of the straw in a study conducted at the Debre Zeit Agricultural Research Center (Table 9; DZARC, 1989). The results showed that the rankings based on grain yield were different from the rankings based on IVOMD showing the need and possibility to explore the variabilities and combine both aspects to optimize overall benefit. Adugna (2001) has shown that there is a possibility of making a compromise without seriously affecting grain yield. White *et al.* (1981) also indicated that varieties with higher straw digestibility did not always have lower grain yields, thus, giving a chance to select for high quality crop residues without sacrificing grain yield. The differences in nutritive value may partly be due to differences in botanical fractions of the varieties. Seyoum *et al.* (1996) indicated that improved tef varieties had higher proportion of the more digestible leaf and panicle fractions compared to unimproved varieties.

Table 9. Comparison of *in vitro* organic matter digestibility (IVOMD) of straw and grain yield for eight tef varieties including the local check.

Variety	IVOMD		Grain yield	
	%	Ranking	Kg/ha	Ranking
DZ-01-481	66.2	1	2278	4
DZ-01-155	65.5	2	2095	6
DZ-01-46	65.4	3	1768	8
DZ-01-1445	65.2	4	2296	3
Local check	64.2	5	2033	7
DZ-Cr-255	63.3	6	2171	5
DZ-01-112	63.3	7	2518	1
DZ-01-354	62.3	8	2470	2

Source: DZARC (1989)

Inclusion of residue quality and quantity as a screening criterion in the tef improvement effort can be achieved by taking the potential utility index (a measure that integrates grain and digestible straw yield) as one of the parameters used in the comparison of varieties. Thus, plant breeders and animal nutritionists should jointly strive for increased overall output from the farm by improving both grain and crop residue yield and quality. The potential utility index can be calculated using the following formula recommended by Fleischer *et al.* (1989).

$$\boldsymbol{Potential\ utility\ index} = \frac{\boldsymbol{Grain\ yield(kg/ha) +\ Digestibledry\ matter\ yield\ of\ residue\ (Kg\ /ha)}}{\boldsymbol{Total\ above\ ground\ plant\ dry\ matter\ yield\ (kg\ /ha)}} \times \mathbf{100}$$

Substantial differences existed in *in vitro* digestibility between 10 varieties (4 improved and 6 local) varieties studied by Seyoum *et al.* (1996) at Holetta. The improved varieties had higher organic matter digestibility than the unimproved ones. The potential utility indices of the improved varieties were also slightly higher than that of the unimproved varieties.

17.3.7. Animal performance on tef straw-based diets

Wide variability exists in the performance of animals fed on tef straw based diets depending on the type and amount of supplements used, quality of straw and type of animal species fed (Table 10).

Feeding urea treated tef straw supplemented with linseed cake based concentrate mixture significantly ($P<0.01$) increased feed intake, milk yield, live weight gain and body condition score of cows. Due to the improvement in daily milk yield by 3.48 kg (7.14 kg *vs*. 3.66 kg) coupled with a 1.35 % cost reduction/kg of milk produced, the net profit increased from Ethiopian Birr (ETB) 4.73/cow/day in the control group to

ETB 9.39/cow/day in those fed the treated straw diet supplemented with linseed cake. This study demonstrated that the intervention diet increased the net profit for farmers to ETB 4.66/cow/day (Mesfin *et al.*, 2009)

Table 10. Animal performance on tef straw based diets.

Animal type	Average weight (kg)	Supplement		Growth (g/day)	Source
		Type	Level (%)		
Steers	186	Concentrate	50	626	IAR (1976)
Calves (crossbred)	158	Forage legume	22	207	Abule (1994)
			45	503	Abule (1994)
Sheep	20	Forage Legumes	29	37	Michael *et al.* (1989)
			40	67	Lema (1993)
		Browse	25	48	Reed *et al.* (1990)

Supplementing the tef straw feed of Arsi oxen (*Bos indicus*) with 1, 2 or 4 kg per animal per day of noug (*Guizotia abyssinica*) meal for 90 days improved growth parameters (Table 11). Supplementation significantly increased feed intake, average daily gain, and weight of dressed carcass and lean meat. Supplementation with 1 kg of noug meal was the most profitable (Ashenafi *et al.*, 2007).

Home-grown *Leucaena* supplements can improve the productivity of small ruminants during dry periods when feed supplies are limited. Weight gains of 79 g/day was obtained by supplementing 238 g dry leucaena to lambs fed on a tef straw-based diet compared to only 10 g/day for lambs on tef straw alone (Lema and Alemu, 1992).

Table 11. Feed intake, weight gain and carcass characteristics of oxen fed on tef straw supplemented with noug meal*.

Parameter	Tef straw alone	Tef straw + 1 kg/day noug meal	Tef straw + 2 kg/day noug meal	Tef straw + 4 kg/day noug meal
Tef straw intake (kg/day)	3.59c	5.32a	5.05a	4.43b
Average daily gain (kg/day)	0.24c	0.51b	0.65a	0.62ab
Dressed carcass weight (kg)	94.0b	129.0a	134.0a	130.0a
Average weight gain (kg)	22	45	53	56
Average net return/animal (ETB)	-164	151	126	114

*Means in the same column followed by different letters are significantly diffrent at P ˛ 0.05. Source: Ashenafi *et al.* (2007).

17.4. The Way Forward

i) Despite availability of scientific information and technology both locally and globally, efficient crop residue utilization has remained traditional. Efforts made to demonstrate and popularize feed technology in the country do not seem to have gone far enough. Problems related to why the available technologies regarding improved utilization of tef straw and crop residues in general did not go as desired need to be assessed.

ii) More intensive research and extension work on the integration of leguminous forage and browse species into the farming system to improve crop production, residue yield/quality and consequently animal productivity is desired.

iii) Formulation and testing of molasses/urea-based blocks of varying formulations depending on the local availability of appropriate ingredients to supplement straw-based diets need to continue. Promotion of such technology as a business venture should also be explored.

iv) Generation of survey data in relation to regional availabilities of quantities of crop residues, variation in grain: residue ratios, and studies directed towards economic aspects of residue transport and alternative uses should be explored.

v) Determining seasonal availability and nutritional values of residues and by-products to formulate and test rations biologically and economically feasible for different situations should be pursued.

vi) Assessment of the economics of different methods of straw utilization (e.g. on-farm research geared towards comparing the economic feasibility of different processing methods like urea treatment, urea supplementation, ensiling, hydration and the economics of each method for different situations) should be made. Evaluation of straw-based complete feed technology/ *densified* complete feed block technology needs to be pursued in this connection.

vii) Inclusion of residue quality and quantity as a screening criterion in the tef improvement effort by taking the potential utility index of the whole crop as one of the parameters used in the comparison of varieties is essential. Thus, plant breeders and animal nutritionists should jointly strive for increased overall output by improving both grain and crop residue yield and quality. Attention must, thus, be paid to residue yields and quality in crop improvement programs. Surveys to understand farmer perceptions that involve agricultural economists and animal nutritionists are needed.

viii) Development of simple machinery such as choppers, and less labor-intensive technologies of urea treatment and straw transport would be beneficial in improving utilization. Collaboration with agricultural engineers on the design and use of appropriate technologies is called for.

ix) More thought should be given to the transfer of technology already available to farmers and extension personnel. The case of, for example, promoting the animal drawn carts used in East Shoa to transport crop residues to areas with similar terrain in other parts of the country is worthwhile.

x) Extension workers need to train farmers and demonstrate to them as to how to implement the already known simple, feeding-value-improvement techniques such as physical processing (chopping or threshing), supplementation and urea utilization.

17.5. Abbreviations

AEZ: Agro-ecological zone; **BWG**: Body weight gain; CP: crude protein; **DMI**: Dry matter intake; **DZARC**: Debre Zeit Agricultural Research Center; **ETB**: Ethiopian Birr; **FLs**: Forage legumes; **IAR**: Inistitute of Agricultural Research; **IVDMD**: *In vitro* dry matter digestibility; **IVOMD**: *In vitro* organic matter digestibility; **ME**: metabolizable energy; **MPTs**; Multi-purpose trees; **NDF**: Neutral detergent fiber; **NEg**: Net energy gain; **NEm**: Net energy maintenance; **OMI**: Organic matter intake; **TLU:** Tropical Livestock Unit; **SNNPR**: Southern Nations, Nationalities, and People's Region.

17.6. References

Abdulrazak SA, Muinga RW, Thorpe W and Orskov ER. 1997. Supplementation with Gliricidia sepium and Leucaena leucocephala on voluntary intake, digestibility, rumen fermentation and live-weight of crossbred steers offered Zea mays stover. Livest. Prod. Sci. 49: 55-64.

Abule Ebro. 1994. Performance of crossbred calves fed tef (Eragrostis tef) straw supplemented with graded levels of cowpea (Vignia unguiculata) and Dolichos lablab (Lablab purpureus) hay. MSc Thesis, Alemaya University of Agriculture, Alemaya, Ethiopia.

Adugna Tolera. 2001. Integrated food and feed production on smallholder mixed farms: Effect of early harvesting or variety on maize grain and stover yield and nutritive value of stover. Proceedings of the Second National Maize Workshop of Ethiopia, 12-16 November, 2001, pp 187-194.

Adugna Tolera. 2008. Feed resources and feeding management: A manual for feedlot operators and development workers, SPS-LMM, pp 38.

Alemayehu Seyom Tefera, Paul Dorosh and Sinafikeh Asrat. 2011. Crop production in Ethiopia: regional patterns and trends. ESSP II working paper 16. IFPRI and EDRI. Pp 32.

ARC. 1980. Agricultural Research Council. The nutrient requirement of ruminant livestock. Commonwealth Agricultural Bureaux. London.

Ashenafi Mengistu, Abule Ebro, Tadesse Assefa, Adane Hirpa and Belete Shenkute. 2007. Effect of supplementation of tef (Eragrostis tef) straw with different levels of noug (Guizotia abyssinica) meal on worked Arsi oxen (Bos indicus), Trop. Sci. 47:49–51.

Bonsi MLK, Osuji PO, Nsahlai IV and Tuah AK. 1994. Graded levels of Sesbania sesban and Leucaena leucocephala as supplements to tef straw given to Ethiopian Menz sheep. Anim. Prod. 59:235-244.

CSA. 2006. Central Statistical Agency, Agricultural sample survey 2005/2006 Vol.IV. Report on livestock and livestock characteristics (private peasant holdings). CSA, Addis Ababa, Ethiopia

CSA. 2011. Central Statistical Agency. Agricultural sample survey for 2010. Volume I, Statistical Bulletin 505 Addis Ababa, Ethiopia.

DZARC. 1989. Debre Zeit Agricultural Research Center-AU. (1989). Annual Research Report 1988/89, Debre Zeit, Ethiopia pp 271.

Fernandez A and Hughes-Jones M. 1981. Rumen fermentation and rumen function in bulls receiving a basic diet of molasses/urea supplemented with poultry litter, sweet potato forage or wheat bran. Tropical Animal production 6:630.

Fleischer JE, Barnes AR, BAwumbile B, Amoning-Kartery K and Tieku CK. 1989. Grain yield and nutritive value of crop residues from three varieties of Maize (Zea mays L) crop. In: Said AN. and Dzowela BH (eds.). Overcoming Constraints to Efficient Utilization of Agricultural By-products as Animal Feed. Proceedings of the Fourth Annual Workshop, 20-27 October 1987, Institute of Animal Research, Mankon Station, Bamenda, Cameroun, pp 239-255.

IAR. 1976. Institute of Agricultural Research. Results of experiments in animal production. Research Report No.1. Addis Ababa, Ethiopia.

Kabaija E and Little DA. 1989. Potential of agricultural by-products as sources of mineral nutrients in ruminant diets. In: Said AN and Dzowela BH (eds.). Overcoming Constraints to Efficient Utilization of Agricultural By-products as Animal Feed. Proceedings of the Fourth Annual Workshop held at the Institute of Animal Research, Mankon Station, Bamenda, Cameroun. 20-27 October 1987, pp 142-154.

Kernan JA, Coxworth ED, Crowle WC and Spurr DT. 1984. The nutritional value of crop residues from several wheat cultivars grown at different fertilizer levels. Anim. Feed Sci. Technol. 11:301-311.

Lema Gizachew. 1993. Comparison of legume hay, urea and noug cake as protein supplements for sheep fed on tef straw. Proceedings of the 4th National Livestock Improvement Conference (NLIC), 13-15 November, 1991. Addis Ababa, Ethiopia, pp 211-215.

Lema Gizachew and Alemu Tadesse. 1992. Effects of feeding hydrated tef straw and protein sources on tef straw voluntary intake and growth of young Horro sheep grazing native pasture during the dry season. In: Stares JES,. Said AN and Kategile JA (eds.), The Complementarity of Feed Resources for Animal Production in Africa. Proceedings of the Joint Feed Resources Networks Workshop,4-8 March, 1991, Gaborone, Botswana,. pp47.

Lema Gizachew and Smit GN. 2005. Crude protein and mineral composition of major crop residues and supplemental feeds produced on Vertisols of the Ethiopian highlands. Animal Feed Science and Technology 119:143-153.

Leng RA. 1990. Factors affecting the utilization of poor quality forages by ruminants particularly under tropical conditions. Nutrition research reviews 3:277-303.

Mesfin Dejene, Seyoum Bediye, Aemiro Kehaliw, Getu Kitaw and Kedir Nesha. 2009. On-farm evaluation of lactating crossbred (Bos taurus x Bos indicus) dairy cows fed a basal diet of urea treated tef (Eragrostis tef) straw supplemented with escape protein source during the dry season in crop-livestock production system of North Shoa, Ethiopia. Livestock Research for Rural Development 21 (5): www.lrrd.org/lrrd21/5/deje21061.htm

Meyreles L and Preston TR. 1982. The role of poultry litter in molasses/urea diets for fattening diets for fattening cattle. Tropical Animal Production 7:138-141.

Meyreles L, Pound B and Preston TR. 1982. The use of Leucaena leucocephala or sugar cane tops as sources of forage in cattle diets based on molasses/urea supplemented with chicken litter and/or wheat bran. Tropical Animal Production 7:92-97.

Michael B, Teshome Shenkoru and Goshu Mekonnen. 1989. Aspects of local and exotic legumes as protein supplements for small ruminants. In: Proceedings of the 2nd National Livestock Improvement Conference (NLIC). Institute of Agricultural research, Addis Ababa, Ethiopia, pp 208-210.

Nordbloom T. 1988. The importance of crop residues as feed resources in west Asia and North Africa. In: Reed D, Capper BS and Neate JHP (eds.). Plant Breeding and the Nutritive Value of Crop Residues. ILCA, Addis Ababa, Ethiopia, pp 41-63.

Nsahlai IV, Umunna NN and Bonsi MLK. 1998. The utilization of tef (Eragrotis tef) straw by sheep fed supplementary forage legumes with or without either crushed maize grain or wheat bran. Small Ruminant Research 29:303-315.

Nuwanyakpa MY and Butterworth MH. 1987. Effects of urea, molasses, molasses-urea, noug cake and legume hay on the intake and digestibility of tef straw by highland sheep. In: Little DA and Said AN (eds.). Proceedings of a Workshop on Utilization of Agricultural By-products as Livestock Feeds in Africa. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp 87-98.

Owen E and Aboud AAO. 1988. Practical problems of feeding crop residues. In: Reed D, Capper BS and Neate JHP (eds.). Plant Breeding and the nutritive value of crop residues. ILCA, Addis Ababa, Ethiopia. pp.133-157.

Reed JD, Soller H and Woodward A. 1990. Fodder tree and stover diets for sheep: intake, growth, digestibility and effects of phenolics on nitrogen utilization. Anim. Feed Sci. Technol. 30:39-50.

Reid CWS, Ulyatt MJ and Wilson JH. 1974. Plant tannins, bloat and nutritive value. Proceedings of the New Zealand Society of Animal Production 34:82-92.

Satter L.D. and Slyter L.L. 1974. Effect of ammonia concentration on rumen microbial protein production in vitro. British Journal of Nutrition 20: 163.

Seyoum Bediye and Dereje Fekadu. 2000. Potential of tef straw as livestock feed. In: Hailu Tefera, Getachew Belay and Sorells M. (eds.) Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October, 2000, Addis Ababa, Ethiopia, pp 245-254.

Seyoum Bediye and Zinash Sileshi. 1989. The composition of Ethiopian feeds. Institute of Agricultural Research (IAR). Research Report No. 6. IAR, Addis Ababa, Ethiopia, 33pp.

Seyoum Bediye, Zinash sileshi and Tesfaye Mengiste. 1996. Tef (Eragrostis tef) straw quality as influenced by variety differences and locations. Proceedings of the 4th National Conference of the Ethiopian Society of Animal Production (ESAP), 18-19 April 1996, Addis Ababa, Ethiopia, pp 145-152.

Solomon Melaku, Peters KJ and Azage Tegegne. 2003. Effects of supplementation with L. purpureus, graded levels of L. pallida 14203 or S. sesban 1198 on feed intake and live weight gain of Menz sheep. Proceedings of the 10th Annual Conference of the Ethiopian Society of Animal Production (ESAP), 21-23 August 2003, Addis Ababa, Ethiopia, pp 327-334.

Solomon Melaku, Peters KJ and Azage Tegegne. 2005. Intake, digestibility and passage rate in Menz sheep fed tef (Eragrostis tef) straw supplemented with dried leaves of selected multipurpose trees, their mixtures or wheat bran. Small Ruminant Research 56:139-149.

Tesfaye Alemu Aredo. 2006. Studies on the utilization of crop residues and the potential of urea treated maize stover for cattle performance in East Shoa Zone, Ethiopia. PhD dissertation, Kasetsart University, Thailand. 146pp.

Tesfaye Woldemichael, Osuji PO, Asfaw Yimegnuhal and Alemu Yami. 2002. Effect of wheat bran supplementation on feed intake, body weight change and retained energy in the carcass of Ethiopian highland zebu (Bos indicus) oxen fed tef straw (Eragrostis tef) as a basal diet. Livestock in Food Security - Roles and Contributions. Proceedings of the 9th Annual Conference of the Ethiopian Society of Animal Production (ESAP), 30-31 August, 2011, Addis Ababa, Ethiopia, pp 111-124.

White LM, Hariman GP and Bergman GW. 1981. In vitro digestibility, crude protein and phosphorus content of winter wheat, spring wheat, barley and oat cultivars in eastern Montana. Agron. J. 73:117-121.

Zewdu Sisay, Teshome Shenkoru, Azage Tegegne and Yalemshet Woldeamanuel. 2006. Feed intake, water balance and water economy in highland sheep fed tef (Eragrostis tef) straw and supplemented with graded levels of Leucaena leucocephala. Eth. J. Anim. Prod. 6:67-82.

Zinash Sileshi and Seyoum Bediye. 1991. Utilization of feed resources and feeding systems in the central zone of Ethiopia. Proceedings of the Third Livestock Improvement Conference (NLIC), 24-26 May 1989, Addis Ababa, Ethiopia, pp.129-132.

VI. Economics, Extension & Value-Chain

18. Technological Change & Economic Viability in Tef Production

Setotaw Ferede
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O.Box 32, Debre Zeit, Ethiopia. Email: setotawferede@yahoo.com

Tef is a strategic commodity in the context of enhancing smallholder commercialization and improving food security in Ethiopia. Survey results showed that 27% of the total tef production in Ethiopia is destined for marketing. In terms of purchased input, tef accounts for 34% of the total fertilizer consumption in the cereal sector. The national tef production was increasing at an average rate of 4.1% per annum during the period 1994-2010. About 58% of the increment was due to an increase in productivity while the remaining 42% was due to the expansion in the cultivable land. Although a total of 32 improved tef varieties along with their recommended management practices have been released and disseminated to smallholder farmers, only few of them are adopted for extensive cultivation. These include Enatite (DZ-01-354), Tsedey (DZ-Cr-37), Magna (DZ-01-196), and the recently released variety Quncho (DZ-Cr-387 RIL 355). Profitability analysis of tef production technologies in selected tef growing areas unveiled that the marginal rate of return (MRR) for improved tef production technologies was above the minimum acceptable rate of return. Moreover, the profitability of fertilizer application measured by value cost ratio (VCR) is much higher for tef than for the other cereals. The current national scaling up project being implemented in major tef growing areas of the country has shown that there is a significant yield potential that could be achieved through improved management practices. Hence, productivity in tef could be enhanced through the dissemination and adoption of advanced technologies which include improved seeds, optimum amount of fertilizer, good husbandry and effective pest control measures.

Key words: marginal rate of return (MRR), value cost ratio (VCR), economic viability, adoption, improved technologies

18.1. Introduction

Socio-economic indicators show that tef (*Eragrostis tef*) is the most dominant cereal crop in the Ethiopian agriculture. The major Ethiopian agricultural development strategy is transforming the predominantly subsistence-oriented agricultural production into a market-oriented production system so as to improve the income of smallholder farmers. In this case, tef is a strategic crop in the context of enhancing smallholder commercialization and improving food security in Ethiopia. The crop fetches the highest price of all cereals in the local markets; and hence it serves as a cash crop. Although the consumption of tef prior to the mid-1990s was limited to local markets, it in recent years received growing export market in the Middle East, North America, and Europe (Hailu and Seyfu, 2001). However, its export has been banned in 2007 after the price hikes in the global food grain.

Furthermore, tef is the priority crop among cereals in the use of commercial inputs such as fertilizer and other agro-chemicals. For instance, it accounts for 34% of the total fertilizer consumption in the cereals sector (CSA, 2010a). Being a labor-intensive crop, tef husbandry is a source of employment and livelihood for the majority of the agricultural labor force. About 48% of the total smallholder cereal producers in Ethiopia or equivalent to 12 million people are engaged in tef cultivation (CSA, 2010a). The economic significance of tef is not limited to the grain but also to the straw production which provides an important feed source for livestock in the mixed farming systems in the highlands of Ethiopia (Seyoum and Dereje, 2001).

Despite its economic significance, the productivity of tef remains very low, barely at 1.2 ton ha^{-1}. In order to increase its productivity, recommended production technologies, mainly improved varieties, have been developed and disseminated to the smallholder farmers in the major tef growing areas over the last several decades. The main purpose of this review is, therefore, to present insights into the economic viability, the rate and intensity of adoption, and the efficiency of recommended technologies in tef production.

18.2. Performance of the Tef Sub-Sector

Tef production has been improved over the last 15 years (Fig. 1). The average annual production from 1994 to 2010 was 2.04 million tons while the average yield during the same period was 0.93 ton ha^{-1}. This accounted for about 20% of the total cereal grain production in the country. During the same period, tef was annually cultivated on 2.20 million ha of land that accounted for 29.40% of the total cereal area in the country. The figure depicts that the tef acreage did not show any decline rather it remained persistent. The crop still stands first among food crops in terms of acreage.

Although tef received limited investment in research and development compared to other cereals such as hybrid maize and wheat, it is still competitive to other cereals and is increasing in acreage. This could be attributed to the following inherent merits of the crop: i) it fetches higher price than other cereals and thereby serves as a cash crop; ii) it holds special value in the national diet (Asrat and Frew, 2001) and provides major feed source for livestock (Seyoum and Dereje, 2001); iii) it is a versatile crop due to its adaptation to diverse agro-ecological regions, and it especially performs better than other cereals under both scarce and excess moisture conditions; iv) the seeds of tef have virtually no storage pests under local storage conditions; and v) the plant has also little or no serious threats of disease problems (Hailu and Seyfu, 2001).

According to the yearly production estimates of the Central Statistical Agency (CSA, 1996-2010), tef production in Ethiopia showed a remarkable growth from 1.86 million tons in 1994/95 to 3.18 million tons in 2009/10, and this is equivalent to a 71% increment in only 15 years' period. During the same period, the average growth in total production was 4.1% per annum, while the average annual increments in area and yield were 1.7% and 2.4%, respectively (Fig. 1). These figures indicated that about 60% of the total tef production growth was due to an increase in productivity per unit area, while the remaining 40% was due to the expansion in cultivated area.

18.3. Tef Technology Development and Profitability

From the total of 32 improved tef varieties released to the farming community, 18 were developed by the Debre Zeit Agricultural Research Center while the remaining 14 were by Holleta, Melkassa, Adet, Sirinka, Areka and Bako Research Centers (MoA, 2010). For details on the varieties, see the breeding review by Kebebew *et al*. in this compilation. Among the many varieties released so far, only the varieties, *Magna* (DZ-01-196), *Dukem* (DZ-01-974), and *Enatite* (DZ-01-354) are widely grown in areas with a relatively high rainfall, whereas *Tsedey* (DZ-Cr-37) is dominantly cultivated in low moisture areas. Although *Magna* was until recently the most preferred variety due to its very white seed color for which it fetches high market price, the variety *Quncho* (DZ-Cr-387 RIL 355) has lately become the most popular variety in the country not only due to its market preferred seed color but also due to its high productivity.

Improved management practices starting from land preparation to weeding and to harvesting have also been developed as components of the tef production package. Table 1 shows a partial list of the recommendations.

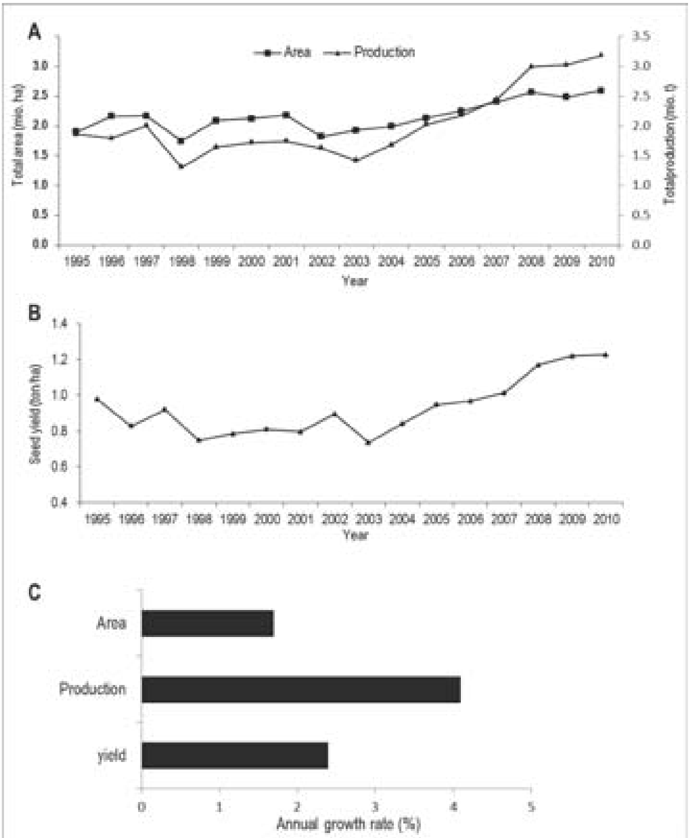

Fig. 1. The trend of tef production in Ethiopia from 1994 to 2010. A) Area of cultivation (million ha) and total grain production (thousand tons), B) grain yield (ton ha^{-1}), and C) Annual growth rate in area, production and yield. The growth rates were calculated using semi-log function ($lnX_t = a + bt$). (Source: computed from CSA Statistical Abstract various issues).

Table 1. Recommended management practices for tef production

Description	Recommended practices
Seedbed preparation	• 2-4 times before planting
Planting date	• light soils: July15-24 • Heavy soils: July 24-August 7 • In drought prone areas: July 15
Seed rate	• 25 kg ha^{-1} for light soils • 30 kg ha^{-1} for black soils
Fertilizer application	• Vertisols: 60 kg/ha P_2O_5 and 60 kg/ha N • Light soil: 60 kg/ha P_2O_5 and 40 kg/ha N • Split application of Urea (first half at planting and the remaining half during tillering)
Weeding	• 1- 2 hand weedings • 2,4-D herbicide at 0.70-1.30 l ha^{-1} at early tillering stage (about 4-5 weeks after sowing)

Source: Hailu *et.al.* (1995).

Improved agricultural technologies must be evaluated for their bio-economic[2] feasibility as well as acceptability to farmers prior to dissemination for wider adoption. The profitability of an agricultural technology, such as improved technology, is greatly influenced by the response rate, the price of the output and the costs associated with the application of the new technology (Mulat, 1999). The response rate of the technology depends on the quality of the technology, the type of agro-ecology, crop management factors, availability and access to complementary inputs. Superior technologies are less risky and generate large economic benefit, and farmers adopt such innovations with enthusiasm. Proper land preparation, planting time, and effective weed and pest control are some of the management factors that influence the productivity of the technology. Here, the extension system plays a vital role in improving the management capacity of smallholder farmers.

The price of farm output depends on the performance of the agricultural marketing system. The development of infrastructures such as roads and market sites reduces the transaction cost and ensures more competitive price. The increased farm output prices from more competitive price formation acts as production incentives for famers to adopt new technologies and increase their production. Similarly, the cost of agricultural inputs is greatly influenced by the performance of the input market. For instance, the cost and access to improved seeds depend on the performance of

[2] Bio-economic feasibility implies that the technology should have best performance (high yield) in the particular agro-ecology as well as be economically profitable.

the seed sector. Similarly, the access and fee of the credit system influence the costs of farm inputs.

The most commonly used indicators in studying the profitability of improved agricultural technologies are the marginal rate of return (MRR)[3], net returns to land and labor, and value cost ratios (VCR)[4]. Accordingly, several tef production technologies consisting of improved varieties along with their management practices have been evaluated under on-farm conditions in major tef growing areas of the country. The MRR values for the improved tef technologies in selected tef growing areas ranged from 268 to 6408% (Table 2). Although improved varieties contributed for considerable benefits in MRR, the highest MRR was obtained from the central highlands by applying 41 kg ha^{-1} of nitrogen and 20 kg ha^{-1} phosphorus fertilizers for *Magna* tef variety. According to CIMMYT (1988), the acceptable MRR values to farmers for using new technologies are between 50 and 100%. Hence, the MRR values on Table 2 showed that the adoption of improved tef production technologies in diverse agro-ecologies provides significant economic gains to farmers.

Furthermore, VCR results showed that the profitability of fertilizer application is higher for tef than for the other major cereals including maize and wheat (Table 3). For instance, the return to fertilizer use in 2010 was positive for tef with a VCR value around the threshold of 2 while the corresponding values for maize and wheat were below the threshold value.

18.4. Adoption of Improved Tef Production Technologies

A number of improved tef varieties were developed and disseminated to farmers along with optimum management practices; but no systematic studies have been made to investigate the rate and intensity of adoption by smallholder farmers. In spite of this, the available evidences indicate that several improved tef varieties have been well adopted by farmers in the major growing regions. Until recently, the varieties such as *Enatite* (DZ-01-354), *Tsedey* (DZ-Cr-37), and *Magna* (DZ-01-196)

---

[3] Marginal rate of return (MRR) is defined as the ratio of marginal net benefit (i.e. the change in net benefits) to marginal costs (i.e. the change in costs) resulting from the adoption of new technologies, and normally expressed as a percentage (CIMMYT, 1988). For instance, a MRR = 200% implies that for every Birr 1 invested in the adoption of improved tef technology, there will be an additional return of Birr 2.

[4] Value-cost ratio (VCR) is defined as the net revenue from fertilizer use divided by the price of fertilizer. The most commonly accepted guideline that provides an incentive for fertilizer use by farmers is a value of VCR ˇ 2.

were widely adopted in many areas (Teklu *et al.*, 2001; Hailu, 2008), and currently, the new tef variety called *Quncho* (DZ-Cr-387) is rapidly expanding to the most tef growing areas of the country.

Table 2. Profitability of two types of tef production technologies in selected major tef growing areas. (Alternative names of tef varieties are *Ziquala* = DZ-Cr-358, *Dukem* = DZ-01-974, *Melko*= DZ-Cr-82 and, *Enatite*=DZ-01-354).

Location	Variety/ Technology	Gross benefit (Birr/ha)	Total variable cost (Birr/ha)	Net benefit (Birr/ha)	Marginal rate of return (MRR) (%)	Referenc e
Improved tef production technology package						
North and West Shewa Zones	Non-adopters	1871.4	480	1391.4		Hailu (2008)
	Adopters	3724.45	738.85	2986.1	616	
Koka, Alem Tena, & Ziway	Local	3009	363.1	2645.59	-	DZARC (2000)
	Ziquala	4050.24	429.01	3621.23	1480.26	
	Dukem	4763	429.76	4333.07	2531.47	
Ada, Akaki, & Lume	Local	4181	469.87	3710.78	-	DZARC (2000)
	Ziquala	4856	533.51	4322.35	960.98	
	Dukem	5647	533.14	5114.01	2217.84	
Ada & Akaki, Koka, Alem Tena, & Ziway	Local	2430.83	381	2049.83	-	DZARC (1997)
	Dukem	3592.16	434.83	3157.33	2057.4	
	Ziquala	3471.09	434.83	3039.26	1838.06	
Ada & Akaki	Local	3046.86	390.56	2656.3	-	DZARC (1997)
	Dukem	4412.4	488.23	3924.17	1298.12	
	Ziquala	4139.17	488.23	3650.94	1018.37	
Moretena Jiru	Local	2427.32	381.35	2045.97	-	DZARC (1997)
	Melko	3092.7	480.11	2612.59	573.73	
	Enatite	3148.98	480.11	2668.87	630.72	
Fertilizer application						
Ada, Lume, Akaki	N/P-0/0	1103.34	176.18	927.16	-	DZARC (1994)
	N/P-20.5/10.5	1679.72	314.77	1364.95	315.9	
	N/P-36.5/15.1	1949.99	394.47	1555.52	239.1	
	N/P-41/20.1	2089.92	396.62	1693.3	6408.4	
	N/P-60.2/26.1	2483.39	503.62	1979.75	267.7	

Table 3. The value cost ratio (VCR) of fertilizer application for major crops in Ethiopia during 2009 and 2010.

Crop	Value cost ratio (VCR)	
	2009	2010
Tef	3.39	2.15
Wheat	3.25	1.88
Maize	2.51	1.36

Source: Computed from NFIU (1995)

An adoption study conducted more than a decade ago in East and West Shewa Zones showed that about 20% of the farmers grow improved tef varieties which accounted for 16% of the total tef acreage (Legesse, 1998). The adoption rate of fertilizer was higher than that of improved tef varieties. Fertilizers were applied on 93% of the total area allocated for tef. A study conducted in 1997 in North and West Shewa Zones indicated that improved tef varieties such as *Enatite*, *Tsedey* and *Magna* were widely adopted by farmers. According to Hailu (2008), 66% of the total tef growers adopted improved varieties, while 20% of the total tef acreage was planted with improved varieties.

An evaluation of the national extension program in 1999 showed that 15% of the farmers adopted the full package of improved tef technologies which consisted of varieties, fertilizer, and herbicides, while 58% of them applied both fertilizer and herbicide on the local tef cultivar (Teklu *et al.*, 2001). A recent study in Lume and Minjar-Shenkora districts unveiled that 84% of the tef farmers grow *Magna* while only 5% of the farmers grew *Quncho* in the 2008/09 cropping season (Setotaw, 2011). These two varieties accounted for 71% and 4% of the total tef acreage in Lume and Minjar-Shenkora disrticts, respectively.

Factors such as expensiveness and unavailability of seeds and lack of awareness have commonly been cited as the major constraints contributing to the low level of tef technology adoption (Teklu *et al.,* 2001). Lack of awareness was reported by 34% of the farmers as the most important factor for the non-adoption of improved tef varieties. There has been a wider consensus that the weak seed system in Ethiopia is the major limiting factor for the slow dissemination of improved tef varieties. Since the formal seed sector which consists of both the private and public seed enterprises is driven by profit, it is virtually engaged in the production of seeds of hybrid maize and wheat. In Ethiopia, the formal seed sector covers only 5% of the tef but 53% of the maize and 20% of the wheat seed requirement (Dawit *et al.*, 2007). In general, smallholder tef farmers in Ethiopia depend on the informal system involving farmer to farmer seed exchange and use of their own recycled seeds. About 50% of farmers in Lume and Minjar areas reported that seed exchange among farmers is the major source of tef seed (Setotaw, 2011).

According to CSA (2010a), only 2.4% of the total tef farmers in Ethiopia grow improved varieties on 1.7% of the total land area allocated for tef during the 2009/10 cropping season (Table 4). However, the actual adoption rate is believed to be higher than this figure since farmers often refer the seeds obtained from other farmers or saved from previous harvest as local varieties even if they are improved varieties.

On the contrary, the adoption of fertilizer application is considerably high in tef than in the other cereal crops. About 45% of tef producers apply fertilizer on their farms, and this accounts for about 40% of the total tef area in the country (Table 4). Considering the entire tef area in the country, on the average, 43 kg ha^{-1} of chemical fertilizer is applied whereas the intensity of fertilizer application is estimated at 105 kg ha^{-1} (CSA, 2010c)[5].

Table 4. Input use by smallholder farmers in Ethiopia during 2009/10 cropping season.

Crops	Total area (million ha)	Total holders		Fertilizer		Improved Seeds		Pesticide	
		Number (million)	(%)	Holders (%)	Area (%)	Holders (%)	Area (%)	Holders (%)	Area (%)
Cereals	9.23	11.86	100	47.88	29.5	11.34	3.50	24.98	13.44
Tef	2.59	5.63	47.48	45.59	41.14	2.35	1.73	30.10	16.69
Wheat	1.68	4.67	39.35	46.24	43.35	4.13	2.25	33.68	23.52
Maize	1.77	7.15	60.29	26.34	24.59	15.74	11.84	6.14	4.76

Source: CSA (2010a)

In order to promote the adoption of improved technologies in the smallholder sector, a number of extension activities have been conducted in the last several decades in the major tef growing areas. The research-extension program of the national agricultural research system played key role in the dissemination of the improved tef technologies through on-farm verification, demonstration and popularization. Tef is also considered as a priority crop by the national extension program of the Ministry of Agriculture due to its significance in food security and commercialization. For instance, during the 2009/10 cropping season, about 22% of the tef farmers in

[5] The intensity of fertilizer application, 105 kg ha^{-1}, on tef is obtained by dividing the total fertilizer consumption in tef production with only the total tef area covered with fertilizer. While the average fertilizer rate, 43 kg ha^{-1}, is estimated by dividing the total fertilizer use in tef production with the total tef acreage in the country.

Ethiopia participated in the national extension package program with the area covered by the extension program amounting to 19% of the total tef acreage (Fig. 2).

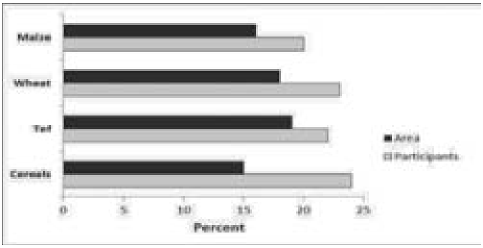

Fig. 2. The proportion of farmers and area included in the extension package program in Ethiopia for selected cereal crops in 2009/10. Source: Compiled from CSA (2010a).

It is important to note that data on tef technology adoption are lacking as compared to cereal crops such as wheat and maize. In addition, those little adoption studies on tef have some limitations. Some of these limitations include: i) some of the studies were not properly designed; hence, they lack rigorous analysis; ii) the outcomes of most of the studies do not show the adoption of a particular variety rather adoption of a group of varieties; iii) sometimes data from different sources are contradictory; and iv) most of those limited studies were very fragmented to impart any policy implications. Additional challenges related to tef adoption studies are that: i) farmers often refer seeds saved from previous harvest or acquired through exchange from other farmers as local or unimproved seeds even though the seeds are actually improved ones; ii) sometimes it is also difficult to identify the specific variety on farmers' fields due to seed contamination problem; and iii) most tef varieties have long and difficult to recall names. These complex names were retained during the release and dissemination of the improved tef varieties.

18.5. Efficiency and Productivity Potential of Tef Production

Conceptually, there are three possible options to increase tef production:

(i) Increasing the level of input use, for example, expansion in the area and increasing the level of other external inputs. In most cases, this is not the most viable option since resources like land are becoming scarce.

(ii) Improving the efficiency of resource utilization. This refers to increasing the technical efficiency of tef production by producing the maximum possible output from the same level of resources using the current technology. It also refers to narrowing the gap between the actual yield and the potential or ceiling yield.

(iii) Technological change which involves the use of new technologies such as developing new high yielding varieties. In this case, the change raises the production frontier to a higher level.

The last two options (i.e. improved efficiency and technological change which also constitute growth in agricultural productivity) are the most important sources of growth in production and have been an area of great interest for both economists and policy makers. The impact of research and development on the growth of agricultural productivity is well documented (Rosengrant and Evenson, 1992; Chavas *et al.*, 1997).

In Ethiopia, substantial resources have been invested in the dissemination of improved agricultural technologies over the past decades. In this regard, there have been several empirical studies on farm-level efficiencies to explore the possibilities for improving production and income of smallholder farmers through better allocation of resources (Abinet *et al.*, 1993; Assefa and Heidhues, 1996; Getu *et al.*, 1998; Gebreegziabher *et al.*, 2005; Khairo and Battese, 2005). Most of these studies showed average technical efficiencies ranging from 75% to 80%. This implies that considerable amount of inefficiency could be improved to increase smallholder production by 20 to 25% using the current technology and without committing extra resources. A recent study to assess the efficiency among participant and non-participant farmers in the extension package program indicated that the technical efficiencies of tef production were on the average 80% and 83% for participant and non-participant farmers, respectively (Gezahegn *et al.*, 2006). This implies that without additional resources tef production could be increased by 17 to 20% by using the current technology.

Although the estimates of technical efficiency showed limited option for further increase in tef production, the remarkable yield increase in tef varieties that has been recorded in the national scaling up program unveils the existence of high potential in elevating the productivity of the crop, and thereby raise the total production. Hence, the yield gap analysis has been used as an appropriate indicator for assessing the productivity potential of tef. The analysis enables to gauge the gap between the actual farmers' and potential yields, identify causes of the gap, and formulate strategies to improve productivity in farmers' fields.

The yield gap is a concept that has been developed from the definition and measurement of yield potential. Conceptually, the yield potential is defined as the yield of a crop when grown without any biophysical limitations other than uncontrollable factors, such as solar radiation, air temperature, and rainfall in rain-fed systems (Lobell *et al.*, 2009)[6]. The yield gap is estimated by the difference between the yield potential and average farmers' yields. Fig. 3 depicts the conceptual framework for yield gap analysis.

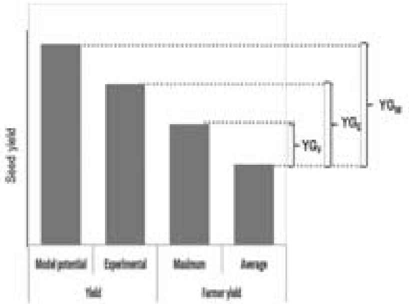

Fig. 3. Conceptual framework depicting yield gaps and measures of yield potential. YG_M = model based yield gap (yield potential is simulated with a model); YG_E = experiment-based yield gap (yield potential is estimated with a field experiment); and YG_F = farmer-based yield gap (yield potential is estimated with maximum of farmers' yields). Source: Adopted from Lobell *et al.* (2009).

Three groups of factors affect the yield gaps in farmers' fields (Duwayri *et al.*, 2000; Lobell *et al.*, 2009). These are: i) biophysical factors including varieties, inferior seed quality, weed pressure, insect damage, diseases and other pests, soil problems, drought, flooding, nutrient deficiencies and imbalances, and lodging; ii) socio-economic factors invoving profit maximization, risk aversion, labor shortage, farmers' knowledge and skills on best practices, lack of access to credit, etc; and iii) institutional factors including governments' policies, output price, agricultural credit and input supply, agricultural research and extension.

It should be noted that the major challenge in yield gap analysis is the identification of those factors that have the greatest impact, and quantify the gains that could be realized if these constraints are removed. Different approaches including on-farm experiment, crop models, and econometrics are commonly used to study the causes of yield gaps.

Based on data from the national scaling up program, farmer-based yield gap analysis was done using the preceding conceptual framework. As indicated in Fig. 4, the grain

[6] The main techniques for measuring crop yield potential include model simulations (crop models), field experiments, and maximum farmer yields (Lobel *et al.*, 2009).

yield of up to 3.6 ton ha^{-1} was reported for tef in the recent national scaling up activities. A tef yield of up to 5.0 ton ha^{-1} was recorded at the on-station trial in the past (Hailu and Seyfu, 2001). While no comprehensive research has been done to assess the yield potential of tef, researchers believe that the crop has the potential for improvement to provide a grain yield of up to 6 ton ha^{-1} through intensive management (Seyfu, 1997).

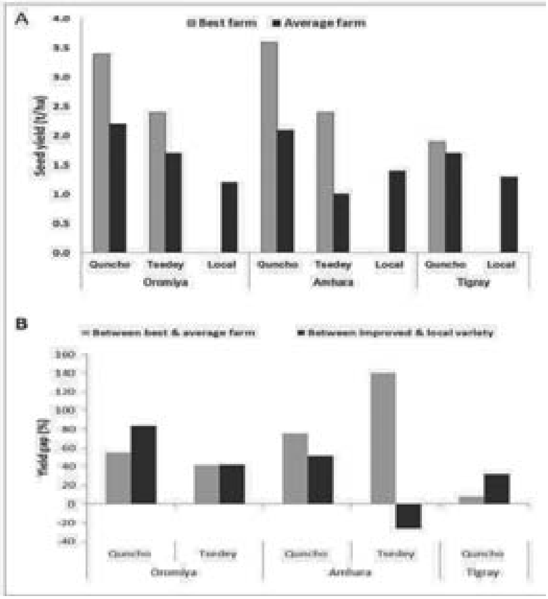

Fig. 4. Differences in tef yield due to management and varieties in Oromia, Amhara and Tigray Regions. A) The yield on best- and average-managed farm, B) the yield gap (%) due to management and varieties. Studies were made in North and South-west Shewa Zones of Oromia; East and West Gojam, and North Gondar of Amhara; and North-west and South Zones of Tigray. Source: Computed from Kebebew *et al.* (2011).

In general, the current evidences showed that there is big gap between the potential tef yield and the actual farmers' yield. Narrowing the gap offers a very lucrative opportunity to increase tef production even by using available technologies. Fig. 5 shows the estimated yield gaps in tef production that have been estimated from the national scaling up activities in Oromiya, Amhara, and Tigray Regional States during the 2009/10 cropping season. The yield gap for *Quncho* variety ranged from 55% in Oromiya to 7 5% in Amhara Regions. This implies that this technology has the potential to increase tef production by 75% and 55% in the respective regions by adopting strategies that could narrow the yield gap such as improved management practices and technical support services. The maximum yield gap of 140% was recorded for *Tsedey* in Amhara region while the same variety had a 41% yield gap in Oromiya region. This is related to the poor performance of *Tsedey* in Amhara region. As indicated on Fig. 5, the average yield of this variety was 26% lower than that of the average of the local variety. This might be due to either poor management or planting of the variety in a non-conducive environment. The same variety had a yield advantage of about 40% over the local varieties in Oromiya region. The recently released and popular *Quncho* variety gave a yield advantage ranging from 32% in Tigray to 83% in Oromiya Region.

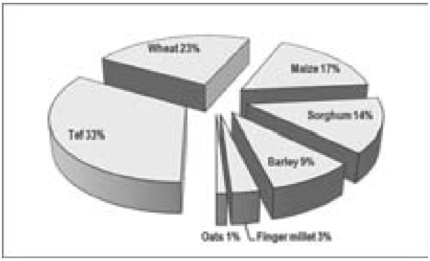

Fig. 5. The share of major crops to the total marketable surplus cereal in Ethiopia during 2009/10. Oats are often confused with emmer wheat what is also known as '*Aja*' in Ethiopia. Source: CSA (2010b).

18.6. Tef Marketing

Tef is an important cash crop for smallholder farmers in most cereal based farming systems of Ethiopia. About 27% of the total production is destined for marketing (Table 5). This makes tef a valuable crop in terms of commercialization. Furthermore, tef accounts for 33% of the total marketable surplus of cereals while wheat and maize constitute 23% and 17% of the total marketable surplus, respectively (Fig. 5). Hence, these showed that tef plays a vital role in food security and commercialization of smallholders.

Table 5. Commercialization of major cereal crops in Ethiopia during 2009/10

Crops	Total Production (thousand ton)	Marketed surplus (%)
Cereals	15 534.23	16.4
Tef	3 179.37	27.4
Barley	1 750.44	13.4
Wheat	3 075.64	19.5
Maize	3 897.16	11.6
Sorghum	2 971.26	12.1
Finger millet	524.19	14.2
Oats "Aja"	33.02	7.8
Rice	103.13	24.6

Source: CSA (2010b).

Tef production is primarily for local markets though there had been, on a limited extent, an emerging export market until it was banned in 2007 due to the soaring local and global food grain prices. In the local market, there are commonly three grades of tef based on seed color. The three grades are *Magna* (very white), *Sergegna* (mixed), and *Key* (Brown) tef. The price of tef varies depending on the grades, and the white (*Magna*) tef fetches the highest price while the brown one fetches the lowest price.

The price of tef has shown an increasing trend in the last 10 years. For instance, the average wholesale price of tef in Addis Ababa market increased from 2090 Birr ton^{-1} in 2000 to 9000 Birr ton^{-1} in 2011 (Fig. 6A). The tremendous increase in price since 2007 was mainly due to the local and global food grain crisis. The current evidences showed that there were no significant seasonal price variations for tef and other major food grains after the crisis in 2007 (Fig. 6B). The lack of seasonal price variability could perhaps be related to the improvement of market integration as a result of infrastructure development. Previous market studies showed significant seasonal price variations for major food grains, and that had been attributed to poor inter-market integration due to weak infrastructure and farmers' obligation to pay taxes as well as debts immediately after harvest (Wolday, 1995; Legesse *et al.*, 1992; Dercon, 1995).

18.7. Conclusion and the Way Forward

Tef is an important cereal crop providing the livelihoods for the majority of smallholder farmers. It is also a strategic crop with the potential to enhance commercialization of smallholder agriculture and improve food security in Ethiopia. The crop showed better performance over the last 15 years, and still remained competitive as witnessed by increases in acreage over the years. Though adoption is limited only to a few varieties, a number of improved tef production technologies have been developed and disseminated to smallholders. Most of these technologies were also proved to be economically viable. While reasonable yields have been achieved under farmers' management conditions, current evidences from the national scaling up program unveiled that large gap exists in productivity. In this regard, tef production could be further increased by applying the recommended technologies involving integrated use of improved variety seeds, fertilizer, appropriate crop husbandry and effective pest control practices.

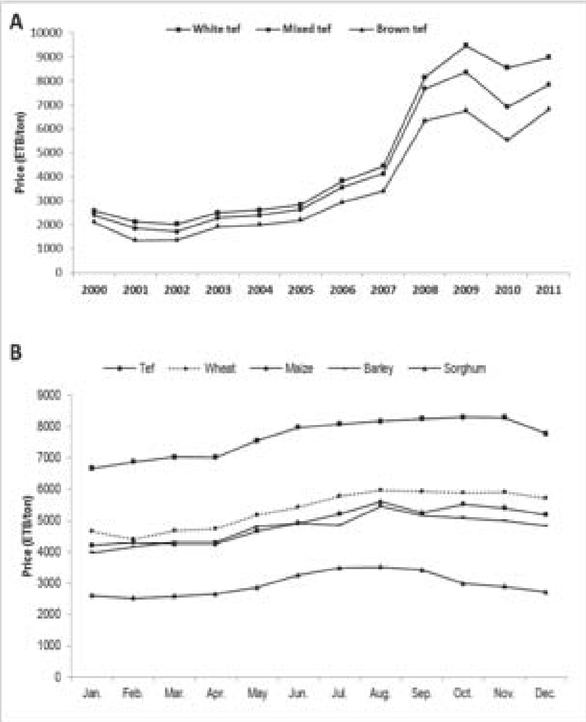

Fig. 6. The wholesale price of tef and other important cereals in Addis Ababa market. A) The annual average price of three types of tef (white, mixed and brown) from 2000 to 2011; B) the monthly average price of tef, wheat, maize, barley and sorghum from 2007 to 2010. The types grains used in the study were white tef, white wheat, white barley and white sorghum. Source: EGTE (2011).

In the future, the following points need to be considered in order to increase the productivity and production of tef:

i) No systematic study has been done on the adoption and impact of improved tef production technologies. Hence, there is a need to systematically study the impact of tef research outputs at farm household and sector levels.

ii) Important issues such as "how much of the tef yield potential is attainable on farmers' field and which factors are responsible for the apparent yield gap?" and "why there are cases where tef yields under farmers' management are well above the yield recorded under on-station conditions?" need further investigation. Although comprehensive study was not yet made to show the yield potential of tef, remarkably high yields from the national scaling-up programs indicated the presence of further yield increase in tef. It is, therefore, important to conduct studies in major tef growing regions in order to assess the gap between the actual farmers' and the potential tef yields. Identifying the major causes of the gap and formulating strategies to narrow the gap are also useful.

iii) There is a need to undertake regular updating of information on the profitability of major tef varieties along with management practices at least every 2 to 3 years in order to assess the economic viability of the technologies based on the market dynamics.

18.8. Abbreviations

CIMMYT: International Maize and Wheat Improvement Center; **CSA**: Central Statistical Agency; **DZARC**: Debre Zeit Agricultural Research Center; **EGTE**: Ethiopian Grain Trade Enterprise; **GB**: Gross Benefit; **MoA**: Ministry of Agriculture; **MRR**: marginal rate of return; **NB**: Net Benefit; **NFIU**: National Fertilizer and Inputs Unit; **TVC**: Total variable cost; **VCR**: value cost ratio; **YG_E**: experiment-based yield gap: **YG_F**: farmer-based yield gap; **YG_M**: model based yield gap.

18.9. References

Assefa Admassie and Heidhues F. 1996. Estimation of technical efficiency of smallholder farmers in the central Highlands of Ethiopia, Ethiopian Journal of Agricultural Economics 1:19-35.

Asrat Wondimu and Frew Tekabe. 2001. Utilization of Tef in the Ethiopian Diet. *In*: Hailu Tefera, Getachew Belay and Mark Sorrells (eds.). Narrowing the Rift: Tef research and development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Addis Ababa, Ethiopia, pp.239-244.

Abinet Belete, Dillon JL and Anderson FM. 1993. Efficiency of small-scale farmers in Ethiopia: a case study in the Baso and Warana sub-districts, Agricultural Economics 8:199-209.

Chavas JP, Aliber M and Cox TL. 1997. An analysis of the source and nature of technical change: the case of U.S. agriculture, The Review of Economics and Statistics 79: 482-492.

CIMMYT. 1988. From Agronomic Data to Farmer Recommendations: An Economics Training Manual. Completely Revised Edition, Mexico, D.F.

CSA. 2010a. Central Statistical Agency. Agricultural sample survey 2009/10. Report on Farm Management Practices (private peasant holdings, *Meher* Season), Statistical Bulletin 468,Addis Ababa, Ethiopia.

CSA. 2010b. Central Statistical Agency. Agricultural Sample Survey 2009/10. Vol. VII. Report on Crop and Livestock Product Utilization (Private Peasant Holdings, *Meher* Season), Statistical Bulletin 468. Addis Ababa, Ethiopia.

CSA. 2010c. Central Statistical Agency. Statistical Abstract 2010. Addis Ababa, Ethiopia.

Dawit Alemu, Mwangi W, Mandefro Nigussie and Spielman DJ. 2007. An analysis of maize seed production and distribution systems in Ethiopia's Rift Valley, Research Report 72, EIAR, Addis Ababa, Ethiopia.

Dercon S. 1995. On market integration and liberalization: Method and application to Ethiopia, Journal of Development Studies 32:112–143.

Duwayri M, Tran DV and Nguyen VN. 2000. Reflections on yield gaps in rice production: how to narrow the gaps. *In*: Minas K, Papademetriou, Frank JD and Edward MH (eds.). Bridging the rice yield gap in the Asia-Pacific Region, FAO, Regional Office for Asia and the Pacific, Bangkok, Thailand, pp. 26-46.

DZARC. 1994. Debre Zeit Agricultural Research Center, Annual Research Report 1991/92, Debre Zeit, Ethiopia.

DZARC. 1997. Debre Zeit Agricultural Research Center, Proceedings of the 1996/97 Annual Research Review/Preview Meeting, 28-30 January 1997, Debre Zeit, Ethiopia.

DZARC. 2000. Debre Zeit Agricultural Research Center, Annual Research Report 1998/99, Debre Zeit, Ethiopia.

EGTE. 2011. Ethiopian Grain Trade Enterprise, Online Market Price Data for Major Grains in Ethiopia, Addis Ababa, Ethiopia.

Gebreegziabher Z, Oskam A and Woldehanna T. 2005. Technical efficiency of peasant farmers in northern Ethiopia: A stochastic frontier approach, Proceedings of the Second International Conference on the Ethiopian Economy, 3-5 June 2004, Addis Ababa, Ethiopia.

Gezahegn Ayele, Mekonnen Bekele and Samia Zekeria. 2006. Productivity and efficiency of agricultural extension package in Ethiopia, Research Report 5, The Ethiopian Development Research Institute (EDRI), Addis Ababa, Ethiopia.

Hailu Beyene. 2008. Adoption of improved tef and wheat production technologies in crop-livestock mixed systems in Northern and Western Shewa Zones of Ethiopia, PhD Thesis, Pretoria University, South Africa.

Hailu Tefera and Seyfu Ketema. 2001. Production and importance of tef in Ethiopian Agriculture. *In*: Hailu Tefera, Getachew Belay, and Mark Sorrells (eds.), Narrowing the Rift: Tef Research and Development, Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Addis Ababa, Ethiopia. pp. 3-7.

Hailu Tefera, Mulu Ayele and Kebebew Assefa. 1995. Improved varieties of tef (*Eragrostis tef*) in Ethiopia: Releases of 1970-1995, Research Bulleting No.1. Debre Zeit Agricultural Research Center, Alemaya University of Agriculture, Debre Zeit, Ethiopia.

Getu Hailu, Bitsch V, Belay Kassa and Storck H. 1998. Technical efficiencies of smallholder annual crop production in moisture stress area of eastern Oromiya of Ethiopia: A stochastic frontier analysis, Ethiopian Journal of Agricultural Economics 2(2): 91-115.

Kebebew Assefa, Asnake Fikre, Dawit Alemu, Adefris T/ Wold (eds.). 2011. Mitigating Crop Technologies and Seed Gaps: Addressing the Unaddressed, EIAR, Addis Ababa, Ethiopia.

Khairo SA and Battese GE. 2005. A Study of technical inefficiencies of maize farmers within and outside the New Agricultural Extension Program in the Harari Region of Ethiopia, South African Journal of Agricultural Extension 34: 136-150.

Legesse Dadi, Asfaw Negassa and Franzel S. 1992. Marketing of maize and tef in Bako area: Implications for post-market liberalization policies, *In*: Franzel S and van Houten H (eds.), Research with farmers: Lessons from Ethiopia. CAB International for IAR, Ethiopia, Redwod Press Ltd, Melkisham, UK.

Legesse Dadi. 1998. Adoption and Diffusion of Agricultural Technologies: case of East and West Shewa Zone, Ethiopia, PhD Thesis, The Manchester University, UK.

Lobell DB, Cassmany KG and Fieldz CB. 2009. Crop yield gaps: Their importance, magnitudes, and causes, Annual Review of Environment and Resources 34:179-204.

MoA. 2010. Ministry of Agriculture. Crop Variety Registered Issue No. 13, Animal and Plant Health Regulatory Directorate, Addis Ababa, Ethiopia.

Mulat Demeke. 1999. Agricultural Technology, Economic Viability and Poverty Alleviation in Ethiopia, Paper presented to the Agricultural Transformation Policy Workshop, 27-30 June 1999, Nairobi, Kenya.

NFIU. 1995. National Fertilizer and Inputs Unit. Evolution of NFIU data bank: results and implications in terms of fertilizer application, General Paper No. 23, NFIU, Addis Ababa, Ethiopia.

Rosegrant MW and Evenson RE. 1992. Agricultural productivity and sources of growth in South Asia, American Journal of Agricultural Economics 74: 757-763.

Setotaw Ferede. 2011. Tef Seed System in the Smallholder Agriculture: a case study in selected major Tef-growing Districts of Ethiopia, Proceedings of Seed System Conference, 01-03 June 2011, Addis Ababa, Ethiopia (In press).

Seyfu Ketema. 1997. Tef. [*Eragrostis tef* (Zucc.) Trotter]. Promoting the conservation and use of underutilized and neglected crops 12, Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy.

Seyoum Bediye and Dereje Fekadu. 2001. Potential of tef straw as livestock feed. In: Hailu Tefera, Getachew. Belay and Mark Sorrells (eds.). Narrowing the Rift: Tef research and development, Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Addis Ababa, Ethiopia, pp.245-254.

Teklu Tesfaye, Fassil Kelemework, Abera Deresa, Elias Zerfu, Kiflu Bedane and Legesse Dadi. 2001. Tef technology transfer and adoption. *In*: Hailu Tefera, Getachew. Belay, and Mark Sorrells (eds.). Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Addis Ababa, Ethiopia, pp. 255-264.

Wolday Amha. 1995. The performance of maize and tef marketing in Southern Ethiopia. Ethiopian Journal of Economics 5: 101-131.

19. Review of Tef Research-Extension in Ethiopia

Sherif Aliy
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O. Box 32, Debre-Zeit, Ethiopia. Email: geda_sherif@yahoo.com

Many improved tef varieties have been generated, verified and disseminated to the small-scale farmers using different extension approaches and methods. However, until recently the adoption by farmers is limited to only a few varieties. This is mainly due to lack of strong collaboration among actors in the agricultural development. A technology (e.g. improved seed) or knowledge, the product of a particular research, is necessary but not sufficient to create innovation. The performance of an innovation depends not only on how an individual institute involved in research, extension or teaching performs in isolation, but on how it interacts with others as an element of collective system, and how each entity interplays with social institutions, values and norms. Moreover, the most appropriate way to improve farmers' wealth of knowledge depends less on knowledge transfer, but more in improving farmers' capacity to learn and experiment themselves. Farmers are considered as 'experts' in diverse aspects since they do not only possess detailed knowledge about their own socio-economic circumstances and livelihood strategies, but during the course of time they have also generated considerable knowledge concerning the technical inter-relationships within their local faming systems. This implies a move away from linear models of thinking about the relationships between research, extension and farmers. This paper presents an overview of the successful technological, institutional and partnership innovations undertaken in tef research-extension in Ethiopia.

Key words: Research-extension, farmer innovation, farmer-researcher Partnership

19.1. Introduction

The Ethiopian agriculture is characterized by subsistence farming and small land-holdings. Per capita land holdings are smaller in high potential areas inhabited by the majority of farmers than in areas of low potential. The national average holdings for annual crops is only 0.8 ha.(Zewdie *et al* , 2008) Individual plots are fragmented into several smaller parcels with an average of three parcels per holding. Most farmers in the northern and central highlands of the country own even smaller farms and grow diverse crops and varieties in their plots (CSA, 2003).

Tef is cultivated in Ethiopia mainly during the *Meher* or the main rainy season and to a lesser extent (like in areas such as, Shashemene, Gurage, Wello and North Shewa) also during the *Belg* or short rains. Although it is mostly grown as a mono-crop, intercropping with sorghum or safflower is not uncommon. Since both the grain and straw of tef fetch high price, it serves as an important cash crop. In addition, tef is considered as a secure crop especially at times of failures of maize and sorghum crops due to low moisture or other calamities.

19.2. The Seed Sector in Ethiopia

The seed system in Ethiopia comprises both the formal and informal sectors (Zewdie *et al.*, 2008). The formal sector includes public seed enterprises such as the Ethiopian Seed Enterprise (ESE), regional seed enterprises [including Amhara Seed Enterprise (ASE), Oromia Seed Enterprise (OSE) and South Seed Enterprise (SSE)], research institutions/centers, and private seed companies. However, the informal seed system is the dominant sector in Ethiopia since about 80-90% of the farmers use their own saved seeds or seeds obtained from their locals (Yonas *et al.*, 2008). The Informal seed sector is also the principal seed system in terms of volume of seed. Likewise, the informal seed system also accounts for about 80% of global seed distribution (Almekinders and Louwaars, 1999; Almekinders *et al.*, 1994; Jaffe and Srivastava, 1992). In Ethiopia, only 3.5% of crop area is covered with improved seeds of cereals and pulses (Abebe *et al.*, 2011). The Ethiopian annual seed requirement for cereals, pulses and oil crops is estimated to be over 400,000 tons (Thijssen *et al.*, 2008), and of this, ESE contributes only about 20,000 tons. Hence, the huge gap between the demand and supply shows that the formal sector could not ensure farmers' easy access to seeds of improved varieties. Stimulated by the fast agricultural growth and development over the recent years, the demand for improved seeds is increasing very rapidly. In line with this, the Ethiopian government encouraged the establishment of private and public seed companies/enterprises at regional level, which in turn increased the number of actors in the seed system. Despite this, substantial shortage of improved seed still exists. The major constraints for the small holder farmers are poor access, high prices and late delivery of seeds, which are exacerbated by inadequate infrastructure especially in remote and isolated areas.

Regarding tef, the major limitations in the seed system include lack of farmers' preferred varieties, limited capacity of the public seed enterprises, and little involvement of the private sector in the seed business. Wheat and maize account for about 90% of the seed supply system in Ethiopia. Moreover, the scarcity or absence of crop varieties for less favorable, drought-prone environments is worth mentioning. The present seed demand estimation method used by the Agricultural Inputs Marketing Department of the Ministry of Agriculture and Rural Development (MoARD) is no more than an expert estimate. Prospective users particularly farmers were not consulted during the planning phase. The existing market is also more of supply-oriented than demand-driven. An additional constraint related to extension and popularization, is the inadequacy of the seed available. Variety popularizations and seed promotions held by various organizations are extremely small as compared to the seed demand of the vast majority of farmers. In addition, many improved varieties of tef are not yet known by farmers, since seed production in the formal sector is restricted to crops such as wheat and maize.

Compared to the formal system, the informal system offers farmers easy access to the seed as farmer-to-farmer exchange is primarily based on social relations for information flow and exchange of goods that in some cases may make more flexible than the formal sector. Since the informal system frequently operates at the community level between households, it plays key role in strengthening social ties and reducing the transaction costs of obtaining seeds as farmers know and trust the farmer from whom they obtain the seed. The large variety of exchange mechanisms used to transfer seeds between individuals and households (i.e. cash, exchange in kind, barter, gifts or transfer based on social obligations) enhance access, particularly for households that have limited cash resources to purchase the seed. Furthermore, the informal system allows farmers to acquire the seed in small quantities, while the formal sector may provide only in large quantities. On the other hand, the major drawback of the informal sector is its weak link to the sources of new and improved seeds especially to the formal sector, although some improvements were recently reported.

19.3. Review of Agricultural Extension in Ethiopia

Agricultural extension is recognized as the conscious use of communication of information to help people form sound opinions and make good decisions (van der Ban and Hawkins, 1996). The primary goal of agricultural extension is to assist farming families in adopting their production and marketing strategies to rapidly changing social, political and economic conditions so that they can, in the long term, shape their lives according to their personal preferences and those of the community. The task of extension is, thus, to improve interactions among actors within the agricultural knowledge systems (AKS) so that farmers have optimum access to any information that could help them enhance their economic and social situation.

Various agricultural extension programs have been implemented in Ethiopia during the past one hundred years, from the time of Emperor Menelik to the establishment of the present day Participatory Demonstration and Training Extension System (PADETES) (Yonas, 2006). The first organized form of extension program was launched in 1953 by the former Imperial College of Agriculture and Mechanical Arts (now Haramaya University). The program consists of three tires, namely: research; extension; and educational activities, which were modeled after the land grant American Universities. Its aim was to deliver improved agricultural inputs and technologies to the farming community. The program was limited to certain youth groups and had no credit service and adequate human power. Certain demonstration sites were established to disseminate some imported technologies to the surrounding community and youth groups through the out-reach programs of Jimma Technical and Agricultural High School and Debre Zeit Agricultural Experiment Station. Technologies on poultry, beekeeping and vegetables as well as wheat varieties were disseminated to a limited number of farmers.

In August 1953, the Imperial Government transferred the mandate of extension service provision to the Ministry of Agriculture. Likewise, the responsibility of agricultural research was transferred to the Institute of Agricultural Research (IAR) newly established in 1966. Until, its replacement by the Ethiopian Agricultural Research Organization (EARO) in 1997 (now, the Ethiopian Institute of Agricultural Research; EIAR), it had been the only organization in the country with a clear mandate solely for agricultural research (Belay, 2002). Nevertheless, more emphasis was given to livestock improvement interventions such as poultry, beekeeping, and exotic breeds of sheep and dairy cows. The extension program had no defined target groups, but delivered advisory services on beekeeping, vegetable gardening, poultry and dairy production. The ministry’s extension service department focused on youth groups established in about 120 extension stations in the country with the assumption that they will convince their parents and the surrounding community to pursue similar activities. But the participation of the community was little or non-existent. Demonstration stations, youth clubs, and in some cases organized farmers’ days were employed to transfer the extension services to farmers. Though the approach has the opportunity to get access to the large number of farmers, non-involvement of farmers in the selection of technologies that fits into the farmers' interests, short supply of improved technologies and poor extension linkage limited its effectiveness. Until the mid-1960s, policy makers paid little attention to the development of the peasant agriculture (Belay, 2002). For instance, during the First Five-Year (1957-1961) and the Second Five-Year (1963-1967) development plans, despite its importance to the national economy, agriculture received only 14% and 21% of the total investment, respectively. Even worse, almost all the investment allotted to the agricultural sector was channeled to the expansion of large-scale commercial farms engaged in the production of cash crops for export and raw materials for local industries.

Following the increased realization of the continued stagnation of agriculture and pressure from international donors, it was only in its Third Five-Year development plan (1968-1973) that the government gave formal recognition to the peasant sector and made attempts to modernize it. However, considering limited trained manpower, and material and financial resources, the government opted for the comprehensive package approach.

In view of the limitation of the past extension programs and the need to intensify agriculture, the Ministry of Agriculture (MoA) initiated Comprehensive Package Projects (CPPs) such as Chilalo Agricultural Development Unit (CADU), later named Arsi Rural Development Unit (ARDU), in 1967, Wolaita Agricultural Development Unit (WADU) in 1970, and Ada District Development Project (ADDP) in 1972. These comprehensive integrated package projects were promoted until 1973. CADU's implementation program comprised of delivery of extension services; research; multiplication and distribution of seeds; marketing and credit services; production and dissemination of small farm implements; development of rural infrastructure like roads and water supply; and establishment of farmers' cooperatives. According to Mengisteab (1990), the method CADU adopted in reaching the peasants was basically that of demonstration of improved technologies. The project region was divided into extension areas where agricultural extension agents and model farmers demonstrated the effects of the new technologies. WADU targeted both farmers and rural women. Its extension services included: crop production; credit and marketing services, and establishment of cooperatives. It was also involved in non-agricultural activities such as cottage industries in order to address the issue of land scarcity in the densely populated area of Wolaita. However, it was immediately realized that projects in the comprehensive package failed to s erve the primary targets- the tenants and small-scale farmers. According to T esfai (1975), loans given by CADU projects favored more the land owners than the tenants. In addition, by encouraging the process of mechanization in larger commercial farms, the CADU projects accelerated the eviction of tenants (EPID, 1970; Mengisteab, 1990; Taskforce on Agricultural Extension, 1994).

It was also apparent that the CPPs were too expensive both financially and in terms of trained manpower requirements to warrant replication in other areas of the country. Although, their scale was too s mall to boost production, these programs were instrumental in developing Ethiopian expertise in agricultural intensification. Thus, by the end of the Imperial era, Ethiopia's extension services reached only about 16% of the faming population, while input and credit provision were catered largely to the so called nobles or landlords than to the smallholder farmers engaged in food production (Desalegn, 2004).

Due to these problems, in cooperation with SIDA (the Swedish International Development Agency), the Ethiopian government initiated in 1971 the Minimum Package Project - I (MPP-I), which was envisaged to be compatible with the availability of resources in the same year, the Extension and Project Implementation Department (EPID) was established in order to administer the MPPs. During its implementation from1971 to1974, MPP-I increased farmers' access to inputs such as fertilizers and improved seeds while simultaneously reducing the level and cost of services provided to smallholder farmers (Mengesteab, 1990). A minimum package area consists of about 10,000 farm households residing along a main all-weather road, about 50-75 km from the center and 5-10 km on both sides of the main road. During the implementation of MPP-I, the land was owned by the landlords. As the MPP-I was favored by these class of society, similar to CADU program, this also contributed for the displacement of peasant farmers. Since MPP-I was a top-down approach program, the community was not consulted, and did not participate in the planning and implementation process.

The MPP-II (the second phase of MPP-I) was implemented during the military government from 1974 to 1985, when major structural changes were implemented in the rural areas including the formation of peasant associations and producer's cooperatives as well as the implementation of the land reform. During this time, the formal research and extension systems were expanded throughout the country whereby agricultural production was organized around peasant cooperatives or state-owned large farms. The main purpose of MPP-II was to scale-up the extension activities to many parts of the country by targeting resource-poor farmers. To this effect, the project focused on farmers' organizations and human resource capacity building for peasant associations, service cooperatives and producers' cooperatives. It was organized into commodities like crops, livestock, forestry and soil conservation that were organized under different independent departments. Since subject matter specialists (SMS) were transferred to *wereda* or district, the program had poor representation at the grassroots (or village) level. In addition, due to the absence of collaboration among departments involved in community mobilization, organization as well as training and technical services, either resources were not properly utilized or similar activities were duplicated by different government offices. The MPP-II was replaced in 1986 by the Peasant Agricultural Development Extension Program (PADEP) in order to deliver significant changes in peasant agriculture through concerted and coordinated efforts in the areas of agricultural research and extension. The program was designed based on critical evaluation of the past extension strategies and underscored the importance of stratifying the country into relatively homogeneous zones, decentralizing the planning and execution of agricultural development activities, and empowering and providing considerable attention to zones which were to be the centers of development efforts. Accordingly, on the basis of the resemblance in climatic conditions, cropping patterns, natural resource endowments and geographical proximity, the country was divided into eight agricultural development zones. It was initially planned to concentrate on high potential areas in order to raise production and productivity by channeling the limited resources and extension services. To this effect, 148 surplus producing districts were selected out of the then total of 580 *weredas*. PADEP employed the training and visit (T&V) extension system. Following the change of government in 1991, the T&V extension approach was adopted as a national extension system until its replacement by the Participatory Demonstration and Training Extension System (PADETES) in 1995. The later was adopted from the Sasakawa-Golbal (SG) 2000 extension strategy, initiated in Ethiopia in 1993 by the Sasakawa Africa Association and Global 2000 of the Carter Center. According to Takele (1997), this technology transfer method is based on the Extension Management Training Plot (EMTP) which is characterized by on-farm technology demonstration plots established and managed by participating farmers whereby the extension agents play a facilitating role in the management of the plots. The size of each EMTP is usually half a hectare, and adjacent farmers can pool their plots to form an EMTP if they cannot meet the half hectare requirement individually. The impressive yield increments obtained by the farmers participating in the SG 2000 extension program persuaded the Ethiopian government that self-sufficiency in food production could be achieved by adopting the SG 2000 extension approach. Consequently, the government launched in 1995 the PADETES program as the national agricultural extension system, and the half-hectare demo plots were about 36,000 in the first year, and they reached about 3 million in the fourth year (MoA, 1997, 1999). Likewise, the numbers of farmers participating in PADETES also increased from 35,000 in 1995 to 3.7 million in 1998. Under PADETES, development agents were busy as they were supposed to supervise demonstration plots of up to 200 farmers. In addition, administrative matters like credit disbursement and enforcing repayment took much of the time of the development agents (Befekadu and Birhanu, 1999/2000).

In the current extension interventions, the extension packages under promotion are divided into two major categories, namely: integrated household package; and minimum package. In the integrated household package, the socio-economic data of the household are collected and based on the outcome of the study on the needs and interests of the farmers, two or more packages are supplied to the farm households capable of implementing and meeting targeted income per annum. All required inputs and training are provided by the extension system. Market is the basis for the household package selection and implementation of the activities. On the other hand, the minimum package is implemented based on the preference and economic scale of farmers who are required to obtain improved inputs by their own and apply the recommended packages on their plots, while services like training and advice may be delivered to the household by the extension system.

In general, the reported major limitations of the diverse agricultural extension approaches implemented in Ethiopia are: (i) poor research-extension linkages; (ii) limited set of technologies and technical information; (iii) lack of market integration; iv) lack of well-planned and need-based timely training; (v) failure to address gender; (vi) weak monitoring and evaluation system; (vii) poorly organized credit service delivery system; and (viii) lack of consultation with farmers on the implementation of the packages.

19.4. Research-Extension on Tef

Tef extension was started in 1970 with the release of the first variety named *Enatite* (DZ-01-354) having pale white seed color. This variety has spread to the highlands of Ethiopia owing to its excellent adaptation. During the 1970-1985, in areas far from the main market, farmers preference was the pale white seeded tef varieties like *Enatite* than the mixed or brown seeded local cultivars because of high grain and straw yield. However, in areas such as East Shewa farmers preferred very white seeded types such as *Magna* (DZ-01-196) due to high prices, although the yield was lower for *Magna* compared to *Enatite*.

Although over 30 tef varieties were released (MoA, 2010), only few are under production mainly due to unwanted pale seed color of most of the released varieties and poor extension services. It is only recently that the tef research started activities on participatory variety selection (PVS) and participatory plant breeding (PPB). According to (Getachew *et al.*, 2006, 2008), these activities enabled identification of important farmer-and consumer- preferred traits in improved tef varieties. This in turn, allowed designing of targeted crosses that eventually resulted in the development of the popular *Quncho* variety that fits into the two most important farmers' selection criteria - white seed color that fetches high price and high seed yield. The national tef research coordinated from Debre Zeit Agricultural Research Center (DZARC) implements an innovative approach that comprises two-way or multiple processes, in which several parties contribute relevant insights not only for farmers but also for researchers, extensionists, political administrators and private sectors that are involved in the processes. According to Kebebew *et al.* (2011), the fundamental features of the new extension approach comprise the following:

i) Use of technology as a package: Instead of extending a variety alone as in the former piece-meal approach, the variety is used as a driving vehicle along with all the other recommended cultural practices (like planting date, weeding, seed rate, frequency of plowing, fertilizer rate, herbicide or pesticide application rate, etc).

ii) Use of large farmers' fields: In the former approach, newly released varieties are first entered into a two- to three-years of on-farm demonstration on 10 m x 10 m plots followed by another two to three years of on-farm popularization on a similar plot size. But, in the modified approach, the new variety soon after release is on-farm demonstrated on plots of at least a quarter of a hectare. This approach reduces the time of extension activities considerably from four to six years to one year, and it also accelerated farmers' adoption of the technology because of the immediate impacts of using large plot sizes.

iii) Coordinated multi-stakeholder partnership extension method: This refers to th e establishment of collaborative partnerships between all stakeholders involved in agriculture and rural development in the target areas. The major stakeholders involved include: (1) research centers (with multi-disciplinary team of the concerned researchers); (2) bureaus of agricultural development at the zone and at the district or "*wereda*" levels: (3) development agents at the target peasant associations or ("*Kebeles*"); (4) the district or "*wereda*" administration office; (5) farmers, (6) *wereda* bureau for women and children's affairs; (7) farmers' cooperatives and farmers' primary cooperatives and cooperatives' unions; (8) public parastatal seed enterprises; (9) farmers' seed growers associations; (10) private seed growers and agro-processors; and (11) non-governmental organizations (NGOs) involved in humanitarian aid and rural development ventures in the target districts. Unlike the previous approach which involved only researchers, farmers and experts from bureau of agricultural development, the new partnerships- based approach with shared and clearly defined responsibilities and duties among each of the stakeholders has proved effective in accelerating the dissemination and adoption of the improved technologies. All stakeholders are involved from the planning stage throughout the final implementation of the planned extension activities. However, the responsibilities of coordination, and regular follow-ups and supervision of the planned activities are vested upon the bureau of agriculture and research centers. The approach facilitated researcher-to-farmer collaboration at the grassroots or peasant association ("*kebele*") and "*wereda*" levels.

iv) Revolving seed loan: In the new extension approach, participating farmers are given initial planting seeds by the research center as a loan to be paid in equivalent amount in kind after harvesting of the crop. This method has been important in addressing the problem of seed shortage especially for resource-poor farmers, and also has provided confidence and guarantees for participating farmers against uncertainties such as doubts about performance of the technology (or variety) and crop failures due to unexpected calamities.

v) Provision of regular training: In addition to its coordination role, the research center provides technical backstopping in terms of training of the farmers and other relevant stakeholders on the improved technologies and other related matters.

vi) Regular follow-up and supervision: Regular follow-up and supervision of the on-farm performances and activities of farmers by a team of researchers from Debre Zeit Agricultural Research Center in cooperation with the experts and development agents from *wereda* Bureau of Agriculture are crucial to the success of the dissemination undertakings.

vii) Provision of inputs and marketing options: The farmers' cooperatives and their unions play a vital role in the provision of required inputs (mainly fertilizers, herbicides and other pesticides) and market information, and purchase of produce from the farmers.

viii) Exchange visit: It is one of the experience sharing and learning tools by farmers visiting each-others' farms where both best and poor performing technologies are observed and discussed at the spot.

ix) Field days: This event provides opportunities to share ideas and information, and it also facilitates the spread of relevant technologies through farmer-to-farmer and farmer-to-researcher interactions. It also facilitates farmers' empowerment, thereby, increasing their influence over other stakeholders.

x) Monitoring, evaluation and impact assessment: Monitoring is a continuous assessment of both the functioning of the project activities in the context of implementation schedules and the use of the project inputs by the target population in the context of design expectation. It also ensures that inputs, work schedules and outputs are proceeding according to plan. Thus, monitoring is a process which systematically and critically observes events connected to a project in order to c ontrol the activities and adapt them to the condition. It also involves reporting, often through quarterly and annual progress reports, or oral presentations by project staff. Monitoring of the process is accomplished through *inter alia* review meetings and periodic seminars. This permits the management to investigate the progress, identify bottlenecks as well as implement corrective measures while the project is on-going.

As indicated above, regular training of trainers, farmers, research technicians and agricultural experts at various levels, development agents and other stakeholders played an important role in the success of the innovation process. The training was given every year and season in order to create awareness and understanding, and to share experiences on improved seed production, tef husbandry, tef seed systems and improved seed production, and tef value chains especially on the marketing aspects. Accordingly, a total of 21,803 farmers, 1198 development agents, 255 research technicians, 75 researchers, 345 experts from the bureaus of agriculture at various levels and 306 experts from farmers' cooperative unions and other stakeholders were given training on tef technology and production from 2006 to 2011 (Table 1). The participants represent target districts or *weredas*, Zones and Regions in the country.

Table 1. Number of farmers and other stakeholders trained on tef technology and production from 2006 to 2011.

Type of trainee	Number of trained personnel						
	2006	2007	2008	2009	2010	2011	Total
Researchers	10	10	15	20	10	10	75
Research technicians	25	35	45	50	45	55	255
Farmers	360	543	1150	6250	6000	7500	21803
Agricultural experts	35	45	40	85	65	75	345
Development agents	78	110	125	315	210	360	1198
Farmers' cooperative unions	3	3	12	28	15	25	86
Other stakeholders	25	35	25	60	30	45	220

The number of farmers participated and the area covered through the *Quncho* tef technology scaling- up activities and demonstrations from 2006 to 2011 are shown in Table 2. In the six years, the number of farmers' households directly involved in the scaling up was about 37 thousand. During the same period, the area under *Quncho* was increased tremendously, from just 150 ha in 2006 to over 11000 ha in 2011. The figures depicted on Table 2 do not include the area covered through own-saved seeds of farmers involved in the previous season scaling up activities, farmer-to-farmer seed exchange, regular extension activities of the Bureau of Agriculture, and through seeds obtained from other sources such as NGOs and other stakeholders involved in agricultural development. Moreover, we observed that during the 2011/12 main season about 97.5% of the tef area in Ada *wereda* is covered by the *Quncho* tef variety

Table 2. Number of farmers participated, area covered and yield obtained from on-farm demonstration and scaling-up of the *Quncho* tef from 2006-2011.

Year	Number of Farmers participated	Area covered (ha)	Total grain production (ton)	Average grain yield (ton ha^{-1})
2006	300	150	300.0	2.0
2007	506	253	556.0	2.2
2008	1060	530	1166.0	2.2
2009	5875	2938	6763.6	2.2
2010	14546	3635	8360.5	2.3
2011	15146	4012	9628.8	2.4
Total	36927	11518	26774.9	

19.5. Conclusion and the Way Forward

The overall management and orientation of the conventional extension system must be driven by the farmers' expressed needs and priorities. A farmer-driven orientation ensures that the extension system is serving farmers in their areas of highest need and allows for flexibility at the Regional, Zone, *wereda* and *kebele* level. The role of women in the farm household income should also be considered in setting priorities. Since most extension programs lack well-defined objectives and priorities, it is important to develop a clear and meaningful extension program for the country.

Although the main thrust of the extension program is to advance agriculture, a slight shift in emphasis is needed to link farmers to markets in response to the current realities of global competition. Linking farmers to markets is not a new thrust rather it is an emerging and imperative priority. This new thrust requires specialists in marketing and processing. The need of this kind of information requires support from the extension, which is different from the support of extension services provided in the past. Hence, extension needs to shift some of its focus from food security to increasing farm income and rural employment. This shows that extension is back on the agenda and going through major transition which calls for a change in some, if not all, of its goals, direction and expertise.

Indeed, knowledge and information systems need to be recognized as a fourth pillar alongside land, labor and capital. Knowledge is increasingly recognized as more important than physical inputs since the former makes inputs productive and explains why some technologies succeed while others fail, even when they have equal access to a particular technology or applied the same amount of physical inputs.

The numbers of Development Agents (DAs) in Ethiopia have expanded rapidly, and at the present time it exceeds 60,000. Although most DAs have the basic technical expertise and theoretical knowledge, they are deficient in specific skills which farmers demand. Most DAs have inadequate technical and business skills, and lack in entrepreneurial mind-sets. Moreover, DAs carry out the extension program from their own perspectives while farmers seek to diversify their farming system within specific agro-ecological areas. In general, due their age, lack of on-farm experience, and their narrow subject matter focus, most DAs lack the practical, hands-on skills and knowledge to enable them work with farmers effectively. Hence, DAs require training in key areas such as intensification and diversification of farming systems, agricultural marketing, and communication skills.

In a nut shell, a collaborative arrangement that brings together several organizations working towards technical and social change or organizations that are involved in generating, diffusing and adapting new knowledge in agriculture is a way out to improve and build the capacity of the conventional extension system. In Extension, no one size fits all; it is tailor made.

19.6. Abbreviations

AKS: Agricultural knowledge Systems; **ARDU**: Arsi Rural Development Unit; **ASE**: Amhara Seed Enterprise; **CADU**: Chilalo Agricultural Development Unit; **CPP**: Comprehensive Package Projects; **CSA**: Central Statistical Agency; **DA**: Development Agent; **DZARC**: Debre Zeit Agricultural Research Center; **EARO**: Ethiopian Agricultural Research Organization; **EIAR**: Ethiopian Institute of Agricultural Research; **EMTP**: Extension Management Training Plot; **EPID**: Extension and Project Implementation Department; **ESE**: Ethiopian Seed Enterprise; **IAR**: Institute of Agricultural Research; **MoA**: Ministry of Agriculture; **MoARD**: Ministry of Agriculture and Rural Development; **MPP-I**: Minimum Package Project – I; **MPP-II**: Minimum Package Project –II); **NGO**: non-governmental organization; **OSE**: Oromia Seed Enterprise; **PADEP**: Peasant Agricultural Development Extension Program; **PADETES**: Participatory Demonstration and Training Extension System; **PPB**: Participatory Plant Breeding; **PVS**: Participatory Variety Selection; **SG2000**: Sasakawa Global 2000; **SIDA**: Swedish International Development Agency); **SMS**: subject matter specialists; **T&V**: training and visit (T&V); **WADU**: Wolaita Agricultural Development Unit.

19.7. References

Abebe Atlaw, Adefris Teklewold and Dawit Alemu. 2011.Source Seed Quality Assurance Mechanisms in Ethiopia: *In*: Ensuring Seed Quality in Ethiopian Seed System: Status and Challenges, Dawit Alemu, Shiratori Kiyoshi, Abebe Kirub and Kebebew Assefa (eds.), , EIAR/FRG 11, Addis Ababa, Ethiopia.

Almekinders CJM and Louwaars NP. 1999. Farmers' Seed Production: New Approaches and Practices, Intermediate Technology Publications, London, UK.

Almekinders CJM, Louwaars NP and Bruijn GH. 1994. Local seed systems and their importance for an improved seed supply in developing countries. Euphytica 78:207-216.

Befekadu Degife and, Berhanu Niguse. (eds.). 1999/2000. Annual Report on the Ethiopian Economy, Volume II, Addis Ababa, Ethiopia.

Belay Kassa. 2002. Constraints to agricultural extension work in Ethiopia. The insiders view. South African Journal of Agricultural Extension 31:63-79.

CSA. 2003. Central Statistical Authority. Ethiopian Agricultural Sample Enumeration, Report on socio-economic characteristics of the population in agriculture households, land use area and production of crops. Part 1, Addis Ababa, Ethiopia.

Desalegn Rahmeto. 2002. Civil l Society organizations in Ethiopia: The challenge of democracy from below, ed. Zewdie Bishaw and S.Pausewang, Stockholm, Sweden, and Addis Ababa, Ethiopia.

EPID. 1970. A master plan for Extension and Project Implementation Department, Ministry of Agriculture Publication No. 1, Addis Ababa, Ethiopia.

Getachew Belay, Hailu Tefera, Anteneh Getachew, Kebebew Assefa and Giza Metaferia. 2008. Highly client oriented breeding with farmer participation in the Ethiopian cereal tef (*Eragrostis tef* (Zucc.) Trotter. African Journal of Agricultural Research 3(1):22-28.

Getachew Belay, Hailu Tefera, Birhanu Tadesse, Gizaw Metaferia, Daniel Jarra and Tadele Tadesse. 2006. Participatory variety selection in the Ethiopian cereal tef (*Eragrostis tef* (Zucc.) Trotter). Experimental Agriculture 42:91-101.

Jaffee S and Srivastava J. 1992. Seed systems development: The appropriate Roles of the private and public sectors. The World Bank Discussion papers 167, The World Bank, Washington, D.C., USA.

Kebebew Assefa, Sherif Aliye, Getachew Belay, Gizaw Metaferia, Hailu Tefera, Sorrels ME. 2011. Quncho: the first popular tef variety in Ethiopia. International Journal of Agricultural Sustainability 9(1):25-34.

Mengisteab Kifle. 1990. Ethiopia: Failure of land reform and agricultural crisis. Greenwood Press, New York, USA.

MOA. 1997. Ministry of Agriculture. Implementation of the National Extension Intervention Program in 1996/97 production year, (in Amharic), Addis Ababa, Ethiopia.

MoA. 1999.Implementation of the National Extension Intervention Program in 1998/99 production year, (in Amharic), Addis Ababa, Ethiopia.

MoA. 2010. Ministry of Agriculture, Animal Health and Plant Health Regulatory Directorate. rop Variety Register Issue No. 13, June 2010, Addis Ababa, Ethiopia,

Takele Gebre. 1997. Sasakawa Global 2000 in the Intensification of Agriculture in Ethiopia. Paper presented on the 13th Conference of Ethiopian Studies, Kyoto: 12-17 December 1997, Kyoto, Japan.

Task Force on Agricultural Extension. 1994. A Study on the Ethiopian Agricultural Extension System (in Amharic), Ministry of Agriculture (MOA), Addis Ababa, Ethiopia

Tesfai Tadese. 1975. The Evolution of Alternative rural Development Strategies in Ethiopia. Implications for employment and Income distribution, African rural Employment paper No. 12, Michigan State University, Department of Economics.

Thijssen MH, Zewdie Bishaw, Abdurahman Beshir and de Boef WS (eds.). 2008. Farmers, Seeds and Varieties: Supporting Informal Seed Supply in Ethiopia. Wageningen International, Wageningen, The Netherlands, 348 pp.

van den Ban AW, Hawkins H. 1996. Agricultural Extension. Second edition, Blackwell Science Limited, London.

Yonas Metaferia. 2006. Agricultural Extension in Ethiopia: Experiences, Challenges and Opportunities. *In*: Tsedeke Abate (ed.). Success with Value Chain: Proceedings of Scaling up and Scaling out of Agricultural technologies in Ethiopia. An International Conference, 9-11 May 2006, Addis Ababa, Ethiopia, p 225–236.

Yonas Sahlu, Belay Semane and Zewdie Bishaw. 2008. The farmer-based seed production and marketing scheme: lessons learnt. *In*: Thijssen MH, Zewdie Bishaw, Abdurahmann Beshir and Walter S (eds.). Farmers, Seeds and varieties: Supporting Informal Seed Supply in Ethiopia. Wageningen International, The Netherlands, pp 33-46.

Zewdie Bishaw, Yonas Sahlu and Belay Simane. 2008. The status of Ethiopian Seed Industry. *In*: Thijssen MH, Zewdie Bishaw, Abdurahman Beshir and Walter S. (eds.). Farmers, seeds and varieties: Supporting Informal Seed Supply in Ethiopia. Wageningen International, the Netherlands, pp23-32.

20. The Tef Seed System: Challenges & Opportunities

Dawit Alemu*, Abebe Atilaw and Setotaw Ferede
Ethiopian Institute of Agricultural Research (EIAR), P.O. Box 2003, Addis Ababa, Ethiopia. *Corresponding author: dawit96@gmail.com

*The paper presents the tef seed system within the context of the national seed systems with due emphasis to the formal sector. The performance of the formal tef seed system in terms of uptake of released varieties, and narrowing the gap between the national average productivity and the crop's average productivity level is low under farmers' conditions. This is mainly due to limited involvement of formal actors in the production and distribution of tef seed. Generally, the public seed enterprises [*viz.*, the Ethiopian Seed Enterprise (ESE), the Amhara Seed Enterprise (ASE), the Southern Seed Enterprise (SSE) and the Oromia Seed Enterprise (OSE)] and the actors of the national agricultural research system [*viz.*, the Ethiopian Institute Agricultural Research (EIAR) and the Regional Agricultural Research Institutes (RARIs)] are dominantly involved in promoting the tef seed system. The paper recommends strengthening of the tef seed system through: (i) increasing the involvement of the national and regional seed enterprises both in the production and marketing; (ii) advancement of community/farmers'-based seed production and marketing mainly through promotion of group action; and (iii) promotion of a national seed system aligned with the tef brands, which are highly associated with the origin of production.*

Key words: seed system, tef seed, seed enterprise, seed production, seed demand, seed marketing

20.1. Introduction

The creation of a vibrant seed system is considered to be a prerequisite for Green Revolution in Africa (Scoones and Thompson, 2011). Different countries are at different stages in developing their national seed system. Even though its contribution in the system is low especially in terms of the proportion of seed required to cover the planted areas, the role of the formal seed system in Ethiopia has become very critical in boosting productivity.

According to the new Growth and Transformation Plan (2011-2015) of the country, the agricultural sector is considered as a major source of economic growth, and doubling agricultural production by 2015 is the target set (MoFED, 2010). The main source of increased production is expected to be increased productivity through the use of agricultural technologies mainly seeds of improved crop varieties and fertilizer. The poor performance of the Ethiopian seed sector is recognized by the government. The newly established Agricultural Transformation Agency (ATA) gives priority to improve this weak sector.

Theoretically, seed can play a critical role in increasing agricultural productivity as it relatively determines the maximum upper limit of crop yields and the productivity of all other agricultural inputs given optimum environment in any farming system (Mywish *et al.*, 1999, Maredia *et al.*, 1999). Under the Ethiopian condition, the gap in tef productivity due to limited use of improved seed is considerably high. While the national average yield of tef is only 1.1 ton ha^{-1}, the yield using improved varieties range from 1.5 to 2.7 ton ha^{-1} on research sites and from 1.3 to 2.3 ton ha^{-1} on farmers' fields (Dawit *et al.*, 2010). Thus, in the country where about 2.8 million ha of land is allocated to tef (CSA, 2011), an increase in productivity by only a fraction of ton results in a considerable amount of production increment at the national level.

This paper presents the overview of the tef seed system in Ethiopia within the context of the national seed systems with due emphasis to the formal sector in terms of the actors and their linkages, contributions in the system, and the relevance of tef grain quality standards to the seed system.

20.2. The Ethiopian Seed System and its Performance

The national seed system is composed of both the formal and informal dimensions. Although its contribution in terms of volume is small, the formal sector plays a critical role. The formal seed system comprises the National Agricultural Research System (NARS), seed producers, seed distributors and regulators that are involved in breeding, variety release, seed production (breeder, pre-basic, basic and certified seeds), seed distribution/marketing, and regulation. Even though, different public and private actors are involved in seed production, the pricing and marketing of the seed is made centrally by the government along with provisions of loan. The distributors of seed are mostly cooperative unions and their respective member primary cooperatives.

Although the amount of improved tef varieties has been increasing since the late 1990s, only 3-6% of farmers use these improved seeds. This implies that most farmers still rely primarily on farmer-to-farmer exchanges or saved seed. However, these data are often unable to provide real insights into the adoption of improved varieties since information on the type of crop varieties cultivated and the time of seed purchase is lacking. For improved openly-pollinated varieties such as wheat and tef, farmers do not necessarily need to purchase seed each season as they would for hybrid maize; rather, they might purchase seed every 4-5 years to replace their stocks of saved seed with seed that has a higher level of purity, and thus better performance when cultivated (Spielman *et al.*, 2010; Doss *et al.*, 2003).

The performance of the formal seed system is found to be low in terms of (i) the trends in the proportion of revealed demand covered by supply, (ii) the level of use of improved varieties, and (iii) the trends in the productivity gaps that can be achieved if the performance of the system were improved.

20.2.1. The seed demand and supply trends

As indicated on Table 1, the trend in the proportion of revealed demand covered by the supply is consistently increasing since the 2006/07 cropping season for both hybrid and non-hybrid seeds. A huge increase in seed supply was observed in the 2010/11 cropping season. This was associated with the crush seed multiplication program[7] that has been implemented by the Government of Ethiopia since 2009. The crush program has considerably increased the seed supply to reach about one million tons, which was about 80% of the revealed demand for the 2011 cropping season for various regions.

Estimates of revealed demand for improved seed in Ethiopia are entirely based on official projections that are developed at the local community (or *Kebele*) level and then transmitted through the official channels to zone and regional levels, after which they are aggregated nationally to produce estimates of the type and quantity of seed that needs to be supplied in the subsequent season (Dawit *et al.*, 2007). The revealed demand in this sense means the expressed demand or interest of farmers that is assessed almost a year before the target production season; hence, it may not be converted into real demand as farmers may change the expressed demand considering the weather and the market condition. In general, this demand

---

[7]The crush program was an *ad-hoc* program initiated mainly to overcome the critical shortage of hybrid maize seed, and it was implemented by EIAR, ESE and Ministry of Agriculture (MoA). The program was criticized for excluding the private sector and for its high cost.

assessment approach can serve as an indication. However, it ignores (i) the possible demand shift that may occur due to changes in the production and market conditions (weather shift, diseases and pest incidence, price change, shift in product demand, emergence of better opportunities, etc.), and (ii) the need for provision of choice for different types of seeds (inter- and intra-crop varieties).

Table 1. The amount of revealed demand and actual supply of certified hybrid and non-hybrid seeds in Ethiopia from 2006/07 to 2010/11

Year	Certified hybrid maize			Certified non-hybrid crops			Total certified seed		
	Demand	Supply	Share of supply	Demand	Supply	Share of supply	Demand	Supply	Share of supply
	(thousand ton)		(%)	(thousand ton)		(%)	(thousand ton)		(%)
2006/07	12.38	3.52	28	62.94	20.57	33	75.32	24.09	32
2007/08	14.38	8.68	60	84.14	24.60	29	98.53	33.28	34
2008/09	19.31	9.57	50	73.80	27.83	38	93.11	37.41	40
2009/10	33.32	16.81	50	72.36	43.30	60	105.68	60.12	57
2010/11	43.26	36.53	84	93.10	71.65	77	136.36	108.18	79

Source: Data from the National Seed Production and Distribution Committee (2011).

Due to poor demand assessment, considerable amount of seed left-over is observed each year. Considering only the Ethiopian Seed Enterprise (ESE), the data for the 2011 season showed that over 8.7 thousand tons of seed produced by ESE were not sold, and 38% these seeds were hybrid maize. Due to the critical shortage of hybrid maize, each year the distribution and appropriation for different regions are made by higher officials at the federal level. The main reason for the considerable amount of hybrid maize seed left-over in 2011 was associated to the late arrival of rain, which forced farmers to shift from hybrid maize to early maturing crops and varieties.

20.2.2. The use of improved seed varieties

The main target of the National Agricultural Research System (NARS) is generation of crop varieties for different agro-ecologies, where crop improvement programs are promoted for lowland-, intermediate-, and highland-areas involving the most important crops. In addition, breeding programs for different stress conditions are performed. As a result, the NARS has generated more than 500 varieties for different crops. However, the production and dissemination of these varieties in the county is very limited. In this regard, Tripp (2010) documented the characteristics of crop varieties supplied by the Ethiopian Seed Enterprise (ESE) in terms of the number of varieties supplied, their average age and respective proportion in the supply (Table 2). Considering the availability of crop varieties for diverse agro-ecological regions, serious problem is revealed in technology multiplication, delivery and adoption especially for the newly released varieties. In case of tef, two varieties dominate the seed production (supplying more than 80% of the total seed) with average weighted age of about 22 years, even though, there are more than 30 released varieties (MoA, 2010).

Table 2. Seeds of different crop varieties sold by the Ethiopian Seed Enterprise (ESE) in the year 2009 (The average age of varieties and share of new varieties are also indicated).

Crop type	Total amount sold (thousand ton)	Number of varieties accounting for > 80% of seed sale	Weighted average age of varieties (years)	Share of varieties released since 1999		
				Seed production (%)	Number of varieties	Total number of varieties
Bread wheat	12.20	2	14.0	12.7	8	25
Durum wheat	0.12	3	19.2	24.2	2	18
Hybrid maize (public)	2.97	2	15.2	8.2	4	6
Hybrid maize (Pioneer)	2.69	3	9.4	51.7	3	4
OPV maize	0.85	2	33.1	9.1	3	7
Barley (food)	0.32	2	20.8	0.0	0	21
Tef	0.78	2	22.6	3.4	1	17
Sorghum	1.50	2	9.9	91.8	3	21
Field pea	0.04	1	15.9	0.0	0	7
Faba bean	0.23	2	23.4	22.1	1	11
Haricot bean	0.40	2	19.5	0.5	0	16
Chickpea	0.29	1	10.7	95.5	2	4

Source: Tripp (2010)

20.2.3. Performance in terms of narrowing productivity gaps

The stakes for increasing the quality and usage of commercial seed are high since widespread adoption could bring significant benefits to smallholder farmers (Dawit *et al.*, 2010). As shown on Table 3, the current national average yields for cereals and pulses are much lower than those achieved both on the research- and on farmers'-fields using recently released varieties. This demonstrates the presence of considerable yield gaps between the currently realized and potential yield for improved varieties.

20.2.4. Improved tef technology uptake

Based on CSA (2011) estimates, the area covered with improved tef has been increasing, but with an annual increase of less than 2%. Similarly, the cultivated area of tef with application of chemical fertilizer has also increased slowly and reached to about 68% of the area in the 2010/11 production season (Table 4). Due to the dominance of the informal seed system in tef seed distribution and the long-term research and extension in major tef producing areas, the figures need to be cautiously considered as farmers may use the seeds of improved variety from the informal sector and/or some improved varieties may be considered as local. Similarly, the chemical fertilizer application needs cautious consideration as the CSA estimates do not consider whether the optimum (or recommended) amount is applied or not. Recognition of the problem associated with optimum fertilizer application, a program to promote soil test-based fertilizer application, is under way through the Ministry of Agriculture.

Table 3. Productivity of major crops grown in Ethiopia under research and farmers' conditions.

Crops	National average yield (ton ha^{-1})	Research field yield (ton ha^{-1})	Farmers' field yield (ton ha^{-1})	New variety
Tef	1.2	1.5 – 2.7	1.3 – 2.3	Kena
Food Barley	1.4	2.4 – 4.9	2.0 – 4.3	Guta
Bread wheat	1.6	4.4 – 5.0	3.5 – 4.7	Gasay
Durum wheat	1.6	2.3 – 6.8	2.4 – 4.0	Flakit, Obsa
Maize[8]	2.1	8.0 – 11.0	5.0 – 6.0	Morka
Faba bean	1.3	2.4 – 5.2	2.0 – 4.2	Walki
Field pea	1.1	2.8 – 4.0	1.5 – 2.0	Ambericho
Haricot beans	1.0	2.0 – 3.0	1.8 – 2.2	SUG – 131

Source: Dawit *et al.* (2010)

Table 4. The trend of using improved seed and fertilizer for tef cultivation in Ethiopia from 2003 to 2010

Year	Total area allocated to tef (thousand ha)	Improved seeds		Fertilizer	
		Area (thousand ha)	Share (%)	Area (thousand ha)	Share (%)
2003/04	1 989.1	12.2	0.61	996.9	50.12
2004/05	2 135.6	15.4	0.72	1 138.0	53.29
2005/06	2 246.0	24.7	1.10	1 319.6	58.75
2006/07	2 404.7	13.2	0.55	1 425.1	59.27
2007/08	2 565.2	17.6	0.69	1 531.0	59.68
2008/09	2 481.3	16.6	0.67	1 429.9	57.63
2009/10	2 588.7	44.8	1.73	1 265.0	48.87
2010/11	2 761.2	40.0	1.45	1 866.4	67.60

Source: various CSA publications

[8] Morka is an open-pollinated maize variety (OPV), while the national average yield is calculated for both the hybrid and OPV.

A recent study in the major tef growing areas in the central highland particularly in Lume-Ejere and Minjar-Shenkora districts indicates a very high adoption rate of improved tef varieties (Setotaw, 2011) (Table 5). This implies that, even though the volume of certified seed supplied by the formal sector is limited, farmers have established a system whereby they produce and exchange the seed of improved varieties locally.

Table 5. The adoption of improved tef varieties and sources of seed in the central highland of Ethiopia during the cropping season of 2008/09 (Due to multiple responses by individual farmers, the sum of percent adoption for a particular item is more than 100).

Parameters	Tef varieties/seed sources	% of tef farmers
Tef varieties widely grown	*Magna (*DZ-01-196)	84
	Quncho (DZ-Cr-387)	5
	Local	40
Major seed sources	Relatives/neighbors	47
	Own (saving from previous year)	26
	Farmers' union/cooperatives	19
	Local traders	17
	Extension agent	9
	Local seed producers	9
	Research institute	3

Source: Setotaw (2011)

20.3. Actors, Linkages and Decision in Tef Seed System

The linkages and decisions in the tef seed system are depicted on Fig. 1. The main actors in the formal tef seed system are the public seed enterprises, the agricultural research institutes of the National Agricultural Research System (NARS), and cooperatives. All the public seed enterprises (namely, ESE, OSE, ASE, and SSE) are involved in seed production through farmer-based seed multiplication (FBSM). The FBSM has been widely promoted by the public seed enterprises mainly due to shortage of farmland and ever-increasing demand for seed.

In general, the public seed enterprises deal with released tef varieties in the FBSM through formal contracts with farmers in order to form clusters for the purpose of quality maintenance and also simplification of logistics and supervision. Under the prevailing arrangements, participating farmers retain sufficient seed to fulfil own demand and sell the remaining to the public seed enterprises. However, considerable amounts of seeds are usually retained by the farmers despite the agreements with the enterprises. As a result, the bulk of the seed produced by the participating farmers enters to the informal seed distribution mechanism.

As it is the case for most OPV, the seeds of improved tef varieties are mainly produced under FBSM by all the public seed enterprises (Dawit, 2011). The other branch is the supply of the tef seed as part of the technology transfer through the NARS, whereby new tef varieties are introduced to the farmers using different approaches. In order to ensure the use of promotional activities as a source of seed, the public seed enterprises and extension offices are involved. This allows for the produced seed to enter to both the formal and informal seed system as shown in Fig. 1.

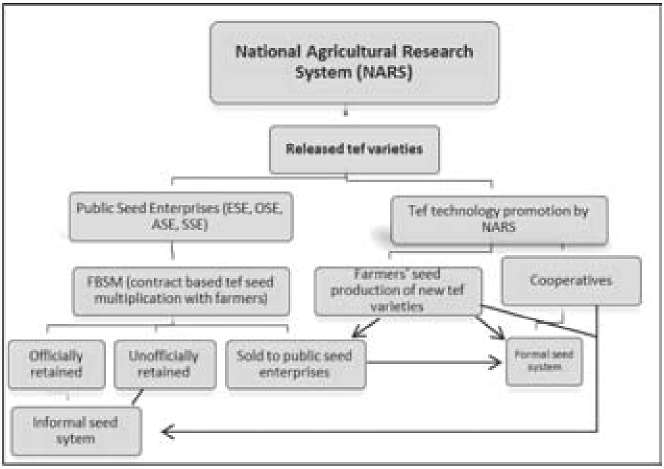

Fig. 1. Linkages and decisions in the tef seed system. NARS: National Agricultural Research System; FBSM: Farmer-Based Seed Multiplication; ESE: Ethiopian Seed Enterprise; OSE: Oromia Seed Enterprise; ASE: Amhara Seed Enterprise; SSE: South Seed Enterprise.

20.4. Tef Seed Supply From the Formal Sector: the FBSM Schemes

The formal tef seed supply is dominated by the public seed enterprises, namely: ESE, ASE, OSE, and SSE, with some contribution from the Ethiopian Institute of Agricultural Research (EIAR), Regional Agricultural Research Institutes (RARIs), and Cooperative unions mainly those found in the major tef production areas. All public seed enterprises depend on farmers- based seed multiplication (FBSM) schemes for the production of tef seed.

Although the overall contribution of FBSM to ESE’s tef seed system was 95% of the total area cultivated, and 96% of the total production, the actual amount of collected seed from FBSM was only 87% of the total ESE seed production. All the five tef varieties produced by ESE are also produced under FBSM (Table 6).

Table 6. Importance of Farmers' Based Seed Multiplication (FBSM) in the overall tef seed production during the 2009/10 cropping season.

<table>
<tr><td rowspan="5">Share of seed produced under FBSM of the total certified seed produced by ESE</td><td rowspan="2">% based on Plan</td><td>Area (ha)</td><td>90.0</td></tr>
<tr><td>Production (ton)</td><td>9.0</td></tr>
<tr><td rowspan="3">% based on Actual</td><td>Area (ha)</td><td>95.0</td></tr>
<tr><td>Total Produced (ton)</td><td>9.6</td></tr>
<tr><td>Total Collected (ton)</td><td>8.7</td></tr>
<tr><td colspan="2" rowspan="3">Total actual certified seed production</td><td>Total area (thousand ha)</td><td>329.3</td></tr>
<tr><td>Total Produced (ton)</td><td>3722.3</td></tr>
<tr><td>Total Collected (ton)</td><td>1245.8</td></tr>
<tr><td colspan="2" rowspan="2">No of varieties under production</td><td>FBSM</td><td>5</td></tr>
<tr><td>Total</td><td>5</td></tr>
</table>

Source: Dawit (2011)

Even though the FBSM contribution is the main means of tef seed production for ESE, there are also challenges, which are mainly related to (i) challenges in organizing farmers, (ii) the requirement of intensive supervision, (iii) reduced amount of supply due to quality rejection, and (iv) low recovery rates. The proportion of tef seed that was approved from the total production based on the quality is also a factor affecting the efficiency of FBSM, where about 83% of the produced seed was approved (Table 7). The recovery rate, i.e., the proportion of collected seed from the total amount approved was very low. In the 2009/10 season, the recovery rate by ESE was 37% for tef seed, which was much lower than the average for cereals (47%) but better than the average for pulses (21%) (Dawit, 2011). The major reason for the low recovery rate was linked to small price incentives given by the ESE to the participating farmers as compared to the market prices.

Table 7. Success rate of of FBSM in the implementation of tef seed production during 2009/10 season.

Parameter	Amount
Proportion of actual to planned area (%)	97.00
Proportion of approved to produced amount (%)	83.00
Proportion of approved to actually collected (%)	37.00
Actual area planted (ha)	3123.08
Total amount collected (ton)	1085.26

Source: Dawit (2011)

20.5. Role of Research-Extension and Farmers Linkage in Tef Seed System

In recent years, different approaches have been followed to strengthen the research-extension-farmers linkages so that agricultural technologies generated by the research system reach the end-users timely and effectively. Among these approaches, the most important are: (i) the pre-extension demonstration and technology popularization undertaken by research centers; (ii) farmers' research groups promoted by research centers and also by Ministry of Agriculture and Rural Development (MoARD); (iii) scaling up of agricultural technologies by research centers in collaboration with other partners; and (iv) institutionalization of Agricultural and Rural Development Partners Linkage Advisory Councils (ARDPLACs) at federal, region, Zone and wereda levels (Dawit *et al.*, 2011).

These approaches have been instrumental in injecting new technologies into the informal seed system; the research-based scaling up approach has specifically played an important role in making the technologies available in areas with limited awareness and access. The research-based scaling up approach has been implemented by the research system to support the national initiative of the "scaling up of best practices" in general and the "scaling up of agricultural technologies" in particular. The approach was designed to make sure that: (i) different agro-ecologies, production areas and regions that have limited access to available technologies are reached; (ii) both the formal and informal seed systems in these areas are triggered to use the available technologies; and (iii) functional linkages among different actors in the research-extension continuum are created. According to the program, about 6000 new farmers have access each year to new tef technologies in the four major regions, namely: Tigray, Amhara, Oromiya and SNNP during the 2009 to 2011 implementation period. The farmers in the program were also linked to other actors in the seed system like the regional seed enterprises and Bureaus of Agriculture for the purchase of the seed.

20.6. Tef Seed and Grain Quality Standards

The tef seed standards set by the ES 416:2000 of the Ethiopian Standards Agency /ESA/ (the former Quality and Standards Authority of Ethiopia) are determined in terms of field and laboratory standards and recognize breeder/pre-basic (A), basic (B), Certified (C1, C2, C3, D), and commercial/emergency class seeds (QSAE, 2000).

The adaptation to different agro-ecologies has created the opportunity to grow tef in most of the country. The Ethiopian Standards Agency recognizes four classes of tef grain regardless of the place of production (ES 671: 2001). These are: (i) very white (or *Magna*) with 98 to 100% very white grain; (ii) white (*Nech*) with 95 to 98% or more white grain; (iii) brown (*Key*) with 94 to 100% brown grain; and (iv) mixed (*Sergegna*) with a mixture of white and brown grain in a greater or in a lesser proportion of the above classes (QSAE, 2001). However, in practice, tef is identified mainly by its origin of production. The major production areas that serve as brands are Ada’a, Wolenkomi, Becho, Tullu Bollo, Ginchi, Minjar, and Gojam (Bichena, Adet, Motta and Dejen). The four classes (namely *Magna, Nech, Key, and Sergegna*) are then recognized for each brand of tef.

20.7. Tef Grain Marketing and Relevance to Seed System

There is considerable difference in the price of tef grain based on the origin of production. Surprisingly, the grain originated from the same variety but grown in dissimilar region receives different prices. As indicated on Fig. 2, *Magna* fetches the highest price compared to other types of tef. However, *Magna* from Ada'a area receives higher price than *Magna* from other locations or regions. The price differences are highly associated with the color preference and "injera" baking qualityf. This led to limited production of *Key tef* in the major production areas especially in Minjar and Ada'a areas as farmers prefer to grow *Magna* tef.

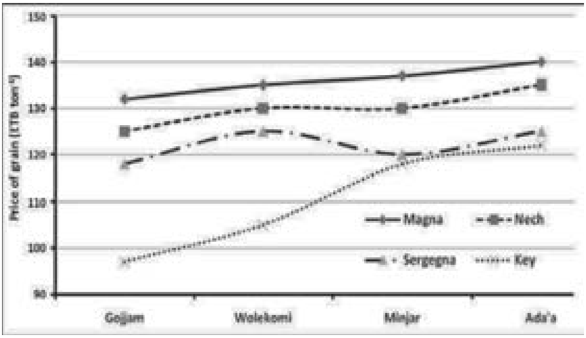

Fig. 2. Influence of type of seed and origin of production on the price of tef. The average price of four types of tef (*Magna*, *Nech*, *Sergegna*, and *Key*) originated from four growing areas (*Gojjam*, *Wolenkomi*, *Minjar* and *Ada’a*) at Addis Ababa market in 2011.

The difference in baking quality might be related to the variability in environmental conditions where the crop is grown. Considerable variability in the baking quality of *injera* was also observed between tef grown in Idaho, USA and that imported from Ethiopia, which might be due to differences in environmental conditions where the crop grows and/or changes in the type of microflora in the dough during fermentation (Piccinin, 2010). Hence, localized seed production and marketing strategy should be based on both market created brand (i.e., origin of production) and class of the seed (i.e., color of the grain). This also promotes modern marketing of tef seed, and its inclusion in the Ethiopian Commodity Exchange (ECX).

The current marketing recognizes a number of other classes of tef as compared to the classes set by the Ethiopian Standard Agency (ES 671: 2001). For each of the four main classes of tef, several subclasses were identified which complicates the marketing system. Thus, it would be important to promote the classes set by the Ethiopian Standard such that the growers would not only produce the seed but also label it according to the four classes, namely *Magna, Nech, Sergegna* and *Key*.

20.8. The Need for Seed Branding

The obvious difference between the grain classes set by the Ethiopian Standard and the market is a challenge for the production and marketing of tef. This affects mainly the modernization of the marketing system like its trade through the Ethiopian Commodity Exchange (ECX). Hence, there is a need to apply the existing norms of the Ethiopian Standards Agency (ESA) on tef grain. If the country implements the standard system based on the origin of production, there would also be a need to promote localized seed system for the major tef growing areas. Since there are also different classes, there is a need for further standardization of the classes for each production area along with promotion of seed brands.

20.9. Conclusion and the Way Forward

The agricultural sector in Ethiopia is expected to play a key role in the overall economic growth with a target of doubling the production by 2015 (MoFED, 2010). The main source of this growth is the productivity gains through the use of available improved technologies. This requires a vibrant seed system that gives the opportunity for farmers to have access to improved seeds in sufficient quantity and time, and at affordable price. However, the performance of the Ethiopian seed system in general and that of the tef seed system in particular is recognized to be very low especially in terms of technology uptake. Although improved cultivars are grown on less than 2% of the total area allocated to tef in Ethiopia (NSPDC, 2009), in some specific locations, the share of improved varieties reaches up to 84% (Setotaw, 2011).

The role of the formal seed system is very limited mainly due to the restricted involvement of the public seed enterprises and non-involvement of private seed companies. Thus, the major share of seed provision is taken by the informal system. Within the informal system, the key role is played by the NARS in injecting new technologies into the system. Thus, it is important to strengthen the role of the public seed enterprises for increased supply of improved seeds along with the promotion of alternative options through group action mainly through capacitating cooperatives as business entities in tef seed production and marketing.

Unlike other cereals, the classes made for the tef grain by the Ethiopian Quality and Standards Agency and the market are different. These differences in classification are a challenge to marketing, and call for a system that also recognizes both the market and the official grain standards in order to promote localized seed system and branding.

20.10. Abbreviations

ARDPLAC: Agricultural and Rural Development Partners Linkage Advisory Council; **ASE**: Amhara Seed Enterprise; **ATA**: Agricultural Transformation Agency; **CSA**: Central Statistical Agency; **ECX**: Ethiopian Commodity Exchange; **EIAR**: Ethiopian Institute Agricultural Research; **ESA**: Ethiopian Standards Agency; **ESE**: Ethiopian Seed Enterprise; **FBSM**: Farmer-Based Seed Multiplication; **MoA**: Ministry of Agriculture; **MoARD**: Ministry of Agriculture and Rural Development; **MoFED**: Ministry of Finance and Economic Development; **NARS**: National Agricultural Research System; **NSPDC**: National Seed Production and Distribution Committee: **OPV**: open-pollinated variety; **OSE**: Oromia Seed Enterprise; **QSAE**: Quality & Standards Authority of Ethiopia; **RARI**: Regional Agricultural Research Institute; **SSE**: Southern Seed Enterprise.

20.11. References

CSA. 2011. Central Statistical Agency. Agricultural sample survey for 2010. Volume I, Statistical Bulletin 505, Addis Ababa, Ethiopia.

Dawit Alemu. 2011. Farmers' based seed multiplication in the Ethiopian seed system: approaches, priorities and performance. Paper presented at the International Conference on the Ethiopian Seed System, June 1-3, 2011, Addis Ababa, Ethiopia.

Dawit Alemu, Adefris Teklewold, Asnake Fikre and Solomon Assefa. 2011. The role of scaling up in mitigating technology and seed gaps. *In*: Kibebew Assefa, Asnake Fikre, Dawit Alemu and Adefris Teklewold (eds). Proceedings of a workshop on Mitigating crop technologies and seed gaps: addressing the unaddressed. Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia, pp 75-83.

Dawit Alemu, Mwangi W, Mandefro Nigussie and Spielman DJ. 2007. An analysis of maize seed production and distribution systems in Ethiopia's Rift Valley. Research Report 72. EIAR, Addis Ababa, Ethiopia.

Dawit Alemu, Rashid S and Tripp R. 2010. Seed system potential in Ethiopia: Constraints and opportunities for enhancing the seed sector. International Food Policy Research Institute. Washington DC. 62pp.

Doss, C. R., W. Mwangi, H. Verkuijl, and H. de Groote. 2003. Adoption of Maize and Wheat Technologies in Eastern Africa: A Synthesis of the Findings of 22 Case Studies. CIMMYT Economics Working Paper 03-06. Mexico, D.F.: CIMMYT

MoFED. 2010. Ministry of Finance and Economic Development (MoFED). Growth and Transformation Plan: 2010/11-2014/15. Federal Democratic Republic of Ethiopia. Volume I: Main Text. Addis Ababa, Ethiopia. 135pp.

Maredia M, Howard J, Boughton D, Naseem A, Wanzala M and Kajisa K. 1999. Increasing Seed System Efficiency in Africa: Concepts, strategies and issues. MSU International Development Working Paper No. 77, 1999. Michigan State University, USA.

MoA. 2010. Ministry of Agriculture, Animal and Plant Health Regulatory Directorate. Crop Variety Register Issue No. 13, June 2010, Addis Ababa, Ethiopia, 227pp.

Mywish M, Howard J and Bouhton D. (1999. Increasing seed system efficiency in Africa: Concepts, strategies and issues. International Development Working Paper. East Lansing, MI: Michigan State UniversityNSPDC. 2009. National Seed Production and Distribution Committee. Improving Seed supply and Future Interventions, Addis Ababa, Ethiopia:, Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia.

Piccinin D. 2010. More About Ethiopian Food: Teff. Available at http://ethnomed.org/clinical/nutrition/more-about-ethiopian-food-teff.

QSAE. 2000. The Quality and Standards Authority of Ethiopia. Ethiopian standard for certifying tef seeds. ES 416:2000, Addis Ababa, Ethiopia, 3pp.

QSAE. 2001. The Quality and Standards Authority of Ethiopia. Ethiopian standard for grading of tef grain (*Eragrostis tef*). ES 671:2001, Addis Ababa, Ethiopia, 3pp.

Scoones I. and Thompson J. 2011. The Politics of Seed in Africa's Green Revolution: alternative narratives and competing pathways. IDS Bulletin Volume 42 Number 4.

Spielman David, Derek Byerlee, Dawit Alemu and Dawit Kelemework. 2010. Policies to Promote Cereal Intensification in Ethiopia: The Search for Appropriate Public and Private Roles. Food Policy. Food Policy 35 (2010) 185–194.

Setotaw Ferede. 2011. Tef seed system in the smallholder agriculture: a case study in selected major tef-growing districts of Ethiopia. Paper presented at the International Conference on Ethiopian Seed System, June 1-3, 2011, Addis Ababa, Ethiopia.

Tripp Robert. 2010. Ethiopia Seed Analysis. A report submitted to Melinda and Gates Foundation.

21. Analysis of Tef Value Chain in Ethiopia

Bekabil Fufa, Befekadu Behute*, Kathryne Benesh, Rupert Simons and Tareke Berhe
Agricultural Transformation Agency, P.O. Box 708, Addis Ababa, Ethiopia.
*Corresponding author: befekadu_be@yahoo.com

Tef is the dominant cereal crop in over 30 of the 83 high-potential agricultural Woredas, covering the highest area planted in the country. Yet, compared to the other major cereals, the tef yield is relatively low (around 1.2 t ha^{-1}) since25-30% of each of pre- and post-harvest losses reduce the quantity available to consumers by up to 50%. Moreover, production costs are relatively high with fertilizer prices, and labor required for land preparation and weeding accounting for the bulk of the costs. The results of this study showed that tef research is constrained by lack of adequate resources. Seed and fertilizer adoption rates are limited by the shortage of improved varieties suitable to diverse agro-ecologies and growing seasons, and the absence of adequate amount of appropriate fertilizer blends and the associated high costs of fertilizers. On the marketing side, the results showed that tef value chain is fragmented leading to high mark-ups and inter-seasonal price variation. It was also found out that processing of tef grain is limited only to flour and injera making mainly with small number of urban processors. The nutritionally rich nature of tef has not been explored for the latent potential as an industrial crop. Likewise, export is very restricted so as to avoid raising consumer prices further and overcrowd domestic demand. Thus, strengthening tef research, investing on technologies that reduce the labor intensiveness of the crop, development of varieties that are less prone to shattering, promotion of harvesting and threshing technologies and strategies that link farm level production to agro-industries would help to increase the production and productivity of tef, and increase value addition.

Key words: Tef, production, pre- and post-harvest losses, value chain efficiency

21.1. Introduction

Over the past few years, the Ethiopian government has designed and implemented several economic development plans, notably the Sustainable Development and Poverty Reduction Plan (SDPRP), which covered the years 2002/03 to 2004/05 and a Plan for Accelerated and Sustainable Development to End Poverty (PASDEP) that ran from 2005/06 to 2009/10. Available data shows that the country had registered a GDP growth rate of more than 11% over the period 2002-2008 (NBE, 2009). Over those years, agriculture remained the main sector of the economy accounting on average for about 45% of the GDP of the country, whereas the average contributions of the industry and service sectors were about 13% and 42%, respectively (MoFED, 2011). Based on the experiences gained from the previous two plans, the Growth and Transformation Plan (GTP) has been adopted as a national planning document for the years 2010/11-2014/15 (MoFED, 2010). The priorities determined for the agricultural sector include: i) increasing capacity and extensive use of labor; ii) increasing agricultural land utilization; iii) linking specialization with diversification; iv) strengthening the agricultural marketing system; and v) scaling up best practices in the sector (MoFED, 2011). According to the plan, the Ethiopian Government aims to double agricultural production in the five years. However, this target is challenged by specific sectoral and systemic constraints, which require new approaches to overcome them.

Tef has enormous potential for growth as it is the second most widely produced and consumed cereal in Ethiopia. The CSA (2010) data show that tef ranked first in terms of area coverage (accounting for 28% of the cereal area) and is second to maize in terms of volume of production among cereals, accounting for about 20% of the total cereal produce in the category. According to Seyfu (1989), tef has remained an important crop to the Ethiopian farmers for several reasons: i) the price for its grain and straw are higher than the other major cereals; ii) the crop performs better than other cereals under moisture-stress and waterlogged conditions; iii) its grain can be stored for a long period of time without being attacked by weevils; iv) there is no disease epidemic that has threatened its performance; v) '*injera*' made of tef flour is a staple diet of most Ethiopians, while the straw provides a nutritious feed for cattle; and vi) the straw is used as a binder of mud used for plastering walls of local houses. The average growth rate of *Meher* (main rainy) season tef production over the past few years has been around 11% per year (CSA data various years). Increased productivity is believed to contribute about 6% of the growth, while about 5% was attributed to expansion in the area cultivated to tef (Table 1).

Tef is likely to remain a favorite crop of the Ethiopian population, and the crop is also gaining popularity as a health food in the western world. It is a gluten free crop, which makes it is suitable for patients with celiac disease, which is an allergy to gluten protein (Dekking and Koning, 2005).

Table 1. The total cultivated area, production and productivity of tef from 2003 to 2010.

Year	Area		Production		Yield	
	million ha	% change	million ton	% change	ton ha^{-1}	% change
2003/2004	1.99	-	1.677	-	0.843	-
2004/2005	2.13	7.36	2.025	20.76	0.948	12.45
2005/2006	2.25	5.17	2.175	7.41	0.969	2.22
2006/2007	2.40	7.06	2.438	12.05	1.014	4.64
2007/2008	2.56	6.67	2.993	22.77	1.167	15.09
2008/2009	2.48	-3.27	3.028	1.17	1.220	4.54
2009/2010	2.59	4.33	3.179	5.00	1.228	0.66
2010/2011	2.76	6.66	3.483	9.57	1.262	2.77
Average	2.40	4.85	2.625	11.28	1.081	6.05

Source: CSA (various years): Central Statistical Agency (CSA) - Estimates of *Meher* season Area, Production and Yield of Tef.

21.2. Research Methodology

This study was conducted by identifying and contacting relevant players and stakeholders along the tef value chain in Ethiopia. It used both primary and secondary data. The primary data were collected through group discussions and key informant interviews by using checklists prepared for the study.

A group discussion was carried out with Debre Zeit Agricultural Research Center's tef research team in order to gather information on available tef technologies and major constraints faced in tef research.

Farm level information on tef production, pre- and post- harvest handling and marketing were collected through Farmers' Group Discussions that were conducted in major tef producing areas of Ethiopia that included Ada, Becho, Shashemene and Dejen. In addition, key informant interviews were conducted with agricultural extension personnel to obtain information on tef technology utilization and constraints faced by farmers.

Furthermore, information related to tef marketing was obtained from those involved in the marketing chain including local assemblers, brokers, whole sellers, millers and processors of *'injera'*. In addition, secondary data were collected from relevant sources such the Central Statistical Agency (CSA), the Ethiopian Grain Trading Enterprise (EGTE) and the Food and Agriculture Organization (FAO) database, workshop proceedings, and published and unpublished documents.

The data collected were analyzed by using qualitative and quantitative analytical tools. Most of the qualitative data collected were narrated, and the quantitative data were analyzed using descriptive statistics tools.

21.3. Current State of the Tef Value Chain

A value chain describes the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use (Kaplinsky and Morris, 2000). For tef, the stages of the value chain identified are research, seeds and inputs, on-farm production, post-harvest and processing, trade and marketing, and consumption and export (Fig. 1).

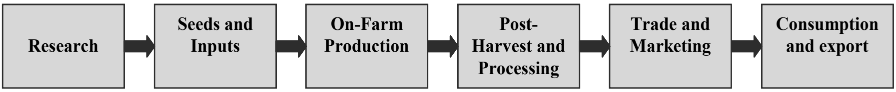

Fig. 1. The tef Value Chain: Consists of steps from research to production and to marketing and consumption.

21.3.1. Tef research

Tef begun to gain some attention in Research beginning the mid 1990's through the support from the McKnight Foundation's Collaborative Crop Research Program (MF-CCRP) and the International Atomic Energy Agency (IAEA). While Debre Zeit Agricultural Research Center (DZARC) is the center of excellence for tef research within the Ethiopian Institute of Agricultural Research (EIAR), other national and regional agricultural research centers are also involved in conducting on-station and on-farm trials on tef. The Institute of Bio-diversity Conservation (IBC) is mandated for issues related to the conservation, access and use of tef genetic resources (Abebe, 2001).

About 18 of the 32 released improved varieties of tef were developed by DZARC (MoA, 2010; Kebebew Assefa, Personal communication). Seed and straw yield, maturity period, seed color, plant height, panicle length, lodging tolerance, and number of seeds/spikelet are the most important criteria by which tef varieties are evaluated at research level. For the released tef varieties, on-station yield ranged between 1.3 to 3.6 t ha^{-1} while the farm-level yields ranged between 1.2 and 2.5 t ha^{-1}. Thus, the yield gap between experimental and farmers' field conditions can be as high as 1.2 t ha^{-1}, showing substantial potential for yield improvement if farmers were able to adopt some of the practices developed at the on-station level.

21.3.2. Seeds and other inputs

Improved seeds, fertilizers and herbicides are the most widely used technologies in tef production. The area covered by improved seeds of tef in Ethiopia is less than 1%. In the highly productive and major tef producing regions of Gojam and Shewa, and in other regions where environmental stress is not severe, local cultivars such as *Alba*, *Ada* and *Enatite* are widely grown, whereas improved varieties are increasingly becoming popular in major growing areas in Ethiopia, though adoption is currently limited. The formal ('commercial') and the informal (saved or bought) seed sectors are the two most important sources of tef seeds for farmers in the country. However, there is low demand by farmers for improved seeds of open-pollinated crops including tef (Spielman *et al*., 2011). According to the farmers interviewed, the major source of improved tef seed is the informal sector (i.e., own saved seeds, exchanges from other farmers and purchase from the market).

On the other hand, the supply and distribution of agricultural inputs including fertilizer has been for the most part owned and run by the government. While private retailers held a majority share of the market in the early 1990s, the public sector and cooperative unions have become almost the sole distributors of inorganic fertilizers (i.e. DAP and Urea) since 2000 (DSA, 2006). According to Spielman *et al.* (2011), while the Agricultural Input Supply Enterprise (AISE) had a market share of less than 50% during the mid- and late-1990s, it had re-gained the majority share by 2001 when private sector wholesalers, except for the holding companies, exit the market. As of 2004, the public sector accounted for over 70% of seed distribution, with private dealers accounting for only 23% of sales nation-wide (EEA/EEPRI, 2006).

21.3.3. On-farm production

21.3.3.1. Major tef growing areas of Ethiopia

Tef can grow under wide and diverse agro-ecologies. Eventhough there are areas where the crop is grown during the short rainy season ('*Belg*'), it is mainly cultivated during the main rainy season (*Meher*). In Ethiopia, tef is mainly produced in Amhara and Oromia regions, but with smaller quantities in the Tigray and SNNP (Southern Nations, Nationalities and Peoples) regions. There are 19 major tef producing zones in the country. These are: i) the Central and South Zones of Tigray Region; ii) East Gojam, West Gojam, North Gonder, South Gonder, North Wello, South Wello, North Shewa, and Awi Zones of Amhara Region; and iii) East Shewa, West Shewa, South-West Shewa, North Shewa, East Wellega, Horo Guduru Wellega, Jimma, Illubabor and Arsi Zones of Oromia Region (See Table 2 for regional distribution of tef production).

Table 21. Area cultivated, production and yield of tef in major growing regions in Ethiopia.

Region	Area		Production		Yield (ton ha^{-1})
	Thousand ha	% of total	Thousand ton	% of total	
Tigray	165.8	6.0	209.51	6.0	1.26
Amhara	1014.3	36.8	1279.11	36.8	1.26
Oromia	1289.4	46.7	1671.80	48.0	1.30
SNNP	265.4	9.6	296.76	8.5	1.12
Benishangul	23.6	0.9	23.11	0.7	0.98
Total	2758.5	100.0	3480.28	100.0	1.26

Source: CSA (2011). Agricultural Sample Survey: Area Planted and Production of Major Crops, 2010/11 *Meher* Season.

The results of this study showed that, in the Ada and Dejen areas, tef is grown widely because of its market value, quality of the straw for animal feed and its suitability to the agro-ecology of the area. In the Becho area, tef is preferred by farmers as the crop is less sensitive to the water-logging problem prevalent in the region. In Shashemene area, however, farmers grow tef mainly for the market because the price is less variable than for the other crops.

21.3.3.2. Land preparation and planting

By its nature, tef is a labor intensive crop. Farmers currently use a high tillage frequency compared to other cereal crops grown in Ethiopia mainly due to small seed size such that the germination is substantially affected by improperly prepared seed-bed. However, the tillage frequency varies from place to place depending on the agro-ecology and farmers' circumstances. While conservation tillage was proved to be effective for tef in countries such as USA, it has not to-date been widely practiced in Ethiopia.

Ethiopian farmers use the method of broadcasting for sowing tef seeds. This is mainly due to the very small seed size which makes row planting difficult. From the field visits, it was learned that farmers apply about 30 to 48 kg ha^{-1} of seed. Except for few farmers in Ada area, farmers are not aware of the benefits of row planting in tef. There are a few row planter technologies available; however they are still being tested for their suitability to farmers' conditions. In addition, in order to enhance germination, tef needs moderate soil compaction to m ake the seedbed firm and smooth so as to prevent the soil surface from drying quickly and thereby cause seed desiccation (TARI, 2007; Fufa *et al.*, 2001). In most parts of the country, soil compaction is done using cattle, sheep, goats and/or donkeys, and sometimes humans.

21.3.3.3. Farmers' tef variety selection criteria

Depending on their circumstances, farmers choose varieties based on multiple criteria. Knowing the criteria used by farmers in the selection of crop varieties assists breeders in identifying important traits to be considered in their breeding program. Knowing farmers' preferences is also useful to extension personnel when supplying varieties demanded by farmers.

In this study, it was learned that farmers apply different criteria in selecting suitable tef varieties for their specific conditions. The most important criteria used by farmers include yield, color, size, purity and marketability of the seed. For instance, in the Ada area, the popular *Quncho* variety ranked first in terms of its high seed yield and very white seed color that is preferred by consumers. AlthoughBecho the improved varieties such as *Enatite* (DZ -01-354) and *Dukem* (DZ-01-974) are the most preferred in the Becho area, a local variety called *Adilo* is vastly cultivated in the Shashemene area. In the Dejen area, however, white tef was found to be the most preferred.

21.3.3.4. Fertilizer use in tef

Over the past few years, about 56% of the total area cultivated to tef received some fertilizer. The national blanket recommendation of rate of fertilizer for tef is 100 kg ha^{-1} DAP and 100 kg ha^{-1} urea as set by the Ministry of Agriculture. During the field visits, it was learned that in the Ada and Dejen areas, the farmers use the recommended rates of fertilizer application (i.e. 100 kg ha^{-1} DAP and 100 kg ha^{-1} urea). However, in the Becho and Shashemene areas, farmers apply fertilizer below the recommended rate mainly to avoid crop lodging caused by high nitrogen fertilizer application. On the other hand, in the Shashemene area, farmers apply only 50 kg ha^{-1} DAP and 25 kg ha^{-1}urea mainly due to the high price of fertilizers. However, an earlier study showed that the major factors affecting the rate of fertilizer application in tef are water-logging, season of planting, cropping history, and weed growth (Kenea *et al.*, 2001).

21.3.3.5. Weed control in tef

As tef is grown under a wide range of climatic and soil conditions, it is exposed to a wide range of weeds that affect its productivity. The tef yield losses due to weeds range between 23% around the Debre Zeit area to 56% in Shewa (Rezene and Zerihun, 2001). Hand weeding is the most widely used practice to control weeds in tef. In addition, 2-4-D herbicide is recommended at rate of 1 litter ha^{-1} to control broad-leaved weeds. However, tef farmers prefer twice hand weeding and in rare circumstances apply herbicide under the close supervision of extension workers.

21.3.3.6. Pre- and post-harvest handling and processing

According to the information obtained from the farmers, pre- and post- harvest losses account for more than 40% of yield loss in tef. As the saying of Oromo people in the Ada area goes *"Hama anii baduu ottu bekaniii nan facaasaniii, jeetee taffiiniii"*. This literally means *"'Had they known how much of me is lost, they would not have grown me' said tef"*.

Almost all varieties of tef are susceptible to lodging particularly those with thin and tall stems. According to farmers lodging accounts for about 30% yield losses in Ada, 25% in Becho, 12% in Shashemene and 10% in Dejen areas. On the other hand, as shattering is also a cause for significant yield loss in tef, the crop needs to be harvested on time. According to the observations from the field visits, about 20% of tef harvests in Ada and Becho areas and 10% in Shashemene area are lost due to shattering.

Significant yield losses are also incurred during threshing. Since threshing is done on the ground, the quality of the tef grain is adversely affected as the grains are mixed with the soil, sand and/or other foreign matter which ultimately affects the market value of the. Apart from farmers in the Shashemene area and a few farmers in Dejen, the use of mechanical threshers for tef is unknown. While there are private suppliers (on rent basis) of thresher in the Shashamene area, only a single machine was recently introduced by SG2000 to Yetnora Kebele in Dejen for demonstration purposes. In the Shashemene area, it was observed that almost all farmers use the mechanical thresher instead of the traditional techniques mentioned above. The use of thresher has the following benefits: i) it reduces post-harvest losses by about 50 kg Timad^{-1} (equivalent to 0.2 t ha^{-1}); ii) according to the farmers, thresher also reduces the work burden on humans and oxen; and iii) thresher improves the quality of tef seed as it avoids contamination by soil, sand and other foreign substances. In monetary terms, the net gain to farmers by using thresher is about 800 Birr ha^{-1} as recorded during the field visit in June 2011.

21.3.4. Tef trade and marketing

21.3.4.1. On-farm profitability analysis of tef

Farmers grow tef not only for its grain but also because of the straw which is a good source of animal feed. Based on the current study, the grain yield of tef on farmers' fields in the Ada area, range from 1.2 t ha^{-1} for local varieties to 2.0 t ha^{-1} for the recently released *Quncho* variety. Similarly, the tef yields range from 0.9 to 1.2 t ha^{-1} in Becho, 0.8 to 1.2 t ha^{-1} in Shashemene, and 1.2 to 1.6 t ha^{-1} in Dejen areas.

In this study, costs associated with important farm-level tef production activities were collected from the farmers visited in each area. This was done so as to identify practices that involve relatively high costs to the farmers and thereby reduce the margin obtained. The costs of production for various items of tef production in Ada and Dejen areas are presented on Table 3 and 4. In both Ada and Dejen areas, DAP and Urea fertilizers contributed for the highest share of cost of production for tef. These two fertilizers together attributed for 36% and 38% of the total costs of tef production in Ada and Dejen, respectively. Next to fertilizers, costs for hand weeding and harvesting contribute to significant amounts of the overall expenses at both locations.

Tef is primarily grown as a cash crop in the areas visited. Accordingly, while the national average marketable surplus of tef is around 26%, the proportion is higher in the sample areas. In the Ada area, about 75% of the tef produced is supplied to the market, and of this about 85% is sold during the months of December and January mainly due to liquidity requirements to cover various expenses such as credit, social obligations, school fees, clothing, and the likes. As a result, the price difference between the production and the slack seasons is very high. For instance, in Ada, the average price difference between the harvest and the rest of the seasons is about 44%.

Table 3. Estimates of farm-level costs of tef production in the Ada area.

Practice	Amount ha^{-1}	Price (Birr $unit^{-1}$)	Total cost ha^{-1} (Birr)	% share
Land preparation (man-days)	20	30	600	10.8
Seeding rate (kg)	30	15	450	8.0
DAP fertilizer (t)	0.1	1100	1100	19.8
Urea fertilizer (t)	0.1	900	900	16.2
Hand-weeding (person-days)	24	30	720	13.0
Herbicide (l)	1	77	77	1.4
Harvesting (person-days)	30	30	900	16.2
Gathering and piling (person-days)	3	30	90	1.6
Threshing (person-days)	24	30	720	13.0
Total cost (Birr)	-	-	5557	100.0

Table 4. Estimates of farm-level costs of tef production in the Dejen area.

Practice	Amount ha^{-1}	Price (Birr $unit^{-1}$)	Total cost (Birr ha^{-1})	% share
Land preparation (man-days)	20	25	500	9.4
Seeding rate (kg)	30	15	450	8.4
DAP fertilizer (t)	0.1	1138	1138	21.3
Urea fertilizer (t)	0.1	870	870	16.3
Hand weeding (person-days)	40	25	1000	18.8
Herbicide (l)	-	-	-	-
Harvesting (person-days)	24	25	600	11.3
Gathering and piling (person-days)	15	25	375	7.0
Threshing (person-days)	16	25	400	7.5
Total cost (Birr)	-	-	5333	100.0

Farmers' immediate sale of tef grain is one of the causes for reduced potential income at farm-level. The profitability difference between the harvest and rest of the seasons was found to be 39% in Ada, 28% in Becho, 26% Shashemene and 43% in Dejen (Table 5 and 6).

21.3.4.2. Tef price analysis

Tef is the highest-priced cereal grown in Ethiopia. Following the prevalence of high food price inflation in the country in 2008, the price of tef has also experienced a huge increase in recent years. As shown on Fig. 2, the price of tef has been increasing over the years. In recent years, it has become a grain that fetches a high price per ton, albeit less per hectare (on account of its inferior yields) than wheat or chickpeas.

Table 5. Farm-level profitability of tef if all produce are sold during harvest season

Area	Average yield (t ha^{-1})	Harvest Season price (Birr t^{-1})	Revenue from grain (Birr ha^{-1}	Revenue from Straw (Birr ha^{-1})	Total Revenue (Birr ha^{-1})	Total Cost (Birr ha^{-1})	Profit (Birr ha^{-1})
Ada	1.6	6000	9600	2520	12120	5557	6563
Becho	1.1	6750	7425	1260	8685	4336	4349
Shashemene	1.1	7340	8074	900	8974	4771	4203
Dejen	1.4	5750	8050	540	8590	5333	3257

Table 6. Farm-level profitability of tef if all produce are sold outside harvest season

Area	Average yield (t ha^{-1})	Off-harvest season price (Birr t^{-1})	Revenue from grains (Birr ha^{-1})	Revenue from straw (Birr ha^{-1})	Total revenue (Birr ha^{-1})	Total cost (Birr ha^{-1})	Profit (Birr ha^{-1})
Ada	16	8630	13808	2520	16328	5557	10771
Becho	11	8250	9075	1260	10335	4336	5999
Shashemene	11	8670	9537	900	10437	4771	5666
Dejen	14	7500	10500	540	11040	5333	5707

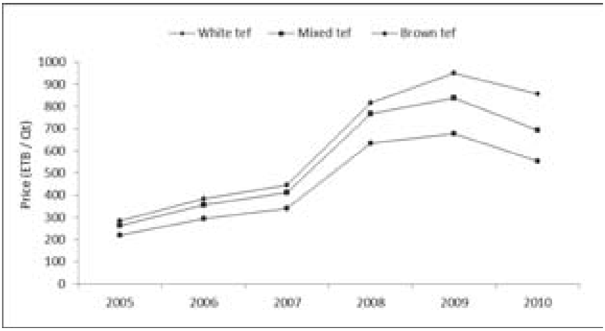

Fig. 2. Price trends of tef and other staple crops in Ethiopia (2005 -2010).

In a competitive market the seasonal price difference is a function of the opportunity cost of holding stock, storage losses, the costs of labor and capital and a normal profit [Timmer *et al.* 1983 as quoted by Rashid and Asfaw (2011)]. However, we learned from the field visits that the costs associated with tef stocking is minimal compared to any other crops due to the low vulnerability of the crop to p ests especially weevils. Nevertheless, seasonal price variability of tef remains as closely high as for the other staple cereals (Rashid and Asfaw, 2011).

Market inefficiency contributes for unfavorable low farm-gate and high consumer prices. Empirical investigations, such as a review by Rashid and Asfaw (2011), showed significant integration of grain markets in Ethiopia which also suggests that transaction costs in cereal markets have decreased over time from over 300 Birr ton^{-1} to less than 60 Birr ton^{-1}, with commensurate declines in traders' margins (Rashid and Asfaw, 2011). This finding is consistent with the relatively low price mark-up margin between producer and consumer prices of tef observed in July 2011 (Fig. 3). According to the rapid market appraisal, it was identified that farmers received tef farm-gate price of around 7000 Birr ton^{-1} during the 2010/2011 production year. Thereafter, presuming that farmers will run out of stocks by June, the price mark-up could go as high as 67%.

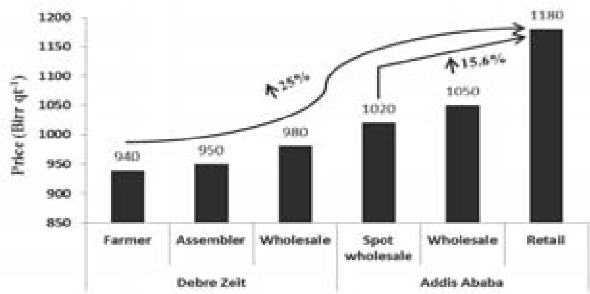

Fig. 3. Tef Mark-up price at various outlets from Debre Zeit to Addis Ababa in mid-June 2011.

21.3.4.3. Tef supply chain analysis

Supply chain integration is also another measure of market efficiency to understand how closely producers and consumers are linked. Cereal markets in Ethiopia in general are considered to be long and complex (Rashid and Asfaw, 2011). The tef supply chain is characterized by the heavy involvement of brokers and middlemen. This is observed in tef supply chain case of Addis Ababa market (Fig. 4). Brokers are the major players in Addis Ababa Ehel Berenda Market. Most trades are undertaken on spot every day, except Sunday, from 8 AM to 10 AM. Brokers arrange for tef purchases by making a phone call to a wholesale trader (brokers and traders typically form long-term relationships to minimize the risk of cheating) from surplus areas. There is very little apparent stocking of tef with Ehel Berenda traders as they stock only enough to satisfy petty trade during the day. Storage of tef could not be observed at any point along the value chain, either with traders at surplus areas or with millers at Addis Ababa. However, given that daily tef trade volumes only fluctuate by a factor of two in the central market, compared with 10 times or more between high and low seasons in the surplus areas, storage is likely to be taking place somewhere between the assembler and wholesaler.

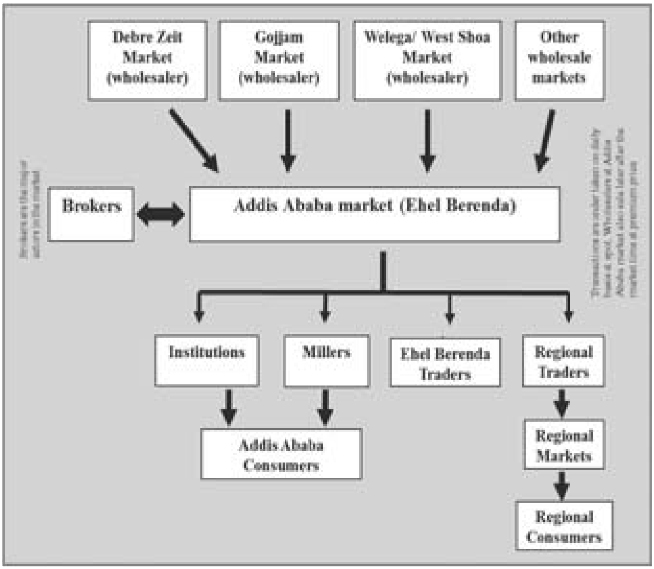

Fig. 4. Tef supply chain (Addis Ababa wholesale market).

Eleni (2001) notes that the structure of the value chain, including the reliance on brokers, is rational from the traders' point of view, given the high variation in tef quality observed and the difficulty in testing this at the point of sale.

Primary assembling and bulking of tef is done either by small local assemblers, often farmers involved in petty trading or regional/area specific traders. These traders use color and purity (quality) as criteria in price determination and bulking. The locally assembled tef, usually bulked on the basis of color, is either directly sold to local consumers or packaged in sacks of 100 kg and transported to the central market or other places where there is demand for the product. At this stage, there is no value addition (except in space and time) to the product, not even cleaning only re-packaging.

The price of tef in the central market is determined by the supplied grain quality,which is usually based on place of origin and color. The price and quality determination is often done by the brokers that have long years of experience in trading and established relationships with the regional traders. Again, at Ehil Berenda Market in Addis Ababa, no value addition in terms of cleaning, storage or re-packaging takes place, and the grain is sold at spot while it is still loaded on the trucks. Millers, institutions, regional traders, hotels and sometimes consumers are the main buyers at this stage.

21.3.5. Value addition, consumption and export of tef

21.3.5.1. value addition in tef

Processing tef grain into flour and *injera* is limited to a small number of urban processors. However, tef has great potential as an industrial crop. It is nutritionally rich and free of gluten; hence, it can be safely consumed by patients suffering from celiac disease (Dekking and Koning, 2005). Tef is also high in fiber, making it an ideal substitute for other cereals such as wheat and barley for diet foods, and it has also got high iron content (important in preventing pregnancy-related anemia) and calcium contents.

Except at the level of millers and *injera* bakers, there is limited value addition along the tef value chain. Millers add value to tef as they clean the grains and make flour. Suppliers of tef flour are also emerging, particularly in Addis Ababa, Dire Dawa and Harar, and it is possible to find tef flour packages of different sizes in some supermarkets. The bakers add value to tef as they change the tef flour to *injera* that is directly supplied to institutions, hotels, super markets, shops and consumers.

On the other hand, tef food product development efforts are at early stages of research. The blending of cereals in an attempt to prepare different food menu is being studied by Haramaya University, and the Ethiopian Health and Nutrition Research Institute (EHNRI).

21.3.5.2. Tef export

Tef can be considered as an important future export commodity, if the current efforts to increase production of tef are successful. The existing increasing demand for tef and its products on the international market will ensure Ethiopian benefits. However, we also need to recognize the existence of huge demand in the domestic market that would be adversely affected by the exports if productivity is not increased first.

In 2005, there was about 30 thousand tons of tef flour exported, earning the country about 13.7 million USD. However, due to policy reasons, tef flour export dropped in 2006, and only 3 million of USD was earned. There were no data showing export of tef and/or its products in 2007. Nevertheless, according to the data from the customs authority, starting from 2008, Ethiopia has been exporting processed tef especially in the form of *fresh injera* and *dry injera* ('*dirkosh*'), and the export such products is steadily increasing.

21.4. Conclusions and the Way Forward

Tef is among the most widely grown cereals in Ethiopia. The crop is a staple diet of the majority of the population, and it is the most widely planted one by farmers. While production and productivity of the crop have increased over time, demand has risen faster and so the price of tef has gone up in recent years. Although, the average yield of tef is low at around 1.2 t ha^{-1}, using improved cultivars and management practices, some farmers achieved up to 2.5 t ha^{-1}. Tef is likely to remain a favorite crop of the Ethiopian population and the crop is also gaining popularity as a healthy food in the western world. Given the importance and potential of the crop for the Ethiopian population and possibly for the world, this diagnostics was initiated with the objective of describing the current state of the tef value chain in order to identify bottlenecks that prevent the sub-sector from achieving its full potential.

The study identified six stages of tef value chain that included tef research, seeds and inputs, on-farm production, post-harvest handling and processing, trade and marketing, and consumption and export. At each stage of the value chain, several bottlenecks were identified and strategies of overcoming them are discussed. Based on the findings of this study, the following recommendations are made to improve the value chain of tef in Ethiopia.

***Research*:** Because of its restriction to Ethiopia as a food crop, tef managed to attract little external research funding compared to the other major world crops. Thus, the government must place tef as a priority crop to receive funding pledges from donors. In addition, tef should be given at least equal footing with other major crops in terms of domestic research funding.

***Seeds*:** The major bottlenecks related to improved tef seed are related to availability, suitability, purity and sustainability. Thus, it is essential to work with regional seed enterprises, farmers' cooperatives, secondary seed producing farmers and the private sector in a coordinated manner to ensure an adequate supply of certified locally suitable seeds.

Fertilizers: Currently, the sole supplier of fertilizer in the country is the Agricultural Inputs Supply Enterprise (AISE). Engaging the private sector in fertilizer supply has the potential to increase competition in the fertilizer market, as well as supply and access. It is also necessary to develop recommendations for organic and inorganic fertilizers that are most suitable for tef. These recommendations should depend on soil maps and controlled trials of blended fertilizers to determine the optimal balance of macro- and micro-nutrients.

***On-farm production*:** At farm-level, the most important problem in tef production is its labor requirement and the associated costs. Thus, immediate demonstration of available technologies and practices that help reduce work burden on farmers is essential. This include testing and promotion of technologies such as moldboard plough that reduce tillage, promotion of row sowing of tef together with the row planter so as to increase yield, and reduce weed infestation and associated costs of weeding. Also, the use of minimum tillage as an option in reducing tillage costs should be further explored.

***Reducing lodging*:** Lodging is the cause of significant yield loss in tef. One immediate intervention that might help reduce lodging in tef is breeding for lodging tolerant lines. Planting at a reduced seed rate and in rows has also demonstrated that lodging can be reduced. In the longer term, it is important to conduct advanced research on means of overcoming or reducing lodging in tef.

***Decreasing post-harvest loss*:** Shattering in tef begins immediately after the plant starts to dry or just before harvesting. The losses due to shattering can be minimized by determining appropriate harvesting stage. Harvesting while the plant is still green is recommended as one option to reduce shattering; however, this might have adverse effects on grain quality. The promotion of multi-crop threshers would also help to significantly reduce post-harvest loss, increase tef grain quality and reduce costs.

Marketing: The immediate sale of tef after harvest is m ainly due to liquidity constraints. Strengthening farmers' level assembly and marketing of tef through the promotion of farmers' organizations (e.g. cooperatives) and the introduction of warehouse receipt system would alleviate farmers immediate cash needs.

Value addition: As is the case with many food crops in the country, the tef value chain is at its early stages of development. While companies specializing in tef flour supply and *injera* baking are emerging, most of the value addition activities are done by the ultimate consumers themselves. The presumed reasons for this are the variation in tef grain quality and consumers' preference. Thus, in the short run, product labeling, whereby at least the place of origin and color of the tef produce are declared (written) on the sacks of tef, would help begin to adding value in the value chain. This practice would make bulking, milling, processing (baking) and distribution of the product easier for the players in the value chain and allow for economies of scale.

21.5. Abbreviations

AISE: Agricultural Input Supply Enterprise; **CSA**: Central Statistical Agency; **DAP**: Diammonium Phosphate; **DSA**: Development Studies Associates; **DZARC**: Debre Zeit Agricultural Research Center; **EARO**: Ethiopian Agricultural Research Organization; **EEA**: Ethiopian Economic Association; **EEPRI**: Ethiopian Economic Policy Research Institute; **EGTE**: Ethiopian Grain Trading Enterprise; **EHNRI**: Ethiopian Health and Nutrition Research Institute; **EIAR**: Ethiopian Institute of Agricultural Research; **ESSP**: Ethiopian Strategy Support Program; **FAO***:* Food and Agriculture Organization; GDP: Gross Domestic Product; **GTP**: Growth and Transformation Plan; **IAEA**: International Atomic Energy Agency; **IDRC**: International Development Research Centre; **MoFED**: Ministry of Finance and Economic Development; **NBE**: National bank of Ethiopia; **PADETES**: Participatory Demonstration and Training Extension System; **PASDEP**: Plan for Accelerated and Sustainable Development to End Poverty; **t**: ton; **SNNP**: Southern Nations, Nationalities and Peoples; **TARI**: Tigray Agricultural Research Institute; **USD**: US dollar.

21.6. References

Abebe Demissie. 2001. Tef Genetic Resources in Ethiopia. *In*: Hailu Tefera, Getachew Belay and Sorrels M (eds), Narrowing the Rift: Tef Research and Development, Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia, pp 27-31.

CSA. 2010. Central Statistical Agency. Agricultural Sample Survey 2009/2010 (2002 E.C.) (September – December, 2009). Vol. IV. Report on Area and Production of Crops (Private Peasant Holdings, *Meher* Season, Statistical Bulletin 446, Addis Ababa, Ethiopia.

CSA. 2011. Central Statistical Agency. Agricultural Sample Survey: Area Planted and Production of Major Crops, 2010/11, *Meher* Season.Volume I, Addis Ababa, Ethiopia.

CSA, 2011 Central Statistical Agency, Agricultural Sample Survey: Report on Farm Management Practices 2010/11. Volume III, Addis Ababa, Ethiopia.

Dekking LS and Koning KF. 2005. The Ethiopian Cereal Tef in Celiac Disease. *The New England Journal of Medicine* 353: 1748-1749.

EEA/EEPRI. 2006. Ethiopian Economic Association/Ethiopian Economic Policy Research Institute. Evaluation of the Ethiopian Agricultural Extension with Particular Emphasis on the Participatory Demonstration and Training Extension System (PADETES), EEA/EEPRI, Addis Ababa, Ethiopia.

Elene Zaude Gabre-Madhin. 2001. Market institutions, transaction costs, and social capital in the Ethiopian grain market. Research Report 124. Washington DC: International Food Policy Research Institute (IFPRI), Washington DC, USA, 93pp

Fufa Hundera, Tesfa Bogale, Hailu Tefera, Kebebew Asefa, Tiruneh Kefyalew, Aberra Debelo and Seyfu Ketema. 2001. Agronomy Research in Tef. *In*: Hailu Tefera, Getachew Belay and Sorrels M (eds.), Narrowing the Rift: Tef Research and Development, Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia, pp 167-176.

Kaplinsky R and Morris M. 2000. *A Handbook of Value Chain Research*. IDRC, Canada.

Kenea Yadeta, Getachew Ayele and Workneh Negatu. 2001. Farming Systems Research on Tef: Small Holders Production Practices. *In*: Hailu Tefera, Getachew Belay and and Sorrels M (eds). Narrowing the Rift: Tef Research and Development, Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia, pp 9-23.

MoA. 2010. Ministry of Agriculture, Animal Health and Plant Health Regulatory Directorate. Crop Variety Register Issue No. 13, June 2010, Addis Ababa, Ethiopia, 227pp.

MoFED. 2010. Ministry of Finance and Economic Development (MoFED). Growth and Transformation Plan 2010/11-2014/15, Addis Ababa, Ethiopia.

MoFED. 2011. Ministry of Finance and Economic Development (MoFED).

NBE. 2009. National Bank of Ethiopia.

Rashid Shahidur and Asfaw Negassa. 2011. Policies and Performances of Ethiopian Cereal Markets. ESSP II Working paper 21, International Food Policy Research Institute (IFPRI), May 2011.

Rezene Fessehaie and Zerihun Tadele. 2001 Weed Research in Tef. *In*: Hailu Tefera, Getachew Belay and Sorrels M (eds.), Narrowing the Rift: Tef Research and Development, Proceedings of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000, Debre Zeit, Ethiopia, pp 201-214.

Seyfu Ketema. 1989. Production trends, germplasm resources, breeding, and varietal improvement of small millets, with special emphasis on tef in Ethiopia. *In*: Seetharam A, Riley KW and Harinarayana G (eds). *Small millets in Global Agriculture*. IDRC, Oxford and IBH Co., India.

Spielman DJ, Dawit Kelemwork and Dawit Alemu. 2011. Seed, Fertilizer, and Agricultural Extension in Ethiopia. Ethiopia Strategy Support Program II (ESSP II), ESSP II Working Paper.

TARI. 2007. Tigray Agricultural Research Institute.

Timmer CP, Falcon WP and Pearson SR. 1983. *Food Policy Analysis*. Washington, D.C.: World Bank.

VII. Successes & Recent Efforts

22. Quncho: the Most Outstanding Tef Variety in Ethiopia

Kebebew Assefa*, Solomon Chanyalew and Gizaw Metaferia
Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O.Box 32, Debre Zeit, Ethiopia. *Corresponding author:
Kebebew.Assefa@yahoo.com

Scientific improvement research on tef, Eragrostis tef (Zucc.) Trotter, began in the late 1950s. Since then, a total of 32 varieties have been released by the national agricultural research system. However, most of the varieties have been little adopted by farmers to have brought any discernible impacts on the productivity and production of the crop. Recently, the tef variety named Quncho has been developed and released following identification of farmers-preferred traits and varieties through participatory variety selection and participatory plant breeding. Following its release, intensified seed multiplication and distribution and innovative technology dissemination approaches were adopted. To that effect, then, the variety has gained ground-breaking acceptance and demand by the farming community in the various parts of Ethiopia. The success with the Quncho variety has, on the other hand, set even a more-demanding task to the overall tef improvement efforts. As such, the further development of tef varieties superior to the Quncho variety requires cumbersome efforts using multi-faceted approaches involving conventional breeding, modern techniques (including genomics and in vitro cultures) as well as agronomic management approaches. And, the task calls for enhanced national and foreign assistance and collaboration in terms of financing, technical support, human resources and facilities.

Key Words: *Eragrostis tef*, extension, participatory plant breeding (PPB), participatory variety (PVS), tef, *Quncho*, seed system, variety

22.1. Introduction

Tef is amongst the principal cereals of Ethiopia. Scientific improvement research on tef in Ethiopia was started in 1956/57. Since then, commendable achievements have been made in the development of improved varieties along with cultural management packages. Until 2010, a total of 32 varieties of tef have been developed by the national agricultural research system (MoA 2010). Nonetheless, the improved varieties have not been widely adopted by farmers to bring about any discernible impacts on the production and productivity of tef in Ethiopia. The slow and low rate of adoption of the improved varieties is due, amongst others, to th e fact that the farmers claim that the varieties were not superior to their local varieties in terms of the preference of traits of the farmers and consumers. This paper attempts to give an overview of the breakthrough achievements and innovations made in relation to a newly released popular tef variety known as *Quncho*, and thereby suggest the way forward on how to next proceed with the development of new tef varieties.

22.2. Development of Quncho Tef Variety

The first step undertaken before starting the breeding work for the development of the *Qucho* variety was participatory variety selection (PVS) and participatory plant breeding (PPB) in order to identify farmer preferred varieties and traits in tef varieties (Getachew *et al.* 2006, 2008). The major outcomes of these studies were that in addition to yield of both grain and straw, the overriding preferred trait by both farmers and consumers is white seed color. Based on this, targeted crossing was made between two selected formerly released tef varieties in order to combine the farmer- and consumer-preferred traits.

The tef variety *Quncho* with the pedigree of [(974 × 196)-HT′-387 (RIL355)] was developed from the cross made by Debre Zeit Agricultural Research Center (DZARC) in 2000. The parental varieties DZ-01-196 (*Magna*) and DZ-01-974 (*Dukem*) are old improved varieties developed through pureline selection and released in 1970 and 1995, respectively (Hailu *et al.* 1995, 2001). The maternal (ovule) parent DZ-01-974 (*Dukem*) is a high-yielding variety (Fig. 1A); however, farmers' preference for this variety was limited because of its pale white seed color that fetches low market price. On the other hand, the male (pollen) parent DZ-01-196 (*Magna*) possesses the popular very white seed color (Fig. 1B), but its productivity has been relatively low (1.6–1.8 t ha^{-1}). Hence, a targeted cross was made between the two varieties, with the objective of selecting recombinants combining the high yield of DZ-01-974 (*Dukem*) and the seed quality trait of DZ-01-196 (*Magna*). Rapid generation advancement up to three generations per year was made using off-season irrigation facilities. Eventually, *Quncho* was developed (Fig. 1C) as a recombinant inbred line (RIL) through an F_2-derived single-seed descent method; and following series of multienvironment yield tests in various major tef growing regions of the country, it was officially released in 2006 (MoA 2010).

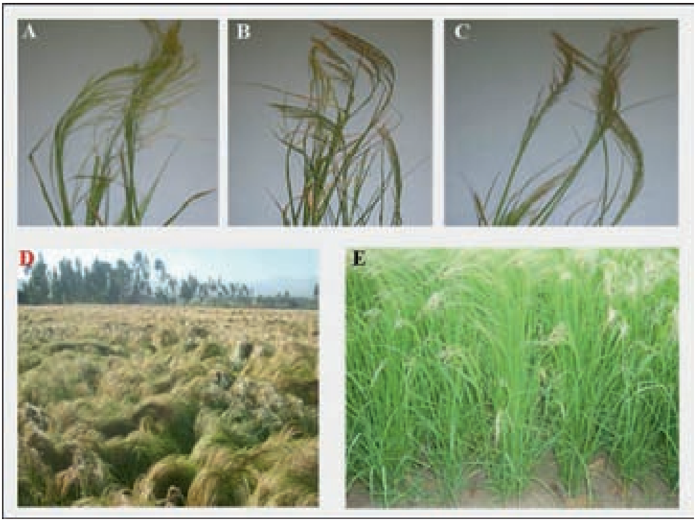

Figure 1. The phenotype and performance of *Quncho* variety. The panicles of (A) parental line *Dukem* (DZ-01-974), (B) parental line *Magna* (DZ-01-196), and (C) *Quncho*. Performance of *Quncho* variety (D) in farmer's field, and (E) using row sowing and optimum plant population density.

Table 1 summarizes the performance and distinguishing features of the new tef variety *Quncho* as compared to the parental and the farmers' (local) varieties. The new variety has inherited its very white seed color and also the lemma color (yellowish green variegated with red tips and margins) from the pollen parent DZ-01-196 (*Magna*). It has taken its high yield potential and panicle form (very loose) from the ovule parent DZ-01-974 (*Dukem*). The variety branding by calling it *Quncho* has played significant role particularly in the popularization and promotion of the variety. The name *Quncho* in most Ethiopian vernaculars means "top brass", "at the helm" or "top most".

22.3. Intensification of Seed Multiplication

In order to speed up the supply of quality seeds of the *Quncho* variety to the ultimate users, an intensified seed multiplication scheme was followed. This new innovative and accelerated seed multiplication involved the following:

i) Enhancement of seed multiplication of research centers both during the off-season using irrigation facilities and during the main season; and
ii) Enhancement of on-farm seed production by strengthening the capacities of farmers through the provision of initial seeds, training and technical support.

Table 1. Performance and characteristics of *Quncho* as compared to the parental lines and the local check.

Traits	DZ-01-974 (*Dukem*)	DZ-01-196 (*Magna*)	*Quncho*	Local variety
Panicle form	Very loose	Fairly loose	Very loose	Mixture
Lemma color	Yellowish green	Yellowish green variegated with red	Yellowish green variegated with red	Mixture
Seed color	Pale white	Very white	Very white	Mixture
Plant height (cm)	107	97	102	103
Days to mature	107	97	105	118
On-station grain yield (t ha^{-1})	2.4-3.4	1.8-2.2	2.2-2.8	1.8-2.2
On-farm grain yield (t ha^{-1})	2.0-2.5	1.4-1.6	1.8-2.2	1.2-2.0
On-station straw yield (t ha^{-1})	12	9.6	10.11	10.09
On-farm straw yield (t ha^{-1})	10.00	8.10	9.10	6.18

Through the use of on-farm seed production, efforts were made towards exploitation of the indigenous knowledge in tef seed production and maintenance. And, our experiences from this venture have taught us that farmers can produce better quality tef seeds than even the formal sector provided that the farmers are given technical backstopping. In this aspect, clustering of adjacent fields of farmers has proven effective in minimizing seed contamination and enabling the production of good quality seeds.

In addition, private seed growers have also been encouraged and many have for the first time engaged themselves in the production of tef seeds especially that of the *Quncho* tef variety.

22.4. Innovative Extension Approach

Instead of the former agricultural extension approach, a more effective innovative approach was adopted in the demonstration, popularization and dissemination of the *Quncho* tef technology. The new approach was characterized by the following major features:

i) ***Dissemination of technology as a package****:* Unlike the previous way of the piece-meal approach with a single technology, the dissemination approach involved "technology as a package" with the *Quncho* tef variety used as the vehicle along with other associated improved management practices.

ii) ***Use of large farmers' fields****:* Instead of the formerly used small (10 x 10 m) plots large field plots of one-fourth of a hectare were used in on-farm demonstrations and scaling-up of the *Quncho* tef technology.

iii) ***Coordinated multi-stakeholders' partnership extension approach****:* The recent technology scaling up activity involved all stakeholders including research centers, extension agents, farmers, NGOs, farmers' association such as farmers' cooperatives and cooperatives' unions, district administration offices, and other institutions involved in rural development each with clearly defined roles and responsibilities.

iv) ***Revolving seed loan****:* In the scaling-up of the technology, seeds of the variety *Quncho* were distributed to participated farmers on "revolving-seed-loan" basis such that the farmers would return in kind the same amount of seed after harvest.

v) ***Provision of regular training****:* Regular training of farmers, development agents and extension personnel on the technologies contributed immensely to success of the demonstration and scaling-up of the technology on the farmers' fields.

vi) ***Regular follow- up and supervision****:* In addition to training, regular follow up and supervision of the scaling-up activities by a team of researchers and extension agents also played an important role in the rapid and effective dissemination of the technology.

vii) ***Provision of inputs and marketing options****:* In as far as possible, provisions were made in terms of inputs and options for marketing of produce mainly through involving farmers' cooperatives and cooperatives' unions in the supply of inputs such as fertilizers and purchase of the produce.

As a consequence of the new extension approaches practiced since the release of the *Quncho* tef variety in 2006, a total of over 31,000 tef producing farmers' households with a total area of more than 10,000 ha were directly participated in the scaling-up activities carried out through the partner research centers and the National Crop Technology Scaling-up Program (Table 2). This venture involved the distribution of a total of about 306 t of seeds of the variety with the average yield obtained by the farmers ranging from 2.0-2.3 t ha^{-1}. At this juncture, it is important to note that these figures do not include the dissemination of the variety made through horizontal farmer-farmer seed exchange and also that made through the formal extension system of the offices of agriculture.

Table 2. Summary of direct dissemination of *Quncho* variety through center level and national scaling up activities carried out from 2006 up to 2011.

Year	No. of farmers' households participated	Farm area covered (ha)	Amount of seed distributed (t)	Total grain yield (t)	Average grain yield (t ha^{-1})
2006	300	150	4.50	300.00	2.0
2007	506	253	7.59	556.60	2.2
2008	1060	530	15.90	1166.00	2.2
2009	5875	2938	88.14	6464.00	2.2
2010	10113	3029	90.87	6967.00	2.3
2011	13157	3292	98.76	-	-
Total	31011	10192	305.76	-	-

Figure 1D shows the performance of the *Quncho* tef variety on farmers' fields in different parts of Ethiopia. Overall, our experiences with the dissemination of the *Quncho* variety have shown that generally there is less problem with good stuff in terms of attracting attention of farmers, extension system and policy makers including the administration.

22.5. Conclusions and the Way Forward

The development of the *Quncho* variety has now set a big challenge to the next breeding efforts such that if any variety has to be released for similar agro-ecologies, it has to beat *Quncho* in terms of yield while still maintaining the very white seed color quality. Hence, the question would be "Can we beat *Quncho*?". Undoubtedly, the answer to this question would be "yes". But it should be emphasized that the task is rather demanding, and strategies and methods should be revisited and devised in order to develop varieties superior to *Quncho*.

The possible strategies with potential success would include: i) cumulating (Pyramiding) yield traits (yield QTLs) in *Quncho* through targeted crossing with varieties yielding higher than *Quncho* coupled with selection of recombinants with better productivity while maintaining the very white seed color quality; ii) Making other targeted crossings of parents having high productivity and the desired very white seed quality; iii) intensifying the hybridization program particularly with an aim of improving lodging resistance; and iv) employing different approaches including conventional breeding, genomics, use of anti-lodging agents (e.g. synthetic growth retardants) and agronomic methods particularly to combat or overcome the problem of lodging which has still persisted to be the major bottleneck in tef production.

Our observations with improved management practices particularly with manipulation of plant population density and planting methods have indicated that it is possible to use seed rates reduced than the conventional recommendations of 25 kg ha^{-1}, and row sowing has also practical advantages of ease of weeding and harvesting provided these management options are practically feasible. The limitation of practical feasibility of distributing small amounts of seeds and row sowing as opposed to b roadcasting, however, should be overcome through the development of farmer-affordable and simple implements that enable these operations.

Overall, there are technically ample opportunities for the development of improved tef varieties that surpass the *Quncho* tef variety and are suitable for the different agro-ecologies of Ethiopia. Nonetheless, the tasks are not easy as such, and these opportunities can only be realized provided that enhanced efforts and focus are given to employing coordinated multi-faceted strategies involving conventional breeding, modern techniques (including genomics and *in vitro* cultures), as well as agronomic management methods. It is also to be emphasized that apart from the need for enhanced national support, the painstaking ventures of the tef improvement generally require enhanced external inputs and support in terms of collaboration, technical and knowledge support, financing and facilities.

22.6. Acknowledgements

The continuous support given by the McKnight Foundation's Collaborative Crop Research Program and the Ethiopian Institute of Agricultural Research to the National Tef Improvement Project is greatly acknowledged.

22.7. Abbreviations

DZARC: Debre Zeit Agricultural Research Center; **MoA**: Ministry of Agriculture; **NGO**: non-governmental organization; **PPB**: participatory plant breeding; **PVS**: participatory variety selection; **QTL**: quantitative trait locus; **RIL**: recombinant inbred line.

22.8. References

Getachew Belay, Hailu Tefera, Birhanu Tadesse, Gizaw Metaferia, Daniel Jarra, Tadelle Tadesse. 2006. Participatory variety selection in the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter]. Experimental Agriculture 42: 91 – 101

Getachew Belay, Hailu Tefera, Anteneh Getachew, Kebebew Assefa, Gizaw Metaferia. 2008. Highly client-oriented breeding with farmer participation in the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter]', African Journal of Agricultural Research 3(1): 022 – 028.

Hailu Tefera, Kebebew Assefa, Fuffa Hundera, Tiruneh Kefyalew, Yifru Teklu, Likyelesh Gugsa, Seyfu Ketema, Temesgen Adnew. 2001. Progress of tef breeding research in Ethiopia, In: Hailu Tefera, Getachew. Belay, M. Sorrells (eds), Narrowing the Rift. Tef Research and Development Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia, 16–19 October 2000, pp157–163.

Hailu Tefera, Mulu Ayele and Kebebew Assefa. 1995, Improved varieties of tef (*Eragrostis tef*) in Ethiopia. Releases of 1970–1995, Research Bulletin No. 1, Debre Zeit Agricultural Research Center, Alemya University of Agriculture, Debre Zeit, Ethiopia.

Kebebew Assefa, Sherif Aliye, Getachew Belay, Gizaw Metaferia, Hailu Tefera and Mark E. Sorrells. 2012. *Quncho*: the first popular tef variety in Ethiopia. International Journal of Agricultural Sustainability 9(1): 25-34, doi:10.3763/ijas.2010.0545

MoA. 2010. Ministry of Agriculture, Animal Health and Plant Health Regulatory Directorate. Crop Variety Register Issue No. 13, June 2010, Addis Ababa, Ethiopia, 227pp.

23. Tef Improvement Project: Harnessing Genetic & Genomic Tools to Boost Productivity

Zerihun Tadele
Tef Improvement Project, Institute of Plant Sciences, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland. E-mail: zerihun.tadele@ips.unibe.ch

The Tef Improvement Project (TIP) was established in mid-2006 to develop cultivars that tackle key production constraints so that the productivity of the crop is increased. TIP implements genetic and genomic tools in order to achieve its goals. It has established strong collaboration with the Ethiopian Institute of Agricultural Research so that candidate materials are introgressed to locally adapted cultivars and field tested before releasing to the farming community. The semi-dwarf and lodging tolerant line called "kegne" ('righty' in Amharic for the right-side twisting phenotype), and two candidates for drought tolerance (dtt: drought tolerant tef) have been crossed to popular tef cultivars such as Dukem, Tsedey and Quncho, and being evaluated in the field in Ethiopia. In general, candidate lines for valuable agronomic traits will have positive impact in boosting the productivity of tef in the future. TIP is financed by the Syngenta Foundation for Sustainable Agriculture and the University of Bern.

Key words: tef, *Eragrostis tef,* orphan crop, conventional breeding, genetic tools, genomic tools

23.1. Introduction

Tef [*Eragrostis tef* (Zucc.) Trotter] is the major food crop in Ethiopia, where it is annually cultivated on about 2.8 million hectares of land (CSA, 2011). It provides quality food and grows under difficult marginal conditions that are poorly suited to most other cereals. However, tef is considered as one of the orphan or under-studied crops since little scientific improvement has been made on the crop compared to the world's major crops such as maize, wheat and rice (Naylor *et al.*, 2004). Despite its versatility in adapting to extreme environmental conditions, the productivity of tef is very low. The major yield limiting factors in tef production are lack of cultivars tolerant to lodging, drought and pests (Kebebew *et al.*, 2009).

23.2. The Tef Improvement Project (TIP)

The Tef Improvement Project (TIP) was established in July 2006 with the financial support of the Syngenta Foundation for Sustainable Agriculture and the University of Bern, and hosted at the Institute of Plant Sciences of the University of Bern, Switzerland. This paper highlights on the objectives, strategies and successes, and the expected impacts of the project.

23.3. Objectives of TIP

The main aim of TIP is to boost the productivity of tef by tackling the major production constraints through developing cultivars with desirable agronomic and nutritional traits. Priority is given for the following agronomic traits.

Lodging tolerance: Lodging is the permanent displacement of the stem from the upright position. Tef possesses tall and weak stems that easily succumb to lodging caused by wind or rain. In addition, lodging hinders the use of high input husbandry since the use of increased amounts of nitrogen fertilizer to boost the yield results in severe lodging. Consequently, both the yield and the quality of the grain and the straw are severely reduced. The lodged plant also poses difficulties in harvesting. Various attempts were made by the research community to develop lodging resistant tef cultivars, but so far no cultivar with reasonable lodging resistance has been obtained. Research on other cereal crops during the 1960's and 1970's particularly on wheat and rice produced semi-dwarf and lodging-tolerant cultivars. The key genes that played significant role during the famous Green Revolution were *Reduced height-1* (*Rht-B1* and *Rht-D1*) in wheat (Peng *et al.*, 1999) and *semi-dwarf* (*sd-1*) in rice (Sasaki *et al.*, 2002). This technology could also be applied to crops like tef that are still severely threatened by the lodging syndrome. Once the problem of lodging is tackled, the optimum amount of fertilizer can be applied and the plant can allocate its resources to producing more grain instead of a long stalk.

Drought tolerance: The project also focuses on developing drought tolerant tef lines suitable for moisture-deficient regions. Some genes known to increase drought tolerance in plants have already been discovered (Wang *et al.*, 2005; Wilson *et al.*, 2009). Recent studies showed that the suppression or knock-out of SAL1 (inositol polyphosphate 1-phosphatase) and ERA1 (α-subunit of farnesyltransferase) genes in the model plant *Arabidopsis* increased tolerance to drought (Wang *et al.*, 2005;

Wilson *et al.*, 2009). The *era1* mutants develop tolerance to drought through a mechanism involving closing of the stomata.

Other valuable traits: Additional traits of importance include breeding for bigger seed size, larger panicle size and resistance to herbicides. Since tef has extremely small seeds, increasing the seed size has a positive impact on seed yield as larger seeds can be sown deeper in the soil such thatthe tolerance against lodging improves. Grain size was found to be controlled in rice by at least two independent genes known as GW2 (Song *et al.*, 2007) and qSW5 (Shomura *et al.*, 2008). A cytokinin oxidase gene in rice regulates seed production through increasing the number of reproductive organs (Ashikari *et al.*, 2005). Developing herbicide tolerance in tef especially through a non-transgenic system is also important since tef is susceptible to weeds. A point mutation in acetolactate synthase gene (ALS) in wheat enables the plant to tolerate to a non-selective imidazolinone herbicide (Hanson *et al.*, 2006). Hence, herbicide tolerant tef lines could be obtained by screening the mutagenized population for tolerance to the above indicated or other non-selective herbicides.

23.4. Strategies of TIP

The strategy of TIP is shown on Fig. 1. Conventional and molecular breeding techniques as well as genomic tools are applied in order to obtain candidate tef lines for diverse goals of the project. In the forward genetics approach, the mutagenized tef population is used for phenotypic screening in order to obtain candidate mutant lines for the traits of interest. For this purpose, about 7000 M_2 mutagenized population is ready for screening for any trait of importance. On the other hand, the same population can be used in the reverse genetics approach such as TILLING (Targeting Induced Local Lesion IN Genomes) to s creen for candidates harbouring mutations in the genes of interest. TILLING is a non-transgenic method, and it is applied in several crops plants including major and orphan crops (for review, Parry *et al.*, 2009; Zerihun *et al.*, 2009). Detailed description and progress of our Tef TILLING Platform is reported by Esfeld and colleagues in this compilation of proceedings. The genome sequence is also applied in identifying the genes of interest and genetic markers such as microsatellites. Likewise, the status of the genome and transcriptome sequencing has been presented by Cannarozzi *et al* in these proceedings. TIP is also optimizing the *in vitro* regeneration method for tef since many techniques such as transformation are dependent on efficient *in vitro* culture and regeneration technique. The main objective of the transformation study is to predict the type of phenotypes obtained from the TILLING or other improvement techniques. The progress on regeneration and transformation has been reported by Plaza-Wüthrich and Zerihun in other sections of these proceedings.

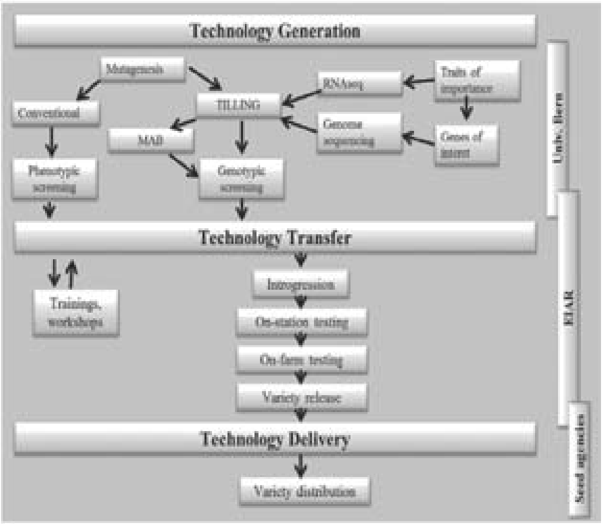

Fig. 1. Strategies of the Tef Improvement Project. In the technology generation process, the project applies modern genetic, molecular and genomic tools used to improve important traits in tef. In the technology transfer phase, promising tef lines are introgressed to high-yielding and widely adapted cultivars and evaluated at the on-station and on-farm sites in Ethiopia before releasing to the farming community. The project is also involved in capacity building through short- and long-term trainings, workshop organization and provision of research supplies.

23.5. Stakeholders of TIP

In order to achieve its goals, TIP collaborates with many stakeholders (Fig. 2). The financial support from Syngenta Foundation and the University of Bern, and the hosting of the Institute of Plant Science are the cornerstones for TIP. The collaboration with the Ethiopian Institute of Agricultural Research (EIAR) has enabled us to evaluate the performance of candidate lines *via* field-testing in Ethiopia. Promising lines are introgressed to high-yielding and widely-adapted cultivars. Further field testing at on-station and on-farm sites in Ethiopia will be done, and the best performing cultivars will be released to farmers. The collaboration with EIAR also focuses on capacity building especially through provision of short- and long-term trainings, and exchange of research materials especially research supplies. The tef genome and transcriptome sequencing has been done by public and private organizations including Functional Genomic Center, Zurich (Switzerland), MWG (Germany), Macrogen (South Korea) and Fasteris (Switzerland). Sequence analysis and annotation has been performed in collaboration with the Swiss Bioinformatics Institute (Vital-IT, Lausanne, Switzerland) and Swissprot (Geneva, Switzerland). TIP also used the modern greenhouse facilities of Syngenta AG at Stein (Switzerland) for phenotypic screening of candidate lines. In general, the collaboration established by TIP involves a prototype of private-public partnership (PPP).

23.6. Achievements of TIP

Phenotypic screening and TILLING for valuable traits allowed us to obtain several candidate lines. Most of these candidates were introgressed to s everal improved cultivars and are being tested in the field in Ethiopia. Fig. 3 shows the performance of candidate lines for lodging and drought tolerance. The semi-dwarf and lodging tolerant *kegne* lines had good performance at both Debre Zeit and Holetta in Ethiopia. Two candidates for drought tolerance (*dtt*: drought tolerant tef) were also crossed to improved tef cultivars and soon will be tested at drought- prone areas in Ethiopia.

The genome sequencing using the next-generation sequencing platforms such as FLX-454 and Illumina generated substantial amount of tef sequence. At present, the sequence is being assembled and annotated. The information from the sequencing is being utilized in identifying and isolating the genes responsible for useful traits. Considerable number of genetic markers particularly microsatellites have been identified based on the sequence information. Sequencing of the transcriptome resulted in the detection of 23 thousand genes producing 38 thousand transcripts. RNASeq experiments using different abiotic stress treatments resulted in genes differentially regulated under drought and water-logging.

23.7. Expected Impact of Improved Tef Varieties

At the moment, it is too e arly to predict the impact of new tef candidates in the productivity per unit area and total production in the country. However, with the modest estimation of an increase in productivity of only 0.5 ton/ha on about 60% of the tef area, the total tef production will be raised from the current 3.3 million ton to 4.2 million tons (Fig. 4). This could be achieved without increase in the cultivable area for tef. Hence, Ethiopia might fulfil its grain requirement and eventually stop importing cereals, although this calculation did not consider the population increase. According to the Index Mundi, Ethiopia imported about 800 thousand tons of wheat in the year 2011 (http://www.indexmundi.com/agriculture/?country=et&commodity=wheat&graph=imports, accessed March 9, 2012).

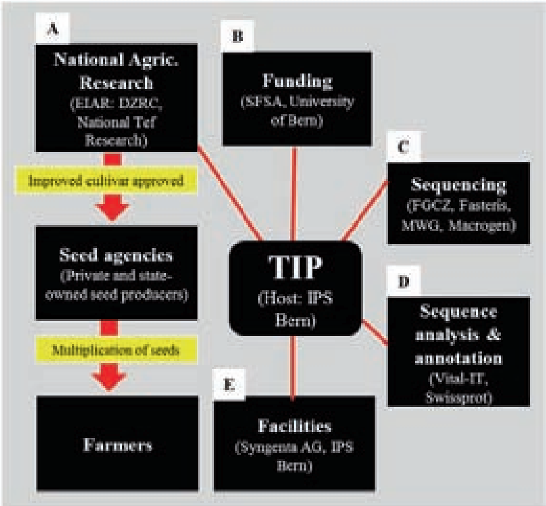

Fig. 2. Stakeholders of TIP. A) The collaboration with the NARS especially with the EIAR is in the area of crossing of candidate tef lines to elite tef cultivars and testing at the on-station and on-farm sites, and training and workshop for EIAR staff. The link to the seed agencies and farmers is through EIAR in general and specifically the National Tef Research Team; B) TIP benefited from the long-term financial support from the SFSA and the starting grant from the University of Bern; C) The tef genome and transcriptome has been sequenced using the next-generation platforms at the FGCZ, Fasteris, MWG and Macrogen; D) The sequence analysis and annotation have been performed through the collaboration of Vital-IT and the Swiss-Prot both belonging to the SIB; E) TIP has access to the facilities at the IPS in Bern and the Green-house of Syngenta AG. *Abbreviations:* DZRC: Debre Zeit Research Center; EIAR: Ethiopian Institute of Agricultural Research; FGCZ: Functional Genomic Center Zurich; IPS: Institute of Plant Sciences at the University of Bern; NARS: National Agricultural Research System; SFSA: Syngenta Foundation for Sustainable Agriculture.

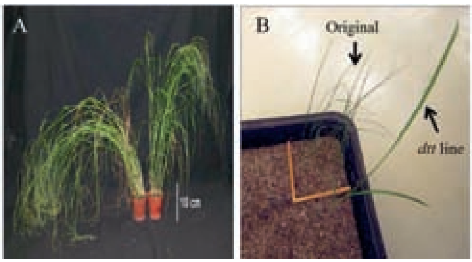

Fig. 3. Candidate tef lines for lodging and drought tolerance. The *kegne* mutant is shorter in height and more lodging tolerant than the original *Tsedey* cultivar (A). The *dtt* (drought tolerant tef) lines are also more drought tolerant than the original *Tsedey* cultivar (B). *kegne* was characterized by Moritz Jöst while the *dtt* lines were identified by Regula Schneider.

23.8. Expected Impact of Improved Tef Varieties

At the moment, it is too early to predict the impact of new tef candidates in the productivity per unit area and total production in the country. However, with the modest estimation of an increase in productivity of only 0.5 ton/ha on about 60% of the tef area, the total tef production will be raised from the current 3.3 million ton to 4.2 million tons (Fig. 4). This could be achieved without increase in the cultivable area for tef. Hence, Ethiopia might fulfil its grain requirement and eventually stop importing cereals, although this calculation did not consider the population increase. According to the Index Mundi, Ethiopia imported about 800 thousand tons of wheat in the year 2011 (http://www.indexmundi.com/agriculture/?country=et&commodity=wheat&graph=imports, accessed March 9, 2012).

23.9. The Way Forward

TIP is aimed at increasing the productivity of tef by developing cultivars with desirable traits. Diverse genetic and genomic tools are being employed in order to achieve these goals. In the future, additional new techniques or tools need to be applied in tef improvement. Tools such as EcoTILLING (Comai *et al.*, 2004) and GWAS (Zhao *et al.*, 2011) could be applied on tef accessions collected from diverse agro-ecological regions of Ethiopia. More than 5000 accessions available at the IBC could be explored using these techniques. Candidate lines from our mutagenized population could also be investigated using the recently discovered method called Mutmap (Abe *et al.*, 2012).

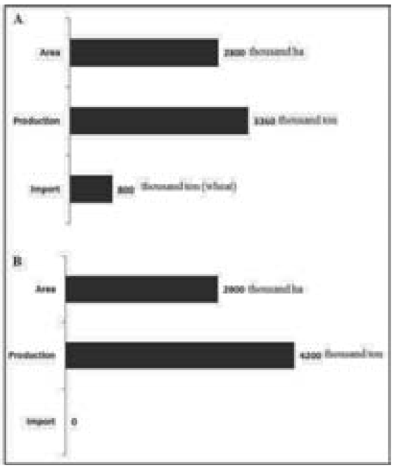

Fig. 4. Expected impact of improved tef cultivars on food requirement. A) According to CSA (2011) tef is cultivated on about 2.8 million ha of land producing about 3.36 million tons. During the same year, due to shortage of grain, Ethiopia imported about 800,000 tons of wheat (http://www.indexmundi.com/agriculture/?country=et&commodity=wheat&graph=imports accessed March 9, 2012). B) A yield increase of only half a ton per hectare on the existing tef area but with sixty percent adoption will produce about 4.2 million tons tef grain. Hence, according to this assumption an additional 840 thousand tons of tef grains can be produced which is equivalent to the amount of wheat grain imported in 2011.

Awareness of the global scientific and financial institutions about tef and other orphan crops is important as these groups of crops play key role in the economy of the developing world. In addition, these crops perform better than major crops of the world in adaptation to challenging environments. In the First International Orphan Crops Conference held in September 2007 in Bern, Switzerland, scientists working on both the orphan and major crops of the world discussed how to apply modern techniques towards the improvement of orphan crops. Proceedings of the conference is available at http://www.ips.unibe.ch/content/e6537/e7756/orphancrops proceedings.pdf. Follow-up conferences or workshops need to be organized in order to assess the progresses made in orphan crops research and to attract funding grants.

Effective collaboration with the national agricultural research system ensures efficient technology transfer and field-testing, which are critical in the development of new cultivars. In general, broader collaboration involving stakeholders from private and public institutions is important for promoting research and development of tef.

23.10. Abbreviations

ALS: acetolactate synthase; **CSA**: Central Statistical Agency; **dtt**: drought tolerant tef; **DZRC**: Debre Zeit Research Center; **EcoTILLING**: TILLING applied to natural population; **EIAR**: Ethiopian Institute of Agricultural Research; **FGCZ**: Functional Genomic Center, Zurich; **GWAS**: Genome-Wide Association Studies; **IPS**: Institute of Plant Sciences of the University of Bern; **MAB**: marker-assisted breeding; **NARS**: National Agricultural Research System; **PPP**: Private-Public Partnership; **Rht**: Reduced height; **Sd**: semi-dwarf; **SFSA**: Syngenta Foundation for Sustainable Agriculture; **TILLING:** Targeting Induced Local Lesion IN Genomes; **TIP**: Tef Improvement Project.

23.11. Acknowledgements

I would like to express my best gratitude to Syngenta Foundation for Sustainable Agriculture and the University of Bern for supports provided to the Tef Improvement Project. I would also like to thank my colleagues in TIP who work hard towards the success of the project. These include Korinna Esfeld, Sonia Plaza, Gina Cannarozzi, Moritz Jöst, Regula Schneider. The collaboration with EIAR in general and the National Tef Research Team at Debre Zeit in particular is key to the success of our project. Further acknowledgements are to our collaborators in TILLING, genome sequencing, breeding and field testing.

23.12. References

Abe A, Kosugi S, Yoshida K, Natsume S, Takagi H, Kanzaki H, Matsumura H, Yoshida K, Mitsuoka C, Tamiru M, Innan H, Cano L, Kamoun S and Terauchi R. 2012. Genome sequencing reveals agronomically important loci in rice using MutMap. Nat Biotechnol. 30:174-178.

Ashikari M, Sakakibara H, Lin S, Yamamoto T, Takashi T, Nishimura A, Angeles ER, Qian Q, Kitano H and Matsuoka M. 2005. Cytokinin oxidase regulates rice grain production. Science 309:741-745.

Comai L, Young K, Till BJ, Reynolds SH, Greene EA, Codomo CA, Enns LC, Johnson JE, Burtner C, Odden AR and Henikoff S. 2004. Efficient discovery of DNA polymorphisms in natural populations by Ecotilling. Plant J. 37:778-86.

CSA.2011. Central Statistical Agency. Agricultural Sample Survey 2010/11, , Statistical Bulletin 505, Addis Ababa, Ethiopia.

Hanson BD, Shaner DL, Westra P and Nissen SJ. 2006. Response of selected hard red wheat lines to Imazamox as affected by number and location of resistance genes, parental background, and growth habit. Crop Sci. 46:1206-1211.

Kebebew Assefa, Getachew Belay, Hailu Tefera, Yu JK and Sorrells ME. (2009) Breeding tef: conventional and molecular approaches. *In*: Zerihun Tadele (ed.) New approaches to Plant Breeding of Orphan Crops in Africa: Proceedings of an I nternational Conference, 19-21 September 2007, Bern, Switzerland, University of Bern, pp 21-41.

Naylor RL, Falcon WP, Goodman RM, Jahn MM, Sengooba T, Hailu Tefera and Nelson RJ. 2004. Biotechnology in the developing world: a case for increased investments in orphan crops. Food Policy 29:15-44.

Parry MA, Madgwick PJ, Bayon C, Tearall K, Hernandez-Lopez A, Baudo M, Rakszegi M, Hamada W, Al-Yassin A, Ouabbou H, Labhilili M and Phillips AL. 2009. Mutation discovery for crop improvement. Journal of Experimental Botany 66: 2817-2825.

Peng J, Richards DE, Hartley NM, Murphy GP, Devos KM, Flintham JE, Beales J, Fish LJ, Worland AJ, Pelica F, Sudhakar D, Christou P, Snape JW, Gale MD and Harberd NP. 1999. Green revolution genes encode mutant gibberellin response modulators. Nature 400: 258-261.

Sasaki A, Ashikari M, Ueguchi-Tanaka M, Itoh H, Nishimura A, Swapan D, Ishiyama K, Saito T, Kobayashi M, Khush GS, Kitano H and Matsuoka M. 2002. Green revolution: a mutant gibberellin-synthesis gene in rice. Nature 416:701-702.

Shomura A, Izawa T, Ebana K, Ebitani T, Kanegae H, Konishi S and Yano M. 2008. Deletion in a gene associated with grain size increased yields during rice domestication. Nat Genet. 40:1023-1028.

Song XJ, Huang W, Shi M, Zhu MZ and Lin HX. 2007. A QTL for rice grain width and weight encodes a previously unknown RING-type E3 ubiquitin ligase. Nat Genet. 39:623-630.

Wang Y, Ying J, Kuzma M, Chalifoux M, Sample A, McArthur C, Uchacz T, Sarvas C, Wan J, Dennis DT, McCourt P and Huang Y. 2005. Molecular tailoring of farnesylation for plant drought tolerance and yield protection. Plant Journal 43:413-24.

Wilson PB, Estavillo GM, Field KJ, Pornsiriwong W, Carroll AJ, Howell KA, Woo NS, Lake JA, Smith SM, Harvey Millar A, von Caemmerer S, Pogson BJ. 2009. The nucleotidase/phosphatase SAL1 is a negative regulator of drought tolerance in Arabidopsis. Plant J. 58:299-317.

Zerihun Tadele, Mba C and Till BJ. 2009. TILLING for mutations in model plants and crops. *In*: Mohan Jain S and Brar DS (eds.) Molecular Techniques in Crop Improvement. Springer, The Netherlands.

Zhao K, Tung CW, Eizenga GC, Wright MH, Ali ML, Price AH, Norton GJ, Islam MR, Reynolds A, Mezey J, McClung AM, Bustamante CD and McCouch SR. 2011. Genome-wide association mapping reveals a rich genetic architecture of complex traits in *Oryza sativa*. Nat Commun. 2:467.

VIII. General Discussion & Recommendations

24. Roadmap Process & Priorities for Action: Improved productivity & income for tef growers

By Workshop Participants

Priority 1. Germplasm, Genomics, Mapping and Markers: *increase availability of novel traits and markers*

1. Complete (genotypic/phenotypic) characterization of IBC's holdings and other tef germplasm collections (>5000 accessions), and reduce redundancy
2. Continue collection of landraces from diverse locations
3. Develop and execute biodiversity conservation plan
4. Complete tef genome assembly and annotation
5. Novel trait discovery (seed size, lodging tolerance, reduced grain shattering, drought resistance, etc.)
6. Enhance mapping and complete development of markers (e.g. QTLS)
7. Improve international data sharing (through tef web-site and mailing list) and co-ordination of efforts (National Agricultural Research System with International collaborators such as the universities of Cornell, Bern, Georgia and Wageningen, and BecA)
8. Utilization of MAS in the Ethiopian tef breeding program by improving resources, capacity building and co-ordination among national and international institutes

Priority 2. Conventional Breeding: *insufficient locally adapted varieties*

9. Define tef ideotypes suitable for crop intensification and regional needs (agro-ecology based)
10. Assess and improve variety evaluation and registration protocols and procedures based on agro-ecologies

11. Develop inter-specific crossing technologies and generate hybrids in order to introgress desirable traits of wild relatives (e.g. lodging tolerance of *Eragrostis curvula*) to tef
12. Strengthen national breeding program (increase the number of crosses per year and variety releases) and involve growers and conumers through participatory variety selection. Participatory approach would be necessary to identify farmer-preferred technologies and eventually to enhance adoption
13. Incorporate grain, food and feed quality parameters into variety selection, and build capacity for laboratory quality evaluations. Establish one strong national laboratory for tef grain, tef products development and quality evaluation
14. Philosophy of screening new varieties under recommended input levels (especially fertilizer) but care needed to ex tend evaluation of breeding materials under representative range of ecologies (including water stress)
15. The following traits are identified as priority for future tef improvement: lodging, drought tolerance, seed size, reduced grain shattering, earliness, response to nutrients, yield and grain quality (e.g. seed color), rust resistance, fodder quality, and weed management

Priority 3. Cropping Systems & Agronomy: *validated technology packages, and farm machinery to improve productivity and conserve soils*

16. Regional soil analysis and identification of limiting factors (macro- and micro-nutrients) and integrate with new national soil mapping initiative
17. Cropping systems research (rotations, inter-cropping, etc.) needed for integration of profitable rotation of crops (e.g. with legumes) to a void tef monocultures
18. Develop tef crop growth and tef cropping systems models
19. Continued development of improved seeding technologies, and fertilizer applications (rate, placement and timing)
20. Identification and adaptation of small-scale farm mechanization to a ddress labor constraints in tillage, planting, harvesting, threshing, cleaning and processing
21. Research on appropriate irrigation and soil moisture management
22. Improved weed control strategies for key weeds (grass weeds, parthenium)
23. Development and validation of soil conservation techniques (e.g. minimum tillage)

24. Pest and disease surveillance – preparedness and resilience to support crop intensification (including leaf rust, shoot fly and head smudge)
25. Rehabilitate tef *Acacia albida* agro-forestry farming systems to p romote organic farming in tef production, soil reclamation to address sustainable farming, fodder, fuel, apiculture, timber, s hade and shelter issues facing the tef farms and farmers

Priority 4. Tef Utilization and Added Value Products: *open new markets for tef to stimulate demand and drive crop productivity and value chain development*

26. Study alternative uses to *injera* and tef flour (e.g. wheat, maize, sorghum mixture and substitution)
27. Development and farmer validation of improved fodder utilization technologies (e.g. fodder as a business)
28. Development and marketing of added value tef products (complementary with ATA value chain study)
    - Assess the export potential of tef
    - *Injera* processing improvements including starter culture development and processing equipments
    - Investigate tef products as functional foods (gluten-free, anti-oxidant potential mineral composition, etc.)
    - Capacity building through tailor made M.Sc./Ph.D, and senior research staff exchange for collaboration and experience sharing
    - Build collaborations among Ethiopian Nutrition Research Institute, Universities and international food research institutions
29. Market-led approaches to create technology 'Pull'

Priority 5. Socio-Economics, Extension and Seed-Systems: *getting technology to farmers faster*

30. Development of agreed upon and consistent databases of technology adoption and market trends to drive evidence-based policy making
    - Conduct formal impact assessments of new varieties (e.g. Quncho variety)

31. Strengthening of the formal seed systems and encouragement of entry of the private sector
    - Regulatory (seed quality) capacity including quality schemes relevant to small-holder seed producers
    - Enabling policy environment including revision of Seed Act
32. Strengthening and recognition of informal seed systems, and encouragement of commercially driven community seed production to compliment the formal sector
33. Strengthening extension capacity
    - Raising awareness and technology promotion and communication
    - Information technology platforms and market information
    - Improving links to R4D
34. Development of tef value chain including grower and marketing organization
    - Improvement of post-harvest processing, storage and handling

Communications and Coordination

35. Establish a network of tef researchers and development workers for easy and faster communication (The University of Bern group took the initiative to organize the email address of tef community under all@tef-research.org).

36. Strengthen the web-site of tef research (www.tef-research.org) by providing information related to tef research and development activities carried out at different institutions, regions, etc.

37. Publish the proceedings of the workshop in the earliest possible time. The Organizing committee of the workshop is given the responsibility to edit and publish the proceedings. The deadline for submitting the first draft of the manuscript is set for the end of December 2011.

38. Participants agreed to hold the next Third International Tef Workshop in three years.

Roadmap Process	**Owner**
39. Workshop priorities	Participants
40. Consultation and refinement	Organizing Committee
41. Workshop procedures	Organizing Committee/SFSA

42. Communication and co-ordination
    - Informal donor contact — SFSA/AGRA/McKnight/USAID
    - Fund raising — All
    - Tef community web-site — University of Bern
43. National tef research strategy — EIAR
44. Implementation — MoA/EIAR

Abbreviations

AGRA: Alliance for Green Revolution in Africa; **BecA**: Biosciences Eastern and Central Africa; **EIAR**: Ethiopian Institute of Agricultural Research; **IBC**: Institute of Biodiversity Conservation, Ethiopia; **MAS**: Marker-Assisted Selection; **MoA**: Ministry of Agriculture; **QTL**: Quantitative Trait Locus; **R4D**: Research for Development; **SFSA**: Syngenta Foundation for Sustainable Agriculture; **USAID**: United States Agency for International Development.

Closing Session

Vote of Thanks

Zerihun Tadele
Tef Improvement Project, Institute of Plant Sciences, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland. Email: zerihun.tadele@ips.unibe.ch

On behalf of the organizing committee which includes Dr. Kebebew Assefa, Dr. Solomon Chanyalew and myself, I would like to express my heartfelt appreciation to all individuals and institutions who made this workshop a success.

Dear Workshop Participants,
Ladies and Gentlemen,

May I first extend my apologies for my excitement in the voice I am now presenting these "Votes of Thanks". My excitement, however, has actually been over reasons. First thing, my blood has been warmed by the very successful accomplishment of our Second International Tef Workshop. Secondly, I have been extremely delighted to have heard through the proceedings of the workshop that we are making progress in tef research and development while there have also been continually increasing partnerships in tef improvement efforts both locally and internationally.

Dear Workshop Participants,
Ladies and Gentlemen,

It is to be recalled that the 'First International Workshop on Tef Genetics and Improvement" was carried out in Addis Ababa from 16-19 October 2000, and its Proceedings were published in 2001 under the title: '*Narrowing the Rift: Tef Research and Development'*. This compilation has literally served us the "Bible of Tef Research and Development". Ever since, however, particularly after a decade has lapsed from the first workshop event, we have been thinking of how we can manage to have a second one so us to know where we have reached and update our "Bible".

As such, we appeared helpless in terms of resources. But Dr. Zerihun Tadele of the University of Bern, upon consultation with the Syngenta Foundation for Sustainable Agriculture, was able to get a positive go ahead support. And, we are grateful to Syngenta Foundation for Sustainable Agriculture to have been the vanguard in extending the lion's share of financial support for the workshop. Having captured

some encouraging amounts of support, the Organizing Committee devised a further fund soliciting scheme, and was able to capture the financial as well as the technical backstopping and moral that eventually made our workshop possible.

Hence, in addition to our heart-felt gratitude to Syngenta Foundation for Sustainable Agriculture, we would like to thank the following sponsors for their generous support: Sasakawa Global 2000, the Ministry of Science and Technology (Ethiopia), Ethiopian Institute of Agricultural Research, University of Bern and Dreamland Hotel at Debre Zeit.

We would also thank Dr. Solomon Assefa, Director General of the Ethiopian Institute of Agricultural Research, for officially opening the workshop, and Dr. Mekasha Chichaibelu, Director of Debre Zeit Agricultural Research Center for delivering the Closing Remarks. The keynote address by Dr. Tareke Berhe also shows his long-term interest and motivation to improve tef.

Our thanks also to the chair persons of different sessions which include Dr. Adefris Teklewold, Dr. Andres Binder, Dr. Eshetu Derso, Dr. Kathryne Benesh, Dr. Jane Ininda and Dr. Mekasha Chichiabelu. The discussants of the workshop also stimulated the discussion and suggested future research areas. The discussants for various sessions were Dr. Tileye Feyissa, Dr. Firew Mekbib, Dr. Abate Bekele, Dr. Ayele Badebo, Dr. Shimelis Admassu, Dr. Mulugeta Tamir, Dr. Ian Barker, Dr. Hailu Araya and myself. In addition, we thank rapporteurs of various sessions.

We would also thank the following individuals for assisting in drafting the action plan for tef research: Dr. Ian Barker, Dr. Tareke Berhe, Dr. Jan Vos, Dr. Andres Binder, Dr. Kebebew Assefa and myself.

We thank all speakers for wonderful presentations and participants for discussion.

Last but not least, our appreciation goes to those who assisted us in organizing the workshop. These include Mr. Mengistu Demissie, Mrs. Alemzewd Sebsibe, Mr. Kassahun, the administration and financial management of Debre Zeit Agricultural Research Center (DZARC), all staff of the Tef Improvement Project at DZARC, and the farmers of Ude-Denkaka area in supporting our field visit.

Thank You!!

Closing Remarks

Mekasha Chichaibelu

Director, Debre Zeit Agricultural Res. Center, Ethiopian Institute of Agricultural Research, P.O.Box 32, Debre Zeit, Ethiopia.

Dr. Kebebew Assefa, Coordinator, National Tef Research Project
Representatives of National & International Institutions
Honorable Invited Guests,
Ladies and Gentlemen,

I feel extremely honored to have been selected to deliver the closing remarks for this important workshop, the second of its kind in the history of tef. It would be important to point out that this workshop has, indeed been a remarkable success because over the last three days, you have not only reviewed the progress and achievements made to-date in tef improvement research and development, but most importantly it has also outlined the roadmap and priorities for our future research and development endeavors. Hence, I believe that you, the participants of the workshop, should be proud of these remarkable achievements.

Dear Workshop Participants,

Indeed, in one of the presentations on this workshop, it has been declared that "Tef is no more an Orphan Crop". Whilst this might be true in terms of The Recent Recognition and emphasis given to Tef research and Development particularly by the Ethiopian Government; however, much still remains in terms of the improvement research to take out tef from the orphanage. The recent government attention, notwithstanding, we can however be only encouraged by the fact that we are now on the road to taking out the crop from the orphanage status.

Many of the bottlenecks in tef research and the constraints to tef production, mainly the low productivity status, and the lodging problem, still remain untouched and we have to be able to make as fast progress as possible before we can declare that the crop is no more an orphan crop.

Looking into the history of genome sequencing in plants is one aspect. In chronological order, genome sequencing has been completed starting with the model plant, *Arabidopsis thaliana* in 2000, then for rice in 2002, for poplar in 2006, for grape in 2007, for papaya in 2008, for sorghum, maize and cucumber in 2009, for Soybean in 2010, and for pigeon pea and strawberry in 2011. It would be important to note, at this juncture, that until the completion of the genome sequencing in 2009, even the one of the major world crop, sorghum, was under the category of orphan, under-utilized or neglected crops. In line with this, we are encouraged by the progress we have heard in the tef genome sequencing efforts being made by the researchers at the University of Bern, Switzerland.

Ladies and Gentlemen,

Through the course of the proceedings of the workshop over the last three days, we have been educated and learnt a lot, and above all, we have been able to know our status as to where we are with respect to the research and development of our invaluable Ethiopian cereal, tef. I have also been convinced of the fact that this workshop, has been able to bring the souls and minds of various professional of varied disciplines involved in tef research and development throughout the world. In this regard, although there have still been some scientists working on tef that have not been able to participate on this workshop for various reasons, in effect, it has been really of international nature as important scientists from Wageningen University and the University of Bern have been here with us and shared us their rich experiences and expertise.

It is also important to note that the fact that this workshop has outlined the prospects for tef research and development in terms of laying out the roadmap and setting the priorities, it is my greatest conviction that we all promise to keep up working and striving to this end, and by doing so we would undoubtedly bee soon able to take tef out of its orphanage.

Dear Workshop participants,
Ladies and Gentlemen,

Last but not least, thanking the organizers, the presenters and all of you, the participants of the workshop for making the workshop proceeding fruitful with remarkable success, I now declare, the workshop officially closed.

Thank You!!!!

Participants

Abate Bekele (PhD)
Agricultural Economist, EIAR
Debre Zeit Agric. Research Center
P.O.Box 32, Debre Zeit, Ethiopia
Email: abatebekele98@gmail.com

Abebe Atilaw (PhD)
Agronomist, EIAR
P.O.Box 2003, Addis Ababa, Ethiopia
Email: Abebe.Atilaw@yahoo.com

Adefris Teklewold (PhD)
Director, Crops Research,
EIAR, P.O.Box 2003, Addis Ababa,
Ethiopia
Email:adechere@yahoo.co.uk

Alemu Yami (PhD)
USAID, P.O.Box 1014, Addis Ababa,
Ethiopia
Email: alemuyami@yahoo.com

Alganesh Tessema (PhD)
Team Leader, Institute of Biodiversity
Conservation (IBC), P.O.Box 30726, Addis
Ababa, Ethiopia
Email: adishihu@yahoo.com

Andres Binder (PhD)
Consultant, SFSA, Schwarzwaldalle 215,
CH-4002 Basel, Switzerland
Email:andres.binder@unibas.ch

Ayele Badebo (PhD)
Pathologist, EIAR, Debre Zeit Agric.
Research Center, P.O.Box 32, Debre Zeit,
Ethiopia
Email:ayele88@yahoo.com

Befekadu Behute
Consultant, Agricultural Transformation
Agency (ATA), P.O.Box 708, Addis Ababa,
Ethiopia
E-mail: befekadu_be@yahoo.com

Biruk Wubshet
Amhara Seed Enterprise (ASE), P.O.Box
1031, Bahir Dar, Ethiopia

Bulo Nida
EIAR, Jima Agric. Res. Center, P.O.Box
192, Jima, Ethiopia

Chilot Yirga (PhD)
Economist, EIAR, Holetta Center, P.O.Box
2003, Addis Ababa, Ethiopia
Email: ctizale@yahoo.com

Dawit Alemu (PhD)
Coordinator, Economics & Extension,
EIAR, P.O.Box 2003, Addis Ababa,
Ethiopia
Email: dawit96@gmail.com

Eshetu Derso (PhD)
Researcher, EIAR, Debre Zeit Agric.
Research Center, P.O.Box 32, Debre Zeit,
Ethiopia
E-mail: ederso@yahoo.com

Firew Mekbib (PhD)
Lecturer & Biotechnologist, Haramaya
University, P.O.Box 138, Dire Dawa,
Ethiopia
Email:firew.mekbib@gmail.com

Friew Kelemu
Researcher, EIAR, Melkassa Agric. Research Center, P.O.Box 436, Adama, Ethiopia
Email: friewkelemu@yahoo.com

Geremew Bultossa (PhD)
Lecturer & Researcher, Haramaya University, P.O.Box 138, Dire Dawa, ETHIOPIA
Email:bultosageremew@yahoo.com

Gina Cannarozzi (PhD)
Bioinformatician, Tef Improvement Project, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland
Email:Gina@cannarozzi.com

Habte Jifar
Tef Breeder, EIAR, Holetta Agric. Res. Center, P.O.Box 2003, Addis Ababa, Ethiopia
Email:habtejifar@gamil.com or

Haftamu Gebretsadik
Researcher, TARI, Axum Agric. Research Center, P.O.Box 30, Axum, Ethiopia
Email:haftifhmail@yahoo.com

Haile Sellassie Weres
Tigray Bureau of Agriculture, P.O.Box 10, Mekelle, Ethiopia

Hailu Araya (PhD)
Team Leader, ISD, Box 171 – 1110, Addis Ababa, Ethiopia
E-mail: hailuara@yahoo.com

Ian Barker (PhD)
Head, Agricultural Partnerships, SFSA, Schwarzwaldallee 215, CH-4002, Basel, Switzerland
Email:Ian.Barker@syngenta.com

Jan Vos (PhD)
Lecturer & Researcher, Wageningen University, CSA, Droevendaalsesteeg 1, 6708 PB Wageningen, The Netherlands
Email:jan.vos@wur.nl

Jane Ininda (PhD)
Program Officer, AGRA, Eden Square, Block 1, 5th Floor, P.O BOX 66773, Westlands, 00800, Nairobi, Kenya
Email:JIninda@agra-alliance.org

Kassahun Zewdie (PhD)
Researcher, EIAR, Holetta Agric. Research Center, P.O.Box 2003, Addis Ababa, Ethiopia
E-mail: Kassahunzewdie@yahoo.com

Kathryne Benesh
Agricultural Transformation Agency (ATA), Ethiopia
E-mail: kat.Benesh@ata.gov.et

Kebebew Assefa (PhD)
National Tef Research Project Coordinator, EIAR, Debre Zeit Agric. Research Center, P.O.Box 32, DebreZeit, Ethiopia
Email:Kebebew.Assefa@yahoo.com

Kidane Georgis (PhD)
EIAR, P.O.Box 2003, Addis Ababa, Ethiopia
Email: kidanegeorgis@yahoo.com

Korinna Esfeld (PhD)
Molecular Biologist, Tef Improvement Project, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland
Email:esfeld@ips.unibe.ch

Mekasha Chichaibelu (PhD)
Director, Debre Zeit Agric. Res. Center, EIAR, P.O.Box 32, Debre Zeit, Ethiopia
Email:mekashach@yahoo.com

Melaku Umeta (PhD)
Addis Ababa University, School of Medicine, P.O.Box 9086, Addis Ababa, Ethiopia
Email: umelaku@yahoo.com.hk

Minale Liben
Amhara Agric. Res. Institute (ARARI), P.O.Box 527, Bahir Dar, Ethiopia
Email: minaleliben@yahoo.com

Mitiku Asfaw
AARI, Adet Agric. Research Center, P.O.Box 8, Bahir Dar, Ethiopia
Email: mitikuasfaw@yahoo.com

Mulugeta Tamir
Food Scientist, EIAR, Melkassa Agric. Research Center, P.O.Box 436, Adama, Ethiopia
Email: muteas@yahoo.com

Setotaw Ferede (PhD)
Economist, EIAR, Debre Zeit Agric. Research Center, P.O.Box 32, Debre Zeit, Ethiopia
Email:setotawferede@yahoo.com

Sherif Aliy
Research & Extension, EIAR, Debre Zeit Research Center, P.O.Box 32, Debre Zeit, Ethiopia
Email:Geda_sherif@yahoo.com

Shimelis Admassu (PhD)
Food Technologist, Addis Ababa Ubiversity (AAU) Technology Faculty, Addis Ababa, Ethiopia
Email:shimelisemire@yahoo.com

Simayehu Tafesse
Amhara Seed Enterprise (ASE), P.O.Box 1031, Bahir Dar, Ethiopia

Solomon Assefa (PhD)
Director General, EIAR, P.O.Box 2003, Addis Ababa, Ethiopia
Email:ssolomet@yahoo.com

Solomon Chanyalew (PhD)
Tef Breeder, EIAR, Debre Zeit Agric. Research Center, P.O.Box 32, Debre Zeit, Ethiopia
Email:solchk2@gmail.com

Solomon Jemal
Agronomist, EIAR, Melkassa Agric. Research Center, P.O.Box 436, Adama, Ethiopia
Email:yemelk80@gmail.com

Sonia Plaza (PhD)
Molecular Biologist, Tef Improvement Project, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland
Email:Sonia.plaza@ips.unibe.ch

Tareke Berhe (PhD)
Special Advisor, Agricultural Transformation Agency (ATA), P.O.Box 708, Addis Ababa, Ethiopia
Email:tbtareke@gmail.com

Tebkew Damte (PhD)
Entomologist, EIAR, Debre Zeit Agric. Research Center, P.O.Box 32, Debre Zeit, Ethiopia
Email:tebkew@yahoo.com

Tesfa Bogale (PhD)
Agronomist, EIAR, Jima Agric. Research Center, P.O.Box 192, Jima, Ethiopia
Email: tesfabogale@gmail.com

Tesfahun Fenta
Pathologist, Agri-Sevice-Ethiopia, P.O.Box 2460, Addis Ababa, Ethiopia
Email:tfenta@yahoo.com

Thibiesta Yohannes
Agricultural Transformation Agency (ATA), P.O.Box 708, Addis Ababa, Ethiopia

Tileye Feyissa (PhD)
Lecturer and Biotechnologist, Addis Ababa University (AAU), Science Faculty P.O.Box 1176, Addis Ababa, Ethiopia
Email:tileye_feyissa@yahoo.com

Tsion Fikre
Tef Researcher/Breeder, EIAR, Debre Zeit Agric. Research Center, P.O.Box 32, Debre Zeit, Ethiopia
Email: tsfikre@yahoo.com

Welday Hailu
Food Science, EIAR, Melkassa Agric. Research Center, P.O.Box 436, Adama, Ethiopia

Yazachew Genet
Tef Researcher/Breeder, EIAR, Debre Zeit Agric. Research Center, P.O.Box 32, Debre Zeit, Ethiopia
Email: yazachewgenet@gmail.com

Yifru Abera
Soil Scientist, EIAR, Debre Zeit Agric. Research Center, P.O.Box 32, Debre Zeit, Ethiopia
Email:yifrua@yahoo.com or

Zerihun Tadele (PhD)
Project Leader, Tef Improvement Project, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland
Email: Zerihun.tadele@ips.unibe.ch

Zewdie Gebretsadik
Agronomist, SG2000, P.O.Box 12771 Addis Ababa, Ethiopia
Zewdiegebretsadik656@gmail.com

Field Visits & Group Photo

Debre Zeit Agricultural Research Center

Debre Zeit Agricultural Research Center

Farmers' field around Ude, Debre Zeit

Group Photo