EFFECTS OF RATES AND TIME OF NITROGEN FERTILIZER APPLICATION ON YIELD AND YIELD COMPONENTS OF TEF [(*Eragrostis tef* (Zucc.) Trotter] IN HABRO DISTRICT, EASTERN ETHIOPIA

M.Sc. Thesis

Abraha Arefaine

May 2013

Haramaya University

EFFECTS OF RATES AND TIME OF NITROGEN FERTILIZER APPLICATION ON YIELD AND YIELD COMPONENTS OF TEF [(*Eragrostis tef* (Zucc.) Trotter] IN HABRO DISTRICT, EASTERN ETHIOPIA

Submitted to the Department of Plant Sciences

College of Agriculture and Environmental Sciences

School of Graduate Studies

Haramaya University

In Partial Fulfilment of the Requirements for the Degree of Master of Science in Agronomy

By

Abraha Arefaine

May 2013

Haramaya University

APPROVAL SHEET

SCHOOL OF GRADUATE STUDIES
HARAMAYA UNIVERSITY

As thesis research advisors, we hereby certify that we have read and evaluated the thesis prepared by Abraha Arefaine under our guidance, which is titled "Effects of Rates and Time of Nitrogen Fertilizer Application on Yield and Yield Components of Tef [*Eragrostis Tef* (Zucc.) Trotter] in Habro District, Eastern Ethiopia". We recommend that the thesis be submitted as it fulfils the requirements.

Major advisor: Dr. Nigussie Dechassa, Signature…………………........Date…………………...

Co-advisor: Dr.Tamado Tana, Signature……………………………..Date……………………

As members of the Board of Examiners of the M.Sc. thesis open defence examination, we certify that we have read and evaluated the thesis prepared by Abraha Arefaine and examined him. We recommend that the thesis be accepted as it fulfils the requirements for the Degree of Master of Science.

Chairperson...Signature.........................Date......................

Internal Examiner....................................Signature.........................Date.......................

External Examiner...................................Signature.........................Date.......................

Final approval and acceptance of the thesis is contingent upon submission of the final copy of the thesis to the council of graduate studies (CGS) through the graduate committee (DGC) of the candidate's Department.

DEDICATION

I dedicate this thesis to my father Arefaine Gebreabzgi, my mother Aregay Tekulu and my uncle Brhane Tekulu for their affection and consistent care in the success of my life.

STATEMENT OF THE AUTHOR

First of all, I declare that this thesis is a result of my genuine work and all sources of materials used for writing it have been duly acknowledged. I have submitted this thesis to Haramaya University in partial fulfilment of the Degree of Master of Science. The thesis is deposited at the library of the University to be made available to borrowers for reference. I solemnly declare that I have not submitted this thesis to any other institution anywhere for the award of any academic degree, diploma, or certificate.

Brief quotations from this thesis are allowed without requiring special permission provided that an accurate acknowledgement of the source is made. Requests for extended quotations from or reproduction of this manuscript in whole or part may be granted by the Head of the Department of Plant Sciences or by the Dean of the School of Graduate Studies of the University when in his or her judgment, the proposed use of the material is for a scholarly interest. In all other instances, however, permission must be obtained from the author.

Name: Abraha Arefaine

Signature: ________________________

Place: Haramaya University

Date of submission: ______________________

BIOGRAPHICAL SKETCH

The author, Abraha Arefaine, was born on 12 August 1985 in Adwa woreda, Central Zone of Tigray Regional State of Ethiopia. He attended elementary education (grade 1-8) at Mydaero Elementary School from 1993 - 2000. After completing elementary education, he was enrolled at Nigiste-Saba Secondary School at Adwa town, where he pursued and completed his Secondary and Preparatory Education from 2001 – 2004 (grade 9-12). He then joined Haramaya University in January 2005 and graduated with the Degree of Bachelor of Sciences in Plant Science in July 2007. Upon graduation, he was employed by Soro woreda Agricultural and rural Development Office in Hadiya Zone, Southern Ethiopia and was assigned to work as an expert of early warning and food security. After serving the Soro woreda Agricultural Development Office for four years, he joined the School of Graduate Studies of Haramaya University in October 2011 to pursue a study leading to the Degree of Master of Science in Agronomy.

ACKNOWLEDGMENTS

I am very much indebted to my major advisor Dr. Nigussie Dechassa for his useful comments, suggestions and constructive criticisms during proposal preparation, for providing me with immense supports as well as for guiding and supervising my work during the entire period of the research and for shaping the final write-up of the thesis. My sincere appreciation also goes to my co-advisor, Dr. Tamado Tana for his valuable guidance and comments throughout the study.

My especial thanks go to the CASCAPE (Capacity Building for Scaling up Evidence-based Best Practices for Agricultural Development) project, which is being implemented by Haramaya University in the Eastern Oromia Region for the financial support provided by the government of the Netherlands through the coordination of the Royal Netherland Embassy in Addis Ababa, for granting me the fund I required to do the research work. I would also like to express my special appreciation to all staff working as innovator team members in the project for the valuable consistent logistic support and advice they gave me during my stay in the Habro district of Western Hararghe Oromia region for conducting the field research.

I would like to express my warm gratitude to the Soro Woreda Agricultural and Rural Development office especially Alemayehu Kabiso and Eriso Ergicho for allowing me to pursue the study leading me to the Degree of Master of Science.

I would also like to further extend my thanks to Dargo Kebede for his constructive comments starting from the write up of the proposal and the thesis, Sintayehu Temesgen and Nisiha Nega for helping me whenever I required their assistance and support.

My gratitude also goes to my friends Abraham Reda, Samson Seife, Abraham Tegegn and Abebe Kebede for their lovely friendship during my stay at Haramaya University.

LIST OF ABBREVIATIONS AND ACRONMYS

ANOVA	Analysis of Variance
CEC	Cation exchange capacity
CSA	Central Statistical Agency
CV	Coefficient of variation
FAO	Food and agriculture organization
GDP	Gross Domestic Product
IAEA	International Atomic Energy Agency
IAR	Institute of Agricultural Research
LGP	Length of growing period
LSD	Least Significant Difference
NUE	Nitrogen use efficiency
OC	Organic carbon
RCBD	Randomized Complete Block Design
SNNPR	South Nations Nationalities and People Region
SAS	Statistical analysis system

TABLE OF CONTENTS

LIST OF TABLES

LIST OF APPENDICES

EFFECTS OF RATES AND TIME OF NITROGEN FERTILIZER APPLICATION ON YIELD AND YIELD COMPONENTS OF TEF [(*Eragrostis tef* (Zucc.) Trotter] IN HABRO DISTRICT, EASTERN ETHIOPIA

ABSTRACT

Tef is a highly valued crop in the national diet of Ethiopians. However, its productivity is constrained by low plant-available soil nitrogen due to depleting soil organic matter content and high leaching losses of mineralized nitrogen during the growing rainy seasons. This problem is compounded by low rates and ill-timing of N fertilizer applications in the country. Therefore, a field experiment was carried out during the 2012 main cropping season from July to November in Habro district of eastern Ethiopia on a farmer's filed with the objectives of studying the effects of rates and time of nitrogen fertilizer application on yield and yield components of tef and determining the most economic rate and time of nitrogen fertilizer application for tef production in the study area. *The treatments consisted of four levels of nitrogen (0, 46, 69 and 92 kg N ha^{-1}) and five application times (full dose at sowing, full dose at tillering, ½ dose at sowing + ½ dose at tillering, 1/3rd dose at sowing + 1/3rd dose at tillering + 1/3rd dose at anthesis, 1/4th dose at sowing + ½ at tillering + 1/4th dose at anthesis). The experiment was laid out as a randomized complete block design with three replications All the parameters evaluated were affected by the main effect of N fertilizer rate and time of N application. However, days to maturity and panicle length did not respond to the time of N fertilizer application. Days to panicle emergence and physiological maturity were delayed as the rate of nitrogen fertilizer was increased. The highest biomass yield, grain yield, straw yield, total nitrogen uptake, apparent nitrogen recovery, and agronomic efficiency were recorded at 69 kg N ha^{-1} applied half dose at sowing and half dose at tillering stage. Most of the parameters including the grain and straw yields exhibited maximum performance under this N treatment level. Thus, application of N fertilizer at a rate of 69 kg ha^{-1} by splitting the dose into two and applying ½ dose at sowing time and the remaining ½ dose at mid-tillering stage of the tef crop can be recommended for the study area.*

1. INTRODUCTION

Tef [*Eragrostis tef* (Zucc.) Trotter] is an annual C_4 grass that belongs to the family *Poaceae* (Kebede *et al*., 1989). It is an indigenous cereal crop in Ethiopia. Ethiopia is the origin and the first domesticator of this unique crop (Vavilov, 1951). Also, it is thought to have been spread to Europe through the Portuguese contact in the 16^{th} century (Taddesse, 1975). According to Costanza *et al*. (1979) tef was distributed to several countries in the 19^{th} century, and now it is cultivated as a forage grass in Australia, India, Kenya, and South Africa. According to Seyfu (1997) the Royal Botanical Gardens Kew imported tef kernel from Ethiopia in 1866 and distributed it to India, Australia, the USA and South Africa. It was reported that Burt Davy in 1916 introduced tef to California, Malawi, Zaire, India, Sri Lanka, Australia, Newzealand, and Argentina (Seyfu, 1997).

In Ethiopia, tef is a highly valued crop and it is primarily grown for its grain that is used for preparing *injera,* which is a staple and very popular food in the national diet of most Ethiopians. It can also be used in many other food products such as *kitta* (unleavened bread), *anebaberro* (double layered injera), porridge, gruel, and local alcoholic beverages such as *tella* and *katikala* (Asrat and Frew, 2001; Hailu *et al*., 2003; Seyfu, 1993). These writers also suggested that tef is not suitable for bread making as it lacks the necessary amount and quality of protein complex called “gluten” that can be formed into dough with the rheological properties required for the production of leavened bread.

Nutritionally, tef has as much or even in certain cases more food value than the major grains: wheat, barley and maize. Tef grain contains 14-15% proteins, 11-33 mg iron, and 100-150 mg calcium and is rich potassium and phosphorous (National Academy of sciences, 1996). Furthermore, Asrat and Frew (2001) reported that the carbohydrate content of tef ranges from 72.1-75.2%, protein 8.1-11.1% and ash 2.5-3.2%; the major component of ash being iron. They also reported that tef has got high lysine content compared to all cereals except rice and oats.

In Ethiopia, tef is cultivated on an area of about 2.73 million hectares. Tef and maize taking up about 22.6% and 17% of the total grain crop area, respectively (CSA, 2012). This makes tef the first among cereals in the country in area coverage. However, out of the total cereal grain produced, maize and tef accounted for 27.77% (6.07 million tons) and 16% (3.498 million tons), respectively (CSA, 2012). Despite the aforementioned importance and coverage of large area, its productivity is very low. The average national yield of tef is about 1.28 tone ha^{-1} (CSA, 2012). Some of the factors contributing to low yield of tef are low soil fertility and suboptimal use of mineral fertilizers in addition to weeds, erratic rainfall distribution in lower altitudes, lack of high yielding cultivars, lodging, water-logging, low moisture, and low soil fertility conditions (Fufa, 1998). On the other hand, under conditions where most growth requirements are available and in organic matter rich soils, application of fertilizers without knowing its fertility status causes yield and fertilizer losses (Tekalign *et al*., 2001).

There are different blanket fertilizer recommendations for various soil types of Ethiopia for tef cultivation. For heavy soils (Vertisols) and sandy clay loam soils (Andosols), 55/30 and 60/26 N/P kg/ha, respectively are recommended (AUA, 1994). Nonetheless, N/P recommendation rates by the Ministry of Agriculture were set at 55/30, 30/40, and 40/35 N/P kg ha^{-1} for tef crop on Vertisols, Nitosols, and Cambisols, respectively across the country (Seyfu, 1993). However, 100 kg DAP ha^{-1} and 100 kg urea ha^{-1} were set by the Ministry of Agriculture and Rural Development later (Kenea *et al*., 2001).

Among the major plant nutrients, N is the most essential and frequently deficient nutrient for successful tef production in most agro-ecological zones. Nitrogen fertilizers are highly soluble and once applied to the soil may be lost from the soil-plant system or becomes unavailable to the plants due to the processes of leaching, NH_3 volatilization, denitrification, and immobilization. Therefore, nitrogen shortage is one of the main constraints limiting the productivity of not only tef, but also of the major crops such as wheat and other cereals (Andrews *et al*., 2004).

For environmental and economic reasons, nitrogen fertilizers should be utilized as efficiently as possible in agriculture. The nitrogen use efficiency of plant depends on several factors including application time, application rate of nitrogen fertilizer, cultivar and climatic conditions (Okamoto and Okada, 2004). The management of the time of nitrogen application is essential to ensure sustained nutrition at the end of vegetative growth. Therefore, the total amount of N should be divided into suitable fractions to be applied to best satisfy the requirement of the growing tef crop. The aim is to avoid increasing early vegetative growth and to encourage the development of the upper most green parts to directly involved in grain formation. Too late application, may lead to N starvation whereas too early supply may also increase tillering and vegetative density. On completion of tillering phase and at the onset of stem elongation it is important to eliminate any possibility of nitrogen starvation by applying the fertilizer in such a way that it can make tiller vigour, enables a high proportion of tillers to produce ears and extensive development of uppermost green tissue, good ear fertility and sufficient filling of the grain.

Farmers in Ethiopian highlands apply N fertilizer in the form of urea at sub-optimal blanket rates mostly only once at the time of sowing, and this limits the potential productivity of cereal crops (Bekele *et al*. 2000). Farmers in Habro district also apply low amounts of nitrogen only one time at sowing or at a vegetative growth stage for tef production (Personal communication). However, no studies have been conducted on response of tef to rate and time of nitrogen fertilizer application in eastern Ethiopia. In general, blanket recommendations, regardless of considering the physical and chemical properties of the soil as well as application of full dose at one time do not lead to increase the crop already very low productivity in the country.

Furthermore, Legg and Meisinger (1982) reported that not more than 50 to 60% of applied N is usually recovered under average field conditions, and efficient timing and placement of N could increase recovery of applied N up to 70% or to 80%. Timing of nitrogen fertilizer application is an important factor affecting the efficiency of fertilizer nitrogen, because the time interval between application and crop uptake determines the length of exposure of the fertilizer nitrogen to loss processes such as volatilization, denitrification and leaching (De Datta and Patrick, 1986; IRRI, 1990).

In general, farmers in the Habro district apply nitrogen fertilizer at varied doses and at once or rarely two times in the study area (Personal communication). This may lead to low nitrogen uptake efficiency of crops due to leaching during the main rainy season or due to low availability or lack of synchrony of maximum growth of the crop with adequate availability of the nutrients in the soil.

Therefore, this study was initiated with the following objectives:

- To study the effects of rates and time of nitrogen fertilizer application on yield and yield components of tef in the habro district of Eastern Ethiopia.
- To determine the most economic rate and time of nitrogen fertilizer application for tef production in the study area.

2. LITERATURE REVIEW

2.1. Origin of Tef (*Eragrostis tef*)

Seyfu (1993) stated to some regard that the word ‘tef’ originated from the Amharic word ‘tefa’ which means lost because of its small grain size which is difficult to find once it is dropped while others state that it was derived from the Arabic word tahf, a name given to a similar wild plant used by Semites of south Arabia during the time of food insecurity. Indeed, Costanza (1980) suggested that the word ‘tef’ may have been derived from the Semitic *tahf* applied in Yemen to a wild harvested cereal. However, according to the same source, Porteres (1958) “listed definitions of ‘tahf’ given in an Arabic dictionary: 'Tahf' is a plant growing in Yemen, whose grains resemble those of red mustard which are eaten during famine.

The fact that the genetic diversity for tef exists nowhere in the world except in Ethiopia, indicates that tef originated and was domesticated in Ethiopia. Vavilov (1951) identified Ethiopia as the centre of origin and diversity of tef. Tef is endemic to Ethiopia and its major diversity is found only in this country. As it is true with several other crops, the exact date and location for the domestication of tef is unknown. However, there is no doubt that it is a very ancient crop in Ethiopia, where domestication took place before the birth of Christ. According to Ingram and Doyle (2003) tef was introduced to Ethiopia well before the Semitic invasion of 1000 to 4000 BC. It was probably cultivated in Ethiopia even before the ancient introduction of emmer and barley. According to Tadesse (1975) tef seeds found by Unger (1866) in the Pyramid of Dashur (3359 BC) and from the ancient Jewish town of Ramses in Egypt were probably *E. aegyptiaca* or *E. pilosa* and thus are not good evidence for the cultivation of tef in ancient Egypt.

2.2. Botany of Tef

Tef is a fine stemmed, tufted annual grass characterized by a large crown, many shoots, and a shallow fibrous root system. The plants germinate quickly and are adapted to environments ranging from drought stress to waterlogged soil conditions. The inflorescence is an open panicle and produces small seeds (1,000 weights 0.3 to 0.4 g). The florets consist of a lemma, three stamens, two stigma and two lodicules. Floret colors vary from white to dark brown. Plant height of tef varies from 25–135 cm depending on cultivar type and growing environments. The panicle length, ranges from 11–63 cm and the spikelet numbers per panicle varies from 190-1410. Panicle types also vary from loose, lax, compact, multiple branching, multi-lateral and unilateral loose to compact forms (Hesselbach and Westphal, 1976).

2.3. Tef Ecosystem, Cultivation and Importance

Tef is predominantly cultivated on sandy-loam to black clay soils (Seyfu, 1993). Moreover, it withstands low moisture conditions and often considered as a rescue crop that survives and grows well in the season when early planted crops (*e.g*. maize) fail due to moisture stress. In addition, its ability to tolerate drainage problems makes it a preferred cereal by farmers. It is a highly valued crop primarily grown for its grain that is used for making *injera*. It is typically hand-broadcast on the field and, in most cases, seeds are left uncovered. Tef can produce a crop in a relatively short growing season and will produce both grain for human food and fodder for cattle (Seyfu, 1997).

Ecologically, tef is adapted to diverse agro-ecological regions of Ethiopia and grows well under stress environments better than other cereals known worldwide (Hailu and Peat, 1996). Because of this, it is said to be a “low-risk" crop for farmers. According to Seyfu (1997) the plant can be grown from sea level up to 2800 metres above sea level under various rainfall conditions, temperature and soil regimes. However, for better performance, it requires an altitude of 1800-2100 metres above sea level, annual rainfall of 750-850 mm, and a temperature range of 10-27^{o}C.

In Ethiopia, tef has been predominantly grown as a cereal crop but not as a forage crop since it is too valuable to be grown merely as animal feed. It has remained an important crop for Ethiopian farmers for several reasons, namely: the price for its grain and straw are higher than that of other major cereals; the crop performs better than other cereals under moisture stress and waterlogged conditions; its grain can be stored for a long period of time without being attacked by weevils; reduction of post harvest management cost, sustained demand from consumer, and there is no disease epidemic that has threatened its performance. Injera made of tef flour is a staple diet of most Ethiopians, while the straw provides a nutritious feed for cattle especially during the dry season. Tef straw, besides being the most appreciated feed for cattle, is also used to reinforce mud and plaster for constructing the walls of local house and local grain storage facilities called 'gottera' (IAR, 1975; Abel, 2005; Seyfu, 1997).

Tef has many prospects outside Ethiopia due to its gluten-freeness, tolerance to biotic and a biotic stresses, animal feed and for erosion control quality. Hailu and Seyfu (1990) suggested that there is an increasing tendency for tef export from year to year to Middle East, North America and Europe mainly for Ethiopian immigrants. Tef is likely to remain a favourite crop of the Ethiopian population and the crop is also gaining popularity as a healthy food in the western world. Studies show that tef is a gluten free crop, which makes it, suitable for patients with celiac disease (Dekking and Koning, 2005).

2.4. Overview of Tef Production in Ethiopia

Tef can grow under wide and diverse agro-ecologies. Even though there are areas where the crop is grown during the short rainy season (Belg), tef is mainly cultivated during the main rainy season (Meher). The length of the growing period (LGP) ranges from 60 to 180 days (depending on the variety and altitude) with an optimum of 90 to 130 days (Deckers *et al*., 2001).

In Ethiopia, tef is mainly produced in Amhara and Oromia, with smaller quantities in the Tigray and SNNP regions. There are 19 major tef producing zones in the country. The Central and South Tigray zones are the major tef producing zones in Tigray. Within the Amhara

Region, East Gojjam, West Gojjam, North Gonder, South Gonder, North Wollo, South Wollo, North Showa and Awi Zones are the major producers of tef. In Oromia region the major tef producing zones include the East Shoa, West Shoa, South West Shoa, North Shoa, East Wallega, Horo Guduroo Wallega, Jimma, Illubabor and Arsi (CSA, 2012).

2.5. Tef Production Constraints in Ethiopia

Environmental stress is the most important factor which affects crop production. According to Cassman (1999) only about 10% of world arable land may be classified into non-stress category. About 20% of the land is limited by mineral stress, 26% by drought stress and 15% by freezing stress. Modifying the environment for proper crop growth means the alleviation of environmental stresses through the current crop management practices (Arkin and Taylor, 1983). In semi-arid and arid areas, rainfall is inadequate, erratic, and non-uniform in distribution. Moreover, because of degradation and poor vegetation cover, soils in semi-arid and arid areas have low fertility with poor water holding capacity. In addition to the above-mentioned problems, weeds also compete with the food crops for the meagre available moisture (Reddy and Kidane*,* 1991); besides, there are occasional outbreaks of pests and diseases.

Tef is harvested very close to the ground because of the high value of the straw, leaving the soil bare for about half a year after harvest and exposing the ground further. Therefore, the loss of soil organic matter and physical erosion are major problems in some tef growing areas. Inorganic fertilizers are able to overcome some, but not all, of these deficiencies. According to Seyfu (1991) tef is mostly grown on soils that are less fertile, have moisture deficit and mostly on waterlogged during the main rainy season, all of which limit the growth and yield of the crop. Moreover, the cultural broadcast sowing influences the availability of adequate space for each plant and consequently influences the uptake and utilization of resources such as nutrients. The low yield is due to low soil fertility status which is a result of continuous cropping, overgrazing, soil erosion, and complete removal of field crop residues without any soil amelioration activities and low or no input of fertilizers (Seyfu, 1993).

2.6. Lodging

Lodging can be defined as displacement of the aerial parts of the plants (Pinthus, 1973; Seyfu, 1993). It can be induced by both external and internal factors like wind, rain, and morphological traits of the crops or by their interactions. Lodging is among the most important factors threatening increased production and productivity of tef (Seyfu, 1993).The grain bearing organs of cereals are found at the top of the stem, and therefore, exert a strain on the stalk especially under high wind or wind driven rain. Moreover, crop husbandry, crop disease and an abundant supply of nutrients in the soil can contribute to the process of lodging (Tams *et al.,* 2004).

As in other small grain cereals, the tef crop is also prone to severe lodging under favourable and high input husbandry (Kebebew, 1991; Fufa *et al.,* 2001; Tekalign *et al.,* 2001). This is ascribed to the morphological features of the plant, hence posing significant losses in quality and quantity of both grain and straw yield. Lodging poses serious economic losses, and also impairs the quality of products, directly or indirectly. Directly, it affects dry matter accumulation, and indirectly, imposing difficulty in harvesting. Bend lodging in tef causes losses in seed and straw, and poses problem during harvesting (Seyfu, 1997). Lodging indirectly prevents the attainment of high grain yield through making mechanized harvesting difficult whereas harvesting by hand as practiced traditionally is time-taking and tiresome. In addition, lodging causes direct loss in tef through affecting important yield components such as thousand seed weight and yield per panicle and it causes damage to the vegetative part of the plant, due to rotting and fast spread of disease and pests (Seyfu, 1993). The overall loss in grain yield due to lodging under natural condition was estimated within the range of 11-22% with an average loss of 17% (Seyfu, 1983).

The ability of a crop to withstand lodging depends on the length of the stems particularly the length of the peduncle (the distance from the last node to the base of the head). Some of the factors that will increase the length of the stem include: the genetic constitution of the cultivar, high fertility level especially nitrogen, low light intensity, and crop density promotes internodes elongation. An increase of 10-25% in the length of the lowest three internodes has been attributed to high nitrogen level in various crops, including semi-dwarf varieties of wheat and barley (Pinthus, 1973). Thus, a tall plant that has weak stem has a greater tendency to lodge than a semi- dwarf cultivar with stiffer straw.

2.7. Role of Nitrogen in Plant Nutrition

Nitrogen is the principal raw material required for the growth of a plant. Since it is a necessary component of all proteins, N is involved in all plant growth processes. Generally, N is involved in cell multiplication, giving rise to the increase in size and length of leaves and stems, especially the stalks of grains and grasses; increases in chlorophyll contents, giving the leaves their dark green colour; plays a part in the manufacture of proteins in the plant and is part of many compounds in the plant, including certain types of basic acids and hormones (Ortiz-Monasterio *et al*., 1997).

Chlorophyll is a green pigment found in plants, and it is necessary for photosynthesis and enables plant development, nutrient storage in different organs and nutrient cycling through transferring energy from sunlight by photosynthesis. Nitrogen is one of the basic components of chlorophyll inside. In addition, it is also effective in the enzymtic carbon metabolism and photosynthetic electron carriers system. Therefore, nitrogen supply to the plant will influence cell size and leaf area, chlorophyll formation and photosynthetic activity. In turn, this influences the amount of protein (Hansen *et al*., 2005).

Photosynthesis capacity is affected by nutrient elements, especially nitrogen. Net photosynthesis rate of C_3 and C_4 plants varies depending on the amount of nitrogen. Nitrogen accumulated in the leaves delays aging of the leaf. In cereals, leaves remain green for long, especially in the greens for a long time in period of ear emergence increases photosynthetic activity (Ozen and Onay, 2007). Leaves are the organ contributing to the formation of yield in plants most. Approximately 70 - 90% of the final grain yield is derived from photosynthates (products of photosynthesis) produced by the plant during the grain filling. The flag leaf and head usually contribute most, but certainly not all, of the photosynthate to the grain (Yildirim *et al*., 2009).

Deficiency in the supply of nitrogen has a profound effect on crop growth and development and can lead to a loss of grain yield in extreme cases (Miller and Donahue, 1995). The most easily observed symptom of nitrogen deficiency is the yellowing (chlorosis) of leaves due to a drop in chlorophyll content. Lack of chlorophyll inhibits the capacity of the plant to assimilate CO_2 and synthesize carbohydrates, leading to poor and premature flowering and fructification, with shortening of the growth cycle (IAEA, 2000). This symptom is usually noticed first in the more mature leaves, and last in the upper actively growing leaves, because the N is translocated from older to new leaves to sustain growth. Thus, the older leaves will wither and result in poor plant growth and yield reduction. Generally, growth is slowed; stunted and firing of the leaf tips and margins is evident (Evans, 1997). Nitrogen deficient plants respond quickly to the addition of N fertilizers if applied in a timely manner and properly. However, adverse effects on annual plants caused by early-stage lack of N cannot usually be corrected by late application of N (IAEA, 2000).

Nitrogen fertilization boosts the grain yield of crops to a certain point through its influence on yield components, phenology and leaf traits. Nitrogen availability influences the efficiency of assimilated mobilization to the sink during leaf senescence, and thus affects leaf viability and activity. Dry plant material contains about 1 to 4% N and N is an indispensable elementary constituent of numerous organic compounds of general importance; amino acids, proteins, nucleic acids (Mengel and Kirkby, 1996). It is involved in all major processes of plant development and yield formation. Besides, a good supply of nitrogen to the plant stimulates root growth and development as well as uptake of other nutrients (FAO, 2000; Brady and Weil, 2002).

2.7. Crop Response to Nitrogen Fertilizer

Nitrogen (N) is one of the most yield-limiting nutrients for crop production in the world. It is also the nutrient element applied in the largest quantity for most annual crops (Huber and Thompson, 2007). The increase in use of nitrogen (N) fertilizers for enhancing the agricultural production has been under consideration for the last fifty years (Hirel *et al*., 2007). The amount of nitrogen required by crop depends on the type of small grain, the previous crop in the rotation, the soil type, weather conditions, supply of residual, nitrogen fertilizer management and cultural practices during the growing season. Crop response to nitrogen fertilizer varies with rate and time of application in relation to plant development (Lory *et al*., 1995). Barley, triticale, oat and wheat require different amount of nitrogen and the amount depends on the yield potential of the crop and the intended use (grain production requires higher nitrogen levels than forage production).

Nitrogen affects crop performance through its ability to determine photosynthetic capacity. Application of nitrogen at onset of stem elongation greatly stimulated leaf area growth, which resulted in significantly greater assimilation capacity, both before and after flowering. Increases in grain yield achieved through improved grain indices have, however, often out stripped improvements in the uptake and partitioning of N to grain (Gooding and Davies, 1997). N stimulates tillering probably due to its effect on cytokinin synthesis (Botella *et al*., 1993).

The presence of N in excess promotes development of the aerial organs with relatively poor root growth. Synthesis of proteins and formation of new tissues are stimulated, and thus carbohydrates of high molecular weight are synthesized in insufficient amounts, resulting in abundant dark green (high chlorophyll) tissues of soft consistency. This increases the risk of lodging, and reduces the plant's resistance to harsh climatic conditions and to foliar diseases and insect predation. A non-limited supply of N also extends the growth cycle (extends the life span of a leaf), delaying maturity, and often reduces the quality of the harvestable products due to loss of chlorophyll during grain filling stage (IAEA, 2003; Yang *et al*., 2000).

2.8. Soil Fertility and Nitrogen Availability

Soil fertility is a complex quality of soils that is closest to plant nutrient management. It is the component of overall soil productivity that deals with its available nutrient status, and its ability to provide nutrients out of its own reserves and through external applications for crop production. It combines several soil properties (biological, chemical and physical), all of which affect directly or indirectly nutrient dynamics and availability.

Soil fertility is manageable soil property and its management is of utmost importance for optimizing crop nutrition on both short-term and a long-term bases to achieve sustainable crop production (FAO, 2006).

Soil fertility decline is considered as an important cause for low productivity of many soils. It has not received the same amount of research attention as soil erosion; possibly as soil fertility decline is less visible and less spectacular and more difficult to assess. Assessing soil fertility status is difficult because most soil chemical properties either change very slowly or have large seasonal fluctuations; in both cases, it requires long-term research commitment.

Growing agricultural crops implies that nutrients (N, P, K, etc.) are removed from the soil through the agricultural produce (food, fiber, wood) and crop residues. Nutrient removal results in a decline of soil fertility when replenishment with inorganic or organic nutrient inputs is inadequate (Talawar and Rhoades, 1998).

The evidence is clear that the soils native ability to supply sufficient nutrients has decreased with the plant productivity levels and with increased human demand for food. One of the greatest challenges for our generation will be to develop and implement soil, water and nutrient management technologies that enhance the quality of soil, water and air. If we do not improve and/or sustain the productive capacity of our fragile soil, we cannot continue to support the food demand of our growing population (Tisdale *et al.,* 1995).

Systems of agriculture that rely heavily on soil reserve to meet the N requirements of plants cannot long be effective in producing high yields of crops (Stevenson, 1982). Except for legumes, which have the ability to fix their own N, N must be supplied to plants for growth. It is usually added as a fertilizer and is required for all types of soils (Clark, 1982). Nitrogen is one of the most widely distributed elements required by plants but, paradoxically, it is the element that most often limits plant growth. This results from the relative inertness of elemental nitrogen in the atmosphere and of combined forms of nitrogen in minerals and organic matter. Since plants can use very little of these forms of nitrogen directly, they mostly depend on microorganism to fix elemental nitrogen or decompose organic nitrogen in to simpler forms. Although rocks and minerals contain larger amounts of nitrogen the fraction that actively enters the nitrogen cycle is too small that it will not be considered (Chichester, 1970).

Most of the nitrogen in soils that is potentially available to plants is associated with organic matter. The accumulation of soil organic matter in natural ecosystem may require several thousand years to reach an equilibrium level. The level attained depends on such factors as climate, vegetation, topography, physical and chemical characteristics of the soil, and activity of microflora and microfauna. Since the system is very dynamic, any change in the environment may lead to a new equilibrium level of organic nitrogen. When the steady state conditions exist, the rate at which nitrogen is added to the soil equals the rate at which it is lost by such process as leaching and denitrification (Stanford *et al*., 1970).

Type of vegetation is especially important in the accumulation, retention, and conservation of soil nitrogen. Other things being equal, organic matter and nitrogen content usually are higher in soils developed under grass land than in soils developed under forest type vegetation. Grass land soils contain a mass of fibrous roots that usually extend throughout the soil to a depth of several feet. These roots not only serve at absorptive organs for water and plant nutrients, but also contribute considerable debris to the soil in the form of excretions, sloughed-off root tissue, and dead root hairs that are continuous being produced during the regenerative process of root proliferation. This carbonaceous material is utilized by wide variety of microorganisms that gradually transform part of the carbon and nitrogen in to stable forms of organic matter. In forest soils, however, plant debris is added to the soil primarily as fallen leaves that accumulate on the surface. The organic layer that forms under these conditions remains at the surface and does not become distributed throughout the root zone. The main roots contribute little to the organic content of the soil, which remains light colored and contains relatively low amounts of nitrogen (Samtsevich, 1968).

2.9. Effects of Nitrogen Fertilizer Rates on Yield and Yield Components

Fertilizer management is an important part of the overall management package target towards realizing higher yield (Bayoumi and El- Demardash, 2008). Use of low rates for high-yielding modern crop cultivars, especially by farmers in developing countries, is another cause of N deficiency (Fageria *et al*., 2003). In developing countries, intensive agricultural production systems have increased the use of N fertilizer in efforts to produce and sustain high crop yields (Fageria *et al*., 2003). Consequently, N losses into the environment have also increased (Schmied *et al*., 2000). Even with the continuing research in N management, average worldwide N use efficiencies (NUE) are reported to be around 50% (Newbould, 1989; Collins *et al*., 2007).

Nitrogen fertilization management offers the opportunity of increasing grain protein content and quality. Increased use of fertilizer nitrogen (N) in agricultural production has, however raised concerns, because the N surplus is at risk of leaving the plant-soil system and thereby causing environmental contamination. Liberal application of nitrogen fertilizer results in nitrate accumulation in ground water, due to nitrate leaching (Prasad and Pawer, 1995). Especially cereals being a shallow-rooted crop with the domain root zone at 20 cm below the soil surface, can lead to considerable nitrate loss by leaching under irrigated or high rainfall conditions (Ren *et al*., 2003) and can thus lead to human and environmental health problems. This is in addition to increased costs associated with the manufacture and distribution of N fertilizer (Alizadeh and Ghadeai, 2006).

Haftom *et al*. (2009) reported that Nitrogen fertilizer rate caused significant effect in yield attributes. Tef plants with higher plant height (92cm) and panicle length (38cm) were found by applying high amount of N fertilizer (92 kg N ha^{-1}). This is because high nitrogen usually favours vegetative growth of tef which results in taller tef plants having relatively greater panicle length. They also reported that the biomass and grain yields were obtained by applying 92 kg N ha^{-1}. Application of nitrogen improves various yield related traits like 1000-grain weight, more productive tillers, more number of spikes per unit area, number of grains per spike and biological yield (Al-Abdul Salam, 1997; Warraich *et al.,* 2002) thus resulting in higher yields. Zahran *et al.* (1997) also reported that plant height, flag leaf area, tillers number and dry weight per unit area of wheat were increased with increasing N rates.

2.10. Effects of Timing of Nitrogen Fertilizer Application

Worldwide interest associated with increasing cereal grain protein has focused added attention on improving the utilization of N in cereals (Desai and Bhatia, 1978). The effectiveness with which N is used by cereals has become increasingly important because of increased costs associated with the manufacture and distribution of N fertilizer and increased use of fertilizer N in agricultural production has raised concerns because of the potential for ground water contamination. This concern has pressurized farmers to use N more efficiently (Jeremy, 2007).

A concern with supplying nitrogen fertilizer to a crop is the timing of post sowing applications in relation to the plant availability of that application. Fertilizers applied to the soil surface need to be dissolved by rain and carried into the crop root zone. On heavier soils in lower rainfall environments the chance of effective post sowing fertilizer application is lower than high rainfall areas, hence the standard recommendation that all nitrogen should be applied at sowing time in low rainfall areas. High levels of nitrogen during tiller and head formation will set up a high yield potential through head and grain numbers. Nitrogen is then redistributed within the plant after flowering for deposition of protein in grain. In good season with late rain, nitrogen fertilizer applied late can be taken up by crop roots, increasing grain protein. Similarly, nitrogen uptake continues late in the season if continuing root growth catches up with earlier nitrogen leached to depth and the crop draws on stored soil moisture (Baldock *et al*., 2003).

The aim of canopy management is to delay nitrogen application until there is plant demand for nitrogen. Early nitrogen stimulates high tiller numbers, many of which die off during stem elongation. Early nitrogen also stimulates a large leaf area which uses more water than a thinner canopy and can lead to early drought of the crop and higher screenings. Leafy crops are also more prone to leaf diseases like mildew and septoria. Delayed application of nitrogen fertilizer reduces these problems while giving the same or better yield and higher protein levels than sowing and tillering application at the same rates of N (Jeremy, 2007).

In practice, the optimal strategy for applying N to rain-fed cereals depends on the interaction between soil nitrogen taken up during the vegetative stage, which is used primarily for vegetative growth, and the N applied after flowering, which is mainly directed towards the synthesis of grain proteins. The beneficial effect of late N application on the baking quality of most cereals has been confirmed by numerous experiments in that it increases the content of crude protein in the grain. However, cereal grains such as wheat, barley and maize are particularly low in lysine and therefore are rather poor in protein quality (Mengel and Kirkby, 1996). Tolessa *et al.* (1994) reported that the best use of nitrogen is obtained when 50% of the total requirement is applied at sowing and the remaining 50% is given as top dressing. The other option is application of the total requirement in three equal splits at sowing, knee-height and flag leaf emergence.

Nitrogen fertilizer applied at the correct time and in the right amount to an actively growing crop will result in optimum yield and very little NO_3^- will remain in the soil at harvest minimizing risk of loss by leaching (Johnston, 1994). On the other hand, luxuriant application of N fertilizer at sowing increased the flush emerging broad leaf weeds, thereby increasing the labour requirements for hand weeding. Hence, split application of nitrogen was considered more economical both in terms of weed management under farmers' conditions and as a risk aversion strategy, efficient nitrogen use for optimizing grain yield and lowering grain protein with lower nitrogen inputs Asnakew *et al.* (1991) and Tilahun *et al*. (1996) reported that split nitrogen application enhanced grain yield, total nitrogen uptake and agronomic efficiency.

2.11. Nitrogen Use Efficiency

In simple terms, efficiency is ratio of output (economic yield) to input (fertilizers) for a process or complex system. Commonly used practice to improving the N use efficiency of crops are split application of fertilizers, selection of crop growth environment (soil type and climate), management practices (sowing date and rate of N application), and crop breeding.

The target is to synchronize the availability of N with the time/stage of maximum N demand by the crop. Greater synchrony between crop demand and nutrient supply is necessary to improve nutrient use efficiency, especially for N. Split applications of N during the growing season, rather than a single, large application prior to planting, are known to be effective in increasing N use efficiency (Cassman *et al*., 2002; Semenov *et al*., 2007). Wuest and Cassman (1992) reported that recovery of N applied at anthesis (0-60 kg N ha^{-1}) ranged from 55 to 80% compared to 30- 50% when all N was applied at planting.

Cassman *et al*. (2002) also looked at N fertilizer recovery under different cropping systems and reported 37% recovery for corn grown in the north central U.S. They found N recovery averaged 31% for irrigated rice grown by Asian farmers and 40% for rice under field specific management. Sowers *et al*. (1994), Limon- Ortega *et al*. (2000) and Zhao *et al*. (2006) indicated that a decrease in NUE with increasing fertilizer rates is because grain yield rises less than the N supply in soil and fertilizer.

Obtaining high NUE is very important in actual crop production. Modifying the timing and the application method of N can also lead to an improvement in absorption efficiency. One of the main causes of low NUE in actual N management practices is the scarce synchrony between N soil input and crop demand (Fageria and Baligar, 2005).

The efficiency of the N applied in satisfying the N demand of the crop depends on the type of fertilizer, timing of fertilizer application, crop sequence, the supply of residual and mineralized N and seasonal trends (Borghi, 2000; Blankenau *et al*., 2002). Therefore, numerous strategies such as use of N sources, slow release fertilizer, placement techniques and nitrification inhibitors have been devised to reduce nitrogen losses and improve fertilizer use efficiency (Slanger and Kerkhoff, 1984; Freney *et al*., 1992).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

The study was conducted in Habro District of western Hararghe zone of Oromia Regional State on a farmer's field from July – November during the main cropping season of 2012. The place is located at $8^0 51'$N and 40^0 39' E at an altitude of 1728 metres above sea level. Gelemso town is the administrative seat of the district. Physiographically, plateaus, mountains, hills, plains and valleys characterize the district.

Habro is classified into *dega* (18%), *woinadega* (57%) and *kola* (25%) agro climatic zones. Crops predominantly grown around the experimental area are maize, sorghum, tef and chickpea.

3.2. Materials Used for the Experiment

3.2.1. Planting material

The tef variety named Quncho (DZ-Cr-387-RIL 355), which was developed and released by Debrzeit Agricultural Research Centre in 2006 was used for the experiment. Quncho is a high yielding white-seeded cultivar adapted to a wide range of altitudes (MoARD, 2008).

3.2.2. Fertilizer material

Urea [46% N, and TSP (46% P_2O_5) were used as a source of nitrogen and phosphorus nutrient elements.

3.3. Treatments and Experimental Design

The treatments consisted of four levels of nitrogen (0, 46, 69 and 92 kg N ha^{-1}) and five timing of applications (full dose at sowing, full dose at tillering, ½ dose at sowing + ½ dose at tillering, $1/3$ dose at sowing + $1/3$ dose at tillering + $1/3$ dose at anthesis, ¼ dose at sowing + ½ at tillering, ¼ dose at anthesis). The experiment was laid out as a randomized complete block design in a factorial arrangement and replicated three times. A plot size of 3 m by 2 m was used and adjacent plots and blocks were spaced 0.5 and 2 m apart, respectively. The net harvestable area was 3.75 m^2 (2.5m x 1.5 m).

3.4. Experimental management

Land was prepared according to the local practice. It was ploughed five times using oxen before planting and the last ploughing was used for sowing. After the seedbeds were levelled and compacted, seeds were broadcasted at the rate of 25 kg ha^{-1}. Weeding was done manually by hand similar to the farmers practice.

Nitrogen fertilizer at the specified rates and time was applied by broadcasting urea. Phosphorus was applied to all plots equally at the blanket recommendation rate of 46 kg P_20_5 ha^{-1} as TSP (triple-superphosphate).

3.5. Soil Sampling and Analysis

Surface soil samples (0-30 cm) were collected randomly in a zigzag pattern before sowing from the entire experimental field of 20 spots and composited and analyzed in the laboratory for selected chemical and physical soil properties. The soil samples were air-dried and passed through a 2 mm mesh sieve for physico-chemical analysis. Soil pH was determined from the filtered suspension of 1:2.5 soils to water ratio using a glass electrode attached to a digital pH meter (potentiometer) (Page, 1982). Texture of the soil was determined by the hydrometer method. The soil was analyzed for total nitrogen, available phosphorus, CEC, and organic carbon contents. Organic carbon and total nitrogen were determined by the method of Walkely and Black and Kjeldhal methods, respectively (Jackson, 1973). Available phosphorus was determined by the methods of Olsen *et al*. (1954).

3.6. Data Collection and Measurements

3.6.1. Phenological data

Days to panicle emergence: This parameter of the plant was determined by counting the number of days from sowing to the time when 50% of the plants started to emerge the tip of panicles through visual observation.

Days to maturity: Days to maturity was determined as the number of days from sowing to the time when the plants reached maturity based on visual observation. It was indicated by senescence of the leaves as well as free threshing of grain from the glumes when pressed between the forefinger and thumb.

3.6.2. Growth, yield and yield component

Plant height: Plant height was measured at physiological maturity from the ground level to the tip of panicle from ten randomly selected plants in each plot.

Panicle length: It is the length of the panicle from the node where the first panicle branches emerge to the tip of the panicle which was determined from an average of ten selected plants per plot.

Number of effective tillers: The numbers of tillers were determined by counting the tillers from an area of 0.25 m x 0.25 m plants by throwing a quadrat into the middle portion of each plot.

Main panicle seed weight: The average seed weight of the main panicle at harvest was recorded from average of five randomly selected pre-tagged plants.

Grain yield: Grain yield was measured by harvesting the crop from the net middle plot area of 2.5 x 1.5 m to avoid border effects.

Biomass yield: At maturity, the whole plant parts, including leaves and stems, and seeds from the net plot area were harvested and after drying for three days, the biomass was measured.

Thousand seed weight: The weight of 1000 seeds was determined by carefully counting the small grains and weighing them using a sensitive balance.

Straw yield: After threshing and measuring the grain yield, the straw yield was measured by subtracting the grain yield from the total above ground biomass yield.

Harvest index: Harvest index was calculated by dividing grain yield by the total above ground air dry biomass yield.

3.6.3. Lodging index

The degree of lodging was assessed just before the time of harvest by visual observation based on the scales of 1-5 where 1 (0-15^o) indicates no lodging, 2 (15-30^o) indicate 25% lodging, 3 (30-45^o) 50% indicate lodging, 4 (45-60^o) indicate 75% lodging and 5 (60-90^o) indicate 100% lodging (Donald, 2004). The scales were determined by the angle of inclination of the main stem from the vertical line to the base of the stem by visual observation. Each plot was divided based on the displacement of the aerial stem in to all scales by visual observation. Each scale was multiplied by the corresponding percent given for each scale and average of the scales represents the lodging percentage of that plot. Data recorded on lodging percentage were subjected to arcsine transformation described for percentage data by Gomez and Gomez (1984).

3.6.4. Plant Sampling and Analysis for Nitrogen Content

At anthesis, whole tef plants from each treatment were mowed at the base from an area of about 0.2 x 0.2 m by laying a quadrat into the centre of each plot. After drying and grinding the plant material, the ground samples were ashed in a furnace at 450 degrees Celsius. Nitrogen concentration in plant tissue was determined using Kjeldahl method by digesting the samples with concentrated sulfuric acid (Jackson, 1973).

At the time of maturity, the above ground parts of plant of the net plot were harvested from each plot, air dried and separated into grain and straw. After the grain and straw were oven dried ground and sieved through 1 mm size sieve, the straw and grain samples were analyzed for N concentrations from each plot separately using the Kjeldahl Methods as described by Jackson (1973). Straw and grain N uptake were calculated by multiplying N content with the respective straw and grain yield ha^{-1}. Total N uptake, by whole biomass was obtained by summing up the N uptakes by grains and straw.

$$\text{N uptake of grain} = \frac{\text{N concentration of grain x grain yield (kg ha}^{-1})}{100}$$

$$\text{N uptake of straw} = \frac{\text{N concentration of straw x straw yield (kg ha}^{-1})}{100}$$

TNU = N uptake of grain + N uptake of straw

Where TNU is total nitrogen uptake.

Apparent nitrogen recovery efficiency (ANRE) is defined as the quantity of nutrient uptake per unit of nutrient applied and it was calculated as the total nitrogen use (TNU) of each fertilized treatment minus TNU of unfertilized plot divided by fertilizer applied.

$$\text{ANRE (\%)} = \frac{\text{TNU fertilized treatment- TNU of unfertilized plot}}{\text{Fertilizer applied (kg ha}^{-1})} \times 100$$

Agronomic efficiency (AE) is defined as the economic production obtained per unit of nutrient applied. It was calculated as

$$\text{AE} = \frac{\text{Grain yield of fertilized treatment (kg ha}^{-1}) - \text{grain yield of unfertilized plot (kg ha}^{-1})}{\text{Fertilizer applied (kg ha}^{-1})}$$

Physiological efficiency (PE) is defined as the biological yield obtained per unit of nutrient uptake. It was calculated as

$$\frac{Yf - Yu}{Nf - Nu} \text{ kg kg}^{-1}$$

Where: Yf = is the total biological yield (grain plus straw) of the fertilized plot (kg ha^{-1}),

Yu = is the total biological yield in the unfertilized plot (kg ha^{-1}),

Nf = is the nutrient accumulation in the fertilized plot (kg ha^{-1}), and

Nu = is the nutrient accumulation in the unfertilized (kg ha^{-1}).

These formulae are suggested by Fageria and Baligar (2003) and Fageria and Baligar (2005).

3.7. Statistical Data Analysis

The data collected were subjected to analysis of variance (ANOVA) using general linear model (GLM) procedures SAS version 9.1.3, (SAS Institute, 2002). Means of significant treatment effects were separated using the Least Significant Difference (LSD) test at 5% level of significance.

3.8. Partial Budget Analysis

Economic analysis was made following CIMMYT methodology (CIMMYT, 1988). The cost of 100 kg urea (1216 birr) and tef grain price of 1200 birr per 100 kg used for the benefit analysis. Marginal rate of return was calculated as change of benefit divided by change of cost

4. RESULTS AND DISCUSSION

.

4.1. Soil Physical and Chemical Properties of the Study Area before Sowing

The pre sowing soil analysis showed that the experimental soil has a pH (H_2O) of 7.16 (neutral). FAO (2000) reported that the preferable pH ranges for most crops and productive soils are 4 to 8. Thus, the pH of the experimental soil is within the range for productive soils. Textural class of the soil is clay with composition of 65% clay, 32% silt and 3% sand. The experimental soil was found to have a CEC of 69.22 cmole kg^{-1} soil. Cation exchange capacity (CEC) is an important parameter of soil because it gives an indication of the type of clay mineral present in the soil and its capacity to retain nutrients against leaching. Total nitrogen content and available phosphorus content of the experimental area were 0.15% and 55.78 mg kg^{-1}, respectively. The soil has organic carbon content of 2.82% (Appendix 1). According to Bruce and Rayment (1982) and Charman and Roper (2007), the nitrogen and organic carbon contents of the experimental site soil are medium and high, respectively. According to Landon (1991) the phosphorus content of the soil is very high.

4.2. Effects on Crop Phenology

4.2.1. Days to panicle emergence

Days to panicle emergence was highly significantly ($P < 0.01$) affected by the main effects of timing of the N fertilizer application and significantly ($P < 0.05$) by N fertilizer rate as well as by the interaction of the two factors (Appendix 2).

In general, increasing the rate of nitrogen application significantly prolonged the days to panicle emergence of the tef plants across all application times. Over all times of nitrogen application, plants grown at the rate of 46 kg N ha^{-1} had significantly hastened days to panicle emergence than those grown at the other two higher rates of nitrogen.

The maximum number of days to panicle emergence was observed when 92 kg N ha^{-1} was applied in three splits of 1/4th of the dose at sowing, ½ at mid-tillering and the other 1/4th dose at anthesis. This maximum value is, however, in statistical parity with the number of days to panicle emergence recorded at 69 kg N ha^{-1} in split application of full dose at sowing and full dose at tillering as well as under 46 kg N ha^{-1} with three split applications of 1/4th at sowing, ½ at mid-tillering, and 1/4th at anthesis. The maximum value of days to panicle emergence is also in statistical parity with the result obtained at 92 kg N ha^{-1} in split application of full dose at mid-tillering, three equal splits (1/3rd at sowing, 1/3rd at mid-tillering and 1/3rd at anthesis).

The less number of days to panicle emergence was recorded under tef plants treated by 46 kg N ha^{-1} with full dose of nitrogen at sowing (Table 1). Thus, plants received 92 kg N ha^{-1} applied in three equal splits of 1/3rd dose at sowing, mid-tillering and at anthesis and three splits of 1/4th dose at sowing, 1/2 dose at mid-tillering, and 1/4th dose at anthesis reached panicle emergence about 5 days later than those grown under full dose application of 46 kg N ha^{-1} at sowing time. Generally, the number of days to panicle emergence recorded over all the treated plots was significantly higher than the unfertilized plot.

The delay in panicle emergence of tef plants in response to the increased N rate and three split applications might be because the fact that high N rate and three-time application promoted vigorous vegetative growth and development of the plants possibly due to synchrony of the time of need of the plant for uptake of the nutrient and availability of the nutrient in the soil. This result is in line with the finding of Getachew (2004) and Mekonen (2005) who reported that the heading was significantly delayed at the highest N fertilizer rate compared to the lowest rate on wheat and barley crops, respectively. In contrast, to the results of the present study, Sewnet (2005) reported early flowering with an increase in the rate of N application in rice.

Table 1. Mean days to panicle emergence of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	49.33^{h}	52.67^{bcde}	51.67^{efg}	52.33^{cdef}	53.67^{abc}	51.93
69	53.33^{abcd}	54.00^{ab}	51.33^{efg}	51.67^{efg}	50.67^{gh}	52.20
92	52.00^{defg}	54.00^{ab}	51.00^{fg}	54.00^{ab}	54.67^{a}	53.13
Mean	51.56	53.56	51.33	52.67	53.00	52.42^{a}
Control						48.00^{b}
	RXT	Treated vs	control			
LSD(0.05)	1.631	1.58				
CV (%)	1.9	0.89				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.2.2. Days to maturity

Days to maturity of tef plant was highly significantly ($P < 0.01$) affected only by the main effect of N fertilizer rate while the main effect of timing of application and the interaction effect of the two factors did not affect this parameter (Appendix 4).

In general, the maturity of tef plants was hastened under lower N rates than under the higher N rates. Thus, increasing the rate of nitrogen from 0 to 46 kg N ha^{-1} prolonged days to maturity by about 17% over that of nitrogen rate. Increasing the rate of nitrogen further from 0 to 69 kg N ha^{-1} prolonged the days to maturity by about 20%. However, increasing the rate of nitrogen from 69 kg N ha^{-1} to 92 kg N ha^{-1} did not further increase the number of days required to reach maturity (Table 2). This result is in line with the report of Marschener (1995), Tanaka *et al*. (1995) and Brady and Weil (2002) that N applied in excess than required delayed plant maturity.

Consistent with the result of this study, Gobeze (1999) reported that N rates delayed the maturity of sorghum. Similarly, Temesgen (2001) found that N fertilization delayed physiological maturity of tef

Table 2. Mean days to maturity of tef as affected by rate of nitrogen fertilizer application

Treatments	Days to Maturity
N rate (kg ha^{-1})	
0	84.8^{c}
46	99.4^{b}
69	101.4^{a}
92	101.7^{a}
LSD (0.05)	1.667
Timing	
S1	96.92
S2	95.75
S3	96.67
S4	97.17
S5	97.58
LSD (0.05)	NS
CV (%)	2.3

Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.3. Effects on Lodging Index

Lodging index was significantly ($P < 0.01$) affected by the main effects of rate and timing of N fertilizer application and by the interaction (Appendix 2).

Increasing the rate of nitrogen increased the lodging index of tef crops across all nitrogen fertilizer application times. This result is consistent also with that of Seyfu (1983) who reported that lodging in cereals is considered to be caused by high rate of nitrogen fertilizer application.

However, marked increases in lodging index due to the increased application of nitrogen fertilizer were observed for crops supplied with the nutrient in one full dose at sowing and mid-tillering as well as for those supplied with the nutrient in two-splits of equal doses at sowing and mid-tillering. In contrast, increasing the rate of nitrogen and applying the nutrient in three-splits of equal doses of 1/3rd at sowing, mid-tillering, and anthesis; as well as in three splits of 1/4th at sowing, ½ at mid-tillering, and the remaining 1/4th at anthesis did no markedly increase lodging index (Table 3). The lowest lodging index was observed for plants grown at the rate of 46 kg N ha^{-1} applied full dose at sowing. The lodging index of plants supplied with 92 kg N ha^{-1} applied full dose at sowing, full dose at mid-tillering, and half dose at sowing and the other half at mid tillering exceeded the lodging index of plants supplied with 46 kg N ha^{-1} full dose at sowing by 39%, 48%, and 36%, respectively.

This result reveals that increasing the rate of nitrogen and applications the nutrient in one full dose or two half doses leads to the detrimental effect of crop losses due to lodging. On the other hand, the result also show that applying higher rates of nitrogen by splitting in to three equal doses or a quarter dose at sowing, half of the dose at mid-tillering, and the remaining quarter at anthesis profoundly prevented losses of tef due to lodging.

The increase in crop lodging with increased nitrogen rate could be due to the profound effect of high N supply on increasing vegetative growth thereby leading to bending of the weak stem of the plant due to the sheer load of the canopy. On the other hand, splitting the nitrogen in three doses as observed from the experiment result might have provided enough time space for the plant to take up N according to its demand, resulting in better synchrony of growth with supply of the nutrient. This may have resulted in better growth of the tef plants with stouter stems. This result is corroborated by that of Cassman *et al*. (2002) who reported that synchrony between crop demand and nutrient supply is necessary to improve nutrient use efficiency and better growth of plants. In over all, the lodging index recorded under fertilized plots exceeded the unfertilized plots by about 51%.

Table 3. Mean lodging index of tef as affected by rates and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	34.43^{i}	41.15^{efg}	45.96^{bcd}	37.66^{ghi}	38.44^{fgh}	39.53
69	36.44^{hi}	45.00^{bcde}	46.91^{abc}	45.00^{bcde}	43.09^{cde}	43.29
92	47.88^{ab}	50.79^{a}	46.91^{abc}	42.12^{def}	41.16^{efg}	45.77
Mean	39.58	45.65	46.59	41.59	40.90	43.52^{a}
Control						28.85^{b}
	RxT	Treated vs	control			
LSD (0.05)	3.999	3.21				
CV (%)	5.6	2.52				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.4. Growth Parameters

4.4.1. Plant height

The analysis of variance showed that plant height was affected highly significantly (P< 0.01) by N fertilizer rates and significantly (P< 0.05) by timing of application and the interaction of the two factors (Appendix 2).

Plant height generally increased with the increase in the rate and frequency of N application (Table 4). Thus, plants treated with split application of higher rates of nitrogen in two to three doses supplied at sowing and mid-tillering and at sowing, mid-tillering, and at anthesis respective found were taller than plants supplied with lower rates of nitrogen in one full dose application at sowing or mid-tillering.

The tallest plants were obtained from the plots received nitrogen at 69 and 92 kg N ha^{-1} with two-time or three-time split applications. Plants received under all rates of nitrogen, the shortest plants were observed from plots supplied with one-dose application at sowing, closely followed by those plots supplied with three application times (Table 4). Thus, the mean height of plants grown at the rates of 69 kg N ha^{-1} applied half dose at sowing and the other half dose at mid-tillering significantly exceeded the mean heights of plants treated with 46, 69, and 92 kg N ha^{-1} rate applied full dose at sowing time by 7.4%, 6.8%, and 7.8%, respectively. This difference may be to the fact that only one-time application of full dose of nitrogen at sowing or any other stage of growth may not lead to efficient recovery of the nutrient by roots and enhanced plant growth.

This could be attributed to that application of full dose of nitrogen at one time to crops may lead to loss due to leaching as nitrate ion ($NO3^{-1}$) as stated by Mengel and Kirkby (2001) and El-Karamity (1998) who reported significant increments in plant height due to application of high nitrogen fertilizer rate.

Many studies revealed significant influence of N on plant height as it plays vital role in vegetative growth of plants. A similar result was reported by Haftom *et al.* (2009) showing that tef plants with higher plant height (92 cm) and panicle length (38 cm) were found by applying a high amount of N fertilizer (92 kg N ha^{-1}). This may be attributed to the fact that N usually favours vegetative growth of tef, resulting in higher stature of the plants with greater panicle length. Legesse (2004) also reported that high N application resulted in tef plants with significantly taller plants due to direct effect of N on vegetative growth of crop plants. In line with this finding Mekonn (1999) reported that plant height measured at physiological maturity increased significantly with increasing levels of N in wheat and sorghum respectively. Similarly, Tenaw (2000) and Zeidan *et al.* (2006) reported a significant effect of increased N fertilizer on the stature of maize plants. The plant height obtained from the all treated plots was significantly higher than the unfertilized plot. This is because nitrogen fertilizer has a great role in plant growth.

Table 4. Mean plant height of tef as affected by rates and timing of nitrogen fertilizer application

N rate kg ha-1	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	112.58^{g}	113.41^{efg}	116.80^{cde}	116.23^{cdef}	114.92^{defg}	114.8
69	113.25^{fg}	116.70^{cde}	120.95^{ab}	117.10^{cd}	117.80^{abcd}	117.2
92	112.22^{g}	117.53^{bcd}	119.07^{abc}	119.00^{abc}	118.27^{abcd}	119.0
Mean	115.7	115.9	118.9	117.4	117.0	116.99^{a}
control						95.75^{b}
	RxT	Treated vs control				
LSD(0.05)	3.437	5.29				
CV (%)	1.8	1.42				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.4.2. Panicle length

Panicle length is one of the yield attributes of tef that contribute to grain yield. Crops with higher panicle length could have higher grain yield. Panicle length was highly significantly (P< 0.01) influenced by the main effect of the rate of nitrogen fertilizer but not by the main effect of timing of application as well as the interaction of the two factors (Appendix 4).

An increase of nitrogen rate from 0 to 46 kg N ha^{-1} increased the tef panicle length by about 10%. Increasing the rate of nitrogen further from 0 to 69 kg N ha^{-1} markedly increased the panicle length of the plants by about 15%. No increase in panicle length was recorded beyond this level of N supply. This result is in contrary with that of Haftom *et al*. (2009) who reported that tef panicle length increased in response to increasing rate of nitrogen application, with the longest panicles being obtained at the highest rate 92 kg N ha^{-1} of nitrogen.

Table 5. Mean panicle length (cm) of tef as affected by rates of nitrogen fertilizer application

Treatments	Panicle length (cm)
N rate (kg ha^{-1})	
0	42.23^{c}
46	46.39^{b}
69	48.45^{a}
92	47.98^{a}
LSD (0.05)	1.352
CV (%)	
Timing	
S1	46.43
S2	46.35
S3	47.08
S4	45.36
S5	46.10
LSD (0.05)	NS
CV (%)	4.0

Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.4.3. Number of effective tillers

Crops with higher number of effective tillers could have higher grain yield, straw yield and biomass yield. The number of effective tillers counted at 0.0625 m^2 was highly significantly ($P < 0.01$) affected by N fertilizer rate. The number of effective tillers was also influenced significantly ($P < 0.05$) by the main effect of timing of application and the interaction effect of the two factors (Appendix 2).

The number of effective tillers was significantly increased in response to increasing rate of nitrogen across the application times. However, there was less consistency in the increase of this parameter with the increase in frequency of application. The maximum number of effective tillers was recorded in response to nitrogen applied at the rate of 69 kg N ha^{-1} with two equal split application of doses (half at sowing and the other half at mid-tillering). However, the number of effective tillers obtained in response to application of 69 kg N ha^{-1} at two split doses was in statistical parity with the numbers of effective tillers obtained in response to applying full dose of the same rate of nitrogen at sowing as well as in response to full dose applying 92 kg N ha^{-1} full dose at tillering as well as 1/4th at sowing, ½ at mid-tillering, and the remaining 1/4th at anthesis. In line with this result, Haftom *et al*. (2009) reported higher number of tef tillers per plant at 69 kg N ha^{-1}, which was in statistical parity with that obtained at 92 kg N ha^{-1}.

The lowest number of effective tillers was obtained from plots treated with 46 kg N ha^{-1} nitrogen in three split applications (1/4th dose at sowing+ $1/_2$ at tillering+ 1/4th at anthesis). The above result indicated that the enhancement of effective tiller development of plants that received nitrogen at higher rates but well spaced in time as the plant demand and N supply in the soil may have been synchronized for high uptake by roots. The current result is in agreement with that of Genene (2003) who reported higher tillering and maximum survival percentage of tillers with increasing N application in bread wheat. Corroborating the results of this study, Botella *et al*. (1993) reported that stimulation of tillering with high application of nitrogen might be due to its positive effect on cytokinin synthesis.

Table 6. Mean number of effective tillers per 0.0625 m^2 of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application(T)					
	S1	S2	S3	S4	S5	Mean
46	11.33^{fg}	15.00^{cde}	13.00^{ef}	14.33^{def}	9.00^{g}	12.53
69	17.33^{abcd}	16.67^{bcd}	20.67^{a}	13.00^{ef}	12.67^{ef}	16.07
92	17.00^{bcd}	19.67^{ab}	16.00^{cde}	16.00^{cde}	18.33^{abc}	17.40
Mean	15.22	17.11	16.56	14.44	13.33	15.33^{a}
control						7.73^{b}
	RxT	Treated vs	Control			
LSD(0.05)	3.480	3.75				
CV (%)	13.6	2.52				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.5. Yield and Yield Components

4.5.1. Grain yield

The analysis of variance showed that grain yield of tef was highly significantly ($P < 0.01$) influenced by the main effect of N fertilizer rate as well as by that of timing of application. Similarly, the interaction of nitrogen rate and time of application significantly ($P < 0.05$) influenced the grain yield of the crop (Appendix 3).

Tef grain yield generally increased with the increase in the rate of nitrogen across the increased numbers of split application (Table 7). However, at the rate of 46 kg N ha^{-1}, there tended to be no change in grain yield across the timing of nitrogen application. Similarly, for one time full dose application at sowing and mid-tillering. Tef yield did not increase with the increase in the rate of nitrogen application (Table 10). This shows that at the sub-optimal rate of 46 kg N ha^{-1}, applied as the full dose at any time or in splits did not increase yield, indicating that the rate was too low to favour growth, development, and yield of the crop plant. Similarly, the result of this study revealed that applying a full dose of even the highest rate of nitrogen did not increase grain yield of the crop. This may be attributed to the asynchrony in the time of availability of sufficient amounts of the nutrient in the soil proportionate with the demand of the plant for uptake. Thus, applying the whole dose of nitrogen at sowing was perhaps wastage as the small tef seedlings would not have the capacity to take up the nutrient in any significant amounts at that stage of growth. Similarly, applying the whole dose of even the highest amount of nitrogen at mid-tillering may enable the plant to take up a maximum amount of the nutrient at that particular time. However, since the plants may have hungered for nitrogen and suffered from its deficiency during the earlier time of vegetative growth, supplying a sufficient amount only at mid-tillering cannot guarantee optimum growth and development. Therefore, yield may be suppressed. In this connection, most of the applied nitrogen left over from uptake by the plant from the fully applied dose at sowing or mid-tillering may have been lost to leaching or volatilization owing to the high rainfall and temperature during the main growing season.

On the other hand, increasing the number of split N application from one time to two equal doses at sowing and mid-tillering significantly enhanced tef grain yield at 69 and 92 kg N ha^{-1} (Table 7). This may be because the plants may have been able to take up balanced amounts of nitrogen throughout the major growth stages due to enhanced synchrony of the demand of the nutrient for uptake by the plant and its availability in the root zone in sufficient amounts. In this case, leaching losses may also be reduced since the amount of nitrogen made available in the root zone may not be too high to be left over from uptake by plants and be predisposed to leaching. The highest grain yield was obtained in response to application of 69 kg N ha^{-1} in two equal split doses at sowing and mid-tillering. This grain yield was, however, in statistical parity with the grain yield obtained in response to applying the same rate of the nutrient in three splits (1/4th at sowing, ½ at mid-tillering and the other 1/4th at anthesis) (Table 10). In line with the result of this study, Damene (2003) reported the highest bread wheat grain yield at 69 kg N ha^{-1}. This result is also in line with that of Mohammad *et al*. (2011) who reported significantly higher yield of wheat from two equal split applications of N with $1/_2$ dose at sowing and $1/_2$ dose at tillering. Likewise, Temesgen (2001) reported that application of different levels of N significantly affected grain yield of tef on farmer's field.

Thus, compared to the tef grain yield obtained in response to applying 46 kg N ha^{-1} and 92 kg N ha^{-1} in two equal splits of half at sowing and half at mid-tillering, the grain yield obtained in response to applying 69 kg N ha^{-1} at the same times and doses was significantly higher by 14% and 21%, respectively. Similarly, the grain yield obtained from the application of 69 kg N ha^{-1} in two equal splits of half dose at sowing and half at mid-tillering exceeded the grain yield obtained from the application of 46 kg N ha^{-1} full dose at sowing by about 40%.

The results of this study are consistent with that of Sage and Pearcy (1987) who reported that a well-balanced supply of N results in higher net assimilation rate and increased grain yield as also found by Al-Abdulsalam (1997). Corroborating the results of this study, Blankenau *et al*. (2002) stated that proper rate and time of N application are critical for meeting crop needs, and indicated considerable opportunities for improving yields. Consistent with the results of this study, also Ashraf and Azam (1998) reported that growth stage of plants at which fertilizer is applied determines the final yield of the crop. In agreement with the results of this study, Michael *et al*. (2000) and Anthony *et al*. (2003) indicated that split N application as dry fertilizer material was effective in attaining higher grain yield of wheat. Consistent with the results of this study, Limaux *et al*. (1999) suggested that supplying N in two or three applications is a good recommendation to increase N use efficiency in wheat. The results of this study are consistent also with that of Cassman *et al*., (2002) who reported that greater synchrony between crop demand and nutrient supply is necessary to improve nutrient use efficiency, and split applications of N during the growing season, rather than a single, large application, are known to be effective in increasing N use efficiency.

The lower grain yield of tef in this study at 92 kg N ha^{-1}, particularly in response to full dose application of nitrogen at sowing and mid-tillering (Table 10) may possibly be attributed to excess supply of the nutrient favour more growth of vegetative plant parts rather than grain parts. This may be substantiated by the fact that the content of organic carbon in the experimental soil is high, and some of the mineralized N from this carbon may have supplemented the applied N thereby making it more than the quantity desired for optimum yield of tef. This suggestion is consistent with that of Murage *et al*. (2000) who stated that soil organic matter is a surrogate of mineral nitrogen in the soil for plant uptake.

In this experiment, the reduction in grain yield with further high N level beyond 69 kg N ha^{-1} might be mainly related to the reductions observed in the number of filled seed per panicle, length of panicle, main panicle seed weight and thousand-grain weight and thereby decreased grain yield ha^{-1}. Consistent with this suggestion, Reinke *et al.* (1994) noted that where the grain yield response is negative, yield reduction is primarily caused by a reduction in the proportion of the number of filled spikelets per panicle. Singh *et al.* (1995) also reported a decrease in grain yield of rice with application of high doses of N fertilizer. The yields obtained from the overall fertilized plots were significantly higher than the yield from the unfertilized plot.

Table 7. Mean grain yield of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	1795^{hi}	2087^{cde}	2197^{bcd}	1657^{i}	1878^{efgh}	1923
69	2023^{defg}	2063^{cdef}	2504^{a}	2266^{bc}	2402^{ab}	2251
92	1818^{ghi}	2083^{cde}	2065^{cdef}	1850^{fghi}	2212^{bcd}	2006
Mean	1879	2078	2255	1924	2164	2062.26^{a}
Control						1605.83^{b}
	RxT	Treated vs	Control			
LSD(0.05)	215.7	391.43				
CV (%)	6.3	6.07				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.5.2. Main panicle seed weight

The result indicated that main panicle seed weight highly significantly ($P < 0.01$) affected by the main effect of N fertilizer rates and the interaction of the two factors as well as it was significantly ($P < 0.05$) affected by timing of application (Appendix 3).

Increasing the rate of N fertilizer from 46 to 92 kg N ha^{-1} across full dose application at sowing time, increased the main panicle seed weigh. Similarly, increasing the rate of nitrogen from 46 to 69 kg N ha^{-1} across S2, S3, and S5 split applications, increased the main panicle seed weight, whereas further increase to 92 kg N ha^{-1}, significantly decreased this parameter of the plant (Table 8).

The highest main panicle seed weight (9.00g) was recorded from 46 kg N ha^{-1} applied at three split applications (1/3rd of the dose at sowing, 1/3rd at mid-tillering, and the other 1/3rd at anthesis). For the rate of 69 kg N ha^{-1}, the highest main panicle seed weight was recorded already under application of 1/4th of the dose at sowing, 1/2 at tillering and 1/4th at anthesis, which was in statistical parity with the two and three-time nitrogen applications. For 92 kg N ha^{-1}, this parameter was markedly low at all application times compared to the other treatments except full dose applied at sowing. However, the lowest main panicle seed weights were recorded under plants treated with 46 and 69 kg N ha^{-1} rates and applied full dose at sowing. These values are in statistical parity with the values of main panicle seed weight obtained under 92 kg N ha^{-1} rate and applied by using the three-time N applications method as well as under 46 kg N ha^{-1} rates applied 1/4th dose at sowing, half at mid-tillering, and the other 1/4th at anthesis and full dose applied at tillering(Table 8).

Table 8. Mean main panicle seed weight of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	4.67^{g}	6.00^{defg}	7.00^{cde}	9.00^{a}	6.00^{defg}	6.533
69	5.33^{fg}	8.00^{abc}	8.67^{ab}	8.67^{ab}	9.00^{a}	7.933
92	7.33^{bcd}	6.33^{def}	6.00^{defg}	5.67^{efg}	6.00^{defg}	6.267
Mean	5.778	6.778	7.222	7.778	7.000	6.91
Control						5.47
	RxT	Treated vs	Control			
LSD(0.05)	1.594	NS				
CV (%)	13.8	7.74				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.5.3. Thousand seed weight

Thousand seed weight is an important yield determining component and reported to be a genetic character that is influenced least by environmental factors (Ashraf *et al*, 1999).
The analysis of variance showed that the main effects of rate and timing of N fertilizer application highly significantly ($P < 0.01$) influenced thousand seed weight. However, the interaction of the two factors did not affect this parameter.

Thousand seed weight was significantly increased with increase in the rate of nitrogen application. Increasing the rate of nitrogen from 0 to 46 kg N ha^{-1} significantly increased thousand seed weight by about 8%. Increasing the rate of N application from 0 to 69 kg N ha^{-1} increased 1000 seed weight by about 13%. Increasing the rate of nitrogen from 69 kg N ha^{-1} to 92 kg N ha^{-1}, however, did not significantly affect 1000 seed weight. The maximum 1000 seed weight (0.3249g) was obtained from plants supplied with 69 kg N ha^{-1}. This value is in statistical parity with the 1000 seed weight (0.3203g) obtained under the nitrogen rate of 92 kg N ha^{-1}. However, the lowest 1000 seed weight (0.2886g) was obtained from the unfertilized plot. Thus, the maximum 1000 seed weight obtained exceeded the minimum by about 13%. This result is in agreement with that of Channabasavanna and Setty (1994) who reported positive response of rice grain weight to N application. However, in contrast to the finding of this study, Melesse (2007) reported no significant effect of application of different rates of nitrogen fertilizer (0, 46 and 69 kg N ha^{-1}) on 1000 kernel of bread wheat.

Table 9. Mean thousand seed weight of tef as affected by main effect of rate and timing of nitrogen fertilizer application

Treatments	Thousand seed weight (g)
N rate (kg ha^{-1})	
0	0.2886^{c}
46	0.3115^{b}
69	0.3249^{a}
92	0.3203^{ab}
LSD (0.05)	0.00933
Timing	
S1	0.3062^{bc}
S2	0.3004^{c}
S3	0.3132^{b}
S4	0.3240^{a}
S5	0.3128^{b}
LSD (0.05)	0.01043
CV (%)	4.1

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = $1/3^{rd}$ at sowing + $1/3^{rd}$ at tillering + $1/3^{rd}$ at anthesis, and S5 = $1/4^{th}$ dose at sowing + $1/_2$ at tillering + $1/4^{th}$ at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.5.4. Biomass yield

The biomass yield was highly significantly ($P < 0.01$) influenced by the main effect of N rate, timing of N fertilizer application ($P < 0.05$) as well as by the interaction effect of the two factors ($P < 0.01$) (Appendix 3).

Biomass yield generally increased significantly with the increase in the rate of nitrogen across the increasing frequency of application. The highest biomass yield (9004 kg ha^{-1}) was obtained under plants supplied with 69 kg N ha^{-1} applied in two equal splits (at sowing and mid-tillering) whereas the lowest biomass yield was obtained from plants grown at 46 kg N ha^{-1} rate and applied full dose at sowing, $1/3^{rd}$ doses at sowing, mid-tillering, and anthesis and 69 kg N ha^{-1} rate of full dose at sowing as well as 92 kg N ha^{-1} rate applied half dose at sowing and the other dose at mid-tillering (S3) (Table 10) as well as $1/3^{rd}$ doses at sowing, mid-tillering, and anthesis (S4). This value is in statistical parity also with biomass yield obtained when 46 kg N ha^{-1} was applied $1/4^{th}$ at sowing, ½ at mid-tillering and the remaining $1/4^{th}$ at anthesis . Thus, the maximum biomass yield exceeded the minimum biomass yield by about 52%. This nitrogen application significantly enhanced biomass yield is in agreement with the result of Amanuel *et al*. (1991) who reported a significant increase in biomass yield of wheat as a result of increased rate of N application.

The application of highest level of N resulted in less biomass yield compared to 69 kg N ha^{-1} rate applied at S3, S4, and S5. This might be due to the effect of lodging resulted from too high amount of N fertilizer that encourage vegetative growth and height leading to lodging before the translocation of dry matter to economic yield since biomass includes the economic yield. This result is, however, in contrast to that of Haftom *et al*. (2009) who found the highest biomass yield of tef in response to the application of 92 kg N ha^{-1}. This may be attributed to possible differences in the inherent fertility of the two soils, whereby the soil on which these authors conducted their experiment may have been lower in organic matter than the soil used for this experiment. This may have rendered the latter soil to have lower ability to supply N from mineralization, thus requiring the application of more external nitrogen (92 kg N ha^{-1}) for increased biomass production of tef than the soil used for this experiment. In general, the biomass yield obtained from the fertilized plots exceeded the biomass yield from the unfertilized plot by about 43%.

Table 10. Mean biomass yield of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	6011^{i}	7061^{def}	7433^{cde}	6181^{ghi}	6093^{hi}	6556
69	6520^{fghi}	6775^{efg}	9004^{a}	8296^{b}	7830^{bc}	7685
92	6708^{fgh}	6825^{efg}	6307^{ghi}	5914^{i}	7630^{bcd}	6677
Mean	6413	6887	7581	6797b	7184	6972.5^{a}
control						4857.8^{b}
	RxT	Treated vs Control				
LSD(0.05)	673.5	1078.5				
CV (%)	5.8	5.19				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.5.5. Harvest index

Harvest index was computed as the ratio of grain yield to the total above ground dry biomass yield. The main effect of rate of nitrogen did not affect harvest index. However, the main effect of timing of nitrogen significantly affected harvest index whereas the interaction effect of rate and timing of nitrogen application highly significantly affected this parameter of the plant (Appendix 3).

Harvest index tended to decrease with increased application of nitrogen. However, there was no consistent trend of increase or decrease in harvest index with the times and doses of nitrogen application. For the rates of 46 kg and 69 kg N ha^{-1}, the highest harvest indix were scored under full dose application of nitrogen with at sowing and three splits (1/4th of the dose at sowing, ½ at mid-tillering, and the remaining 1/4th at anthesis) (Table 11). In line with these results, Abdo (2009) reported highest harvest index from treatments with the lowest rate of nitrogen application.

This may indicates that, full dose application of nitrogen may have led to relatively less shoot biomass growth due to leaching at the seedling stage of the crop, when the plant had no sufficient capacity to take up larger amounts of the nutrient. This is due to the results obtained in proportionally higher seed yield than vegetative biomass yield. However, for 92 kg N ha^{-1}, application of full dose of nitrogen at mid-tillering as well as 1/3rd of the dose at sowing,1/3rd at mid-tillering, and the remaining 1/3rd at anthesis led to the highest harvest indices.

Table 11. Mean harvest index of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	0.3050^{abc}	0.2959^{bcd}	0.2913^{bcde}	0.2681^{f}	0.3082^{ab}	0.2937
69	0.3160^{a}	0.2899^{cde}	0.2778^{ef}	0.2857^{de}	0.3029^{abcd}	0.2944
92	0.2957^{bcd}	0.3053^{abc}	0.2951^{bcd}	0.3184^{a}	0.2901^{cde}	0.3009
Mean	0.3055	0.2970	0.2880	0.2907	0.3004	0.29
Control						0.33
	RxT	Treated vs	Control			
LSD (0.05)	0.0172	NS				
CV (%)	3.5	5.29				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + 1/2 at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.5.6. Straw yield

Straw yield was affected both by main effect of N fertilizer rate ($P < 0.01$) and timing of application ($P < 0.05$). Likewise, the two factors interacted significantly ($P < 0.01$) to influence straw yield (Appendix 3).

Increasing the number of split N application from one time to two equal doses at sowing and mid-tillering doses significantly enhanced tef straw yield. This may be because the plants may have been able to take up sufficient amounts of nitrogen throughout the major growth stages due to enhanced availability of the nutrient in the root zone over the growth stages. The highest straw yield was obtained in response to applying 69 kg N ha^{-1} in two equal split doses at sowing and mid-tillering (Table 12). Thus, compared to the tef straw yield obtained in response to applying 46 kg N ha^{-1} full dose at sowing, the tef straw yield obtained in response to applying 69 kg N ha^{-1} in two equal split doses at sowing and mid-tillering was higher by about 55%.

Increasing level of N up to 69 kg N ha^{-1} significantly increased straw yield but decreased at 92 kg N ha^{-1}. This may be attributed to the vigorous vegetative growth enhancing property of nitrogen whereby increased number of tillers and dry matter may have been produced due to efficient uptake of the nutrient by the plant over the two major growth stages. This result is in agreement with that of Alcoz *et al*. (1993) and Tilahun *et al*. (1996) who reported enhancement of straw yield in response to applying nitrogen in split doses compared to applying the whole dose of the nutrient at seeding or mid-tillering stages of wheat. Similarly, Abdo (2009) reported highest straw yield of durum wheat in response to applying nitrogen at the rate of 69 kg N ha^{-1}.

Table 12. Mean straw yield of tef (kg ha^{-1}) as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Time of application (T)					
	S1	S2	S3	S4	S5	Mean
46	4182^{h}	4975^{cde}	5269^{cd}	4524^{efgh}	4215^{gh}	4633
69	4463^{efgh}	4812^{def}	6500^{a}	5930^{b}	5462^{bc}	5433
92	4723^{efg}	4741^{ef}	4442^{fgh}	4031^{h}	5418^{bcd}	4671
Mean	4456	4842	5404	4828	5031	4914.6^{a}
Control						3251.9^{b}
	RxT	Treated vs	Control			
LSD(0.05)	524.4	776.3				
CV (%)	6.4	4.72				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th

dose at sowing + $1/_2$ at tillering + $1/4^{th}$ at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.6. Partial Budget Analysis

As indicated in Table 13, net benefit obtained in response to half dose at sowing and at mid-tillering application of 46 and 69 kg N ha-^{1} were 22431.6 and 25139.2 birr, respectively. The higher marginal rate of return with least cost was obtained from 46 kg N ha^{-1} in two equal split applications of half dose at sowing and half dose at mid-tillering. The marginal return obtained at 69 kg N ha^{-1} was also showed that further earnings beyond application of 46 kg N ha^{-1} applied was possible. Because the marginal rate of return was above the minimum level (100%). According to the manual for economic analysis of CIMMYT (1988) the recommendation is not necessarily based on the treatment with the highest marginal rate of return compared to that of neither next lowest cost, the treatment with the highest net benefit, and nor the treatment with the highest yield. The identification of a recommendation is based on a change from one treatment to another if the marginal rate of return of that change is greater than the minimum rate of return. Thus, two split applications of half dose at sowing and the remaining dose at mid-tillering of 69 kg N ha^{-1} rate is economically beneficial compared to the other treatments.

Table 13. Partial budget analysis for N Fertilizer rate and time of application

Treatments	Total variable cost (Birr ha^{-1})	Grain yield (kg ha^{-1})	Net benefit (Birr ha^{-1})	Marginal rate of return (%)
0	0	1445.4	17344.8	-
46,S2	1256	1878.3	21283.6	314
46,S3	1296	1977.3	22431.6	2870
69,S3	1904	2253.6	25139.2	445

Where, S2 = full dose at tillering; S3= ½ dose at sowing + ½ dose at tillering

4.7. Concentrations of Nitrogen in Grain and Straw, and N Uptake

4.7.1. Concentration of nitrogen in shoot

Nitrogen concentration in plant shoot at anthesis tended to increase in response to increasing the level of nitrogen from 0 to 92 kg N ha^{-1} up to full dose applied at tillering but in most treatments the nitrogen concentration declined as the frequency of split application increased. The highest shoot nitrogen concentration (1.52%) obtained from plants grown in plots treated with 92 kg N ha^{-1} applied full dose at tillering while the minimum (0.59%) was from the unfertilized plot. The highest nitrogen concentration exceeded the minimum by about 158%.

As the frequency of split applications increased, the nitrogen concentration in plant tissue tended to decrease especially on plots treated with in three equal splits of 1/3rd at sowing+ 1/3rd at tillering+ 1/3rd at anthesis. This might be because the amount of fertilizer applied at anthesis might not be taken by the plant roots immediately as applied and remain in soil. This indicates that late application of N may not enable the plant to take up most of the nutrient from the soil. Therefore, Timing of fertilizer application is an important aspect which can minimize risk of nutrient losses.

Table 14. The nitrogen concentration in plant shoots of tef at anthesis

Treatments	N content in shoot (%)	Treatments	N content in shoot (%)
0	0.59	69,S3	0.93
46,S1	0.81	69,S4	0.84
46,S2	0.77	69,S5	0.66
46,S3	0.88	92,S1	1.26
46,S4	0.61	92,S2	1.52
46,S5	0.76	92,S3	1.32
69,S1	0.89	92,S4	0.85
69,S2	0.93	92,S5	0.87

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + 1/2 at tillering + 1/4th at anthesis.

4.7.2. Grain nitrogen content

The analysis of variance showed that the total nitrogen concentration in grain at maturity was highly significantly ($P < 0.01$) affected by the main effect of N fertilizer rate, timing of application, and by the interaction effect (Appendix 5).

At the levels of 46 and 69 kg N ha^{-1}, increasing the time of split application did not show consistent increase or decrease in the grain N concentration of the crop. However, at 92 kg N ha^{-1}, increasing the frequency of nitrogen application at the varied doses decreased the grain nitrogen content. In general, the higher grain nitrogen concentrations were obtained in response to levels of 92 kg N ha^{-1} applied full dose at sowing, full dose at mid-tillering, and half dose at sowing with the other half dose at mid-tillering. The lowest value (1.233) of this parameter was obtained under 46 kg N ha^{-1} when it was applied at splits of half dose at sowing and the remaining half at mid-tillering. Thus, the maximum grain nitrogen content exceeded the minimum grain nitrogen content by about 25%. This implies a positive response of grain N concentration to increased N rate but a negative response to increased frequency of application of the nutrient. This result is in line with that of Campbell *et al*. (1993) who reported that grain N content of wheat increased in response to increasing rates of nitrogen application.

Increasing rates of nitrogen fertilizer from 46 to 92 kg N ha^{-1}, increased the grain nitrogen content consistently especially with applications of full dose at mid-tillering, half dose at sowing and tillering as well as at three equal split applications of $1/3^{rd}$ at sowing, $1/3^{rd}$ at mid-tillering and $1/3^{rd}$ at anthesis. This might be due to the high rate of N mobilization to the grain at grain filling stage influenced by high rates of N application. Generally, the grain nitrogen content was varied from 1.23- 1.55 (Table 15).

Table 15. Mean grain nitrogen content (%) of tef as affected by rate and timing of nitrogen fertilizer application

N rate	Timing of application (T)					
(kg ha^{-1})	S1	S2	S3	S4	S5	Mean
46	1.367^{fg}	1.323^{gh}	1.233^{i}	1.367^{fg}	1.260^{hi}	1.3100
69	1.247^{i}	1.420^{def}	1.337^{g}	1.437^{cde}	1.383^{efg}	1.3647
92	1.493^{abc}	1.55^{a}	1.52^{ab}	1.460^{bcd}	1.337^{g}	1.4720
Mean	1.3689	1.4311	1.3633	1.4211	1.3267	1.37^{a}
Control						1.11^{b}
	RxT	Treated vs	Control			
LSD (0.05)	0.0665	0.23				
CV (%)	2.9	4.72				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + 1/$_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.7.3. Straw nitrogen content

Straw nitrogen content was highly significantly (P<0.01) affected by the main effect of N rates and timing of application and it also was significantly (P < 0.05) influenced by the interaction effect of the two factors.

Straw N content did not show a consistent increase or decrease across all application times for 46 kg N ha^{-1} and 69 kg N ha^{-1}. This parameter decreased significantly in response to increasing the frequency of split application at 92 kg N ha^{-1}.This indicates increasing the frequency of split application, resulted low nitrogen content in straw. This might be split applications of nitrogen fertilizer cause high amount of nitrogen content to be taken by the grain rather than by straw of tef. Full dose at mid-tillering, half dose at sowing and the remaing half dose at mid-tillering as well as three equal splits of 1/3rd at sowing + 1/3rd at tillering +1/3rd at anthesis, consistently increased the straw nitrogen content as the rates of nitrogen increased (Table 16). Thus, the maximum straw nitrogen content was at 92 kg N ha^{-1} full dose applied at mid-tillering and this result was higher than the minimum straw nitrogen content by 77%. Full dose nutrient applied at tillering might be enhanced vigorous vegetative growth and high amount nitrogen content could be accumulated in straw in which does not translocated to grain.

Table 16. Mean straw nitrogen content (%) of tef as affected by rate and timing of nitrogen fertilizer application

N rate	Timing of application (T)					
(kg ha^{-1})	S1	S2	S3	S4	S5	Mean
46	0.5167^{cde}	0.4667^{def}	0.4200^{ef}	0.4233^{ef}	0.4667^{def}	0.4587
69	0.4633^{def}	0.6367^{ab}	0.4867^{def}	0.5467^{bcd}	0.3933^{f}	0.5053
92	0.6467^{ab}	0.6967^{a}	0.6467^{ab}	0.6167^{abc}	0.4300^{ef}	0.6073
Mean	0.5422	0.6000	0.5178	0.5289	0.4300	0.38^{b}
Control						0.52^{a}
	RxT	Treated vs	Control			
LSD (0.05)	0.1033	0.10				
CV (%)	11.8	6.33				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.7.4. Grain nitrogen uptake

The analysis of variance showed that grain N uptake was highly significantly ($P < 0.01$) affected by the main effects of N rates and timing of application, and the two factors interacted to significantly ($P < 0.05$) influence this parameter (Appendix 5).

Except from the response of nitrogen applied at two and the three splits, grain nitrogen uptake increased consistently as the rates of fertilizer increased. Application of some extra N through increased levels definitely increased the concentration of N in soil and led to greater absorption of nutrients, which ultimately resulted in vigorous growth of tef in terms of higher dry matter accumulation and enhanced the total uptake of nitrogen.

The highest uptake of nitrogen by tef grain was recorded at S3, S4, and S5 for 69 kg N ha^{-1} and at S2 and S3 for 92 kg N ha^{-1} (Table 17). The maximum grain N uptake was, however, obtained at 69 kg N ha^{-1} with the application of half of the nitrogen dose at sowing and the other half at mid-tillering. But the minimum was obtained with 46 kg N ha^{-1} in split applied of 1/3rd at sowing + 1/3rd at tillering +1/3rd at anthesis. This result is consistent with that of Fageria and Baligar, (2001) who reported that N uptake in grain has positive significant associations with grain yield. Similarly, Kumar and Rao (1992), and Panda *et. al*. (1995) reported that the uptake of N by rice crop and concentration in the tissues were increased by increase in N levels.

Table 17. Mean grain nitrogen uptake (kg ha^{-1}) of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	24.53^{def}	27.61^{cd}	27.12^{cd}	22.63^{f}	23.69^{ef}	25.12
69	25.24def	29.28^{bc}	33.98^{a}	32.58^{ab}	33.26^{a}	30.87
92	27.20^{cd}	32.27^{ab}	31.38^{ab}	27.00^{cde}	29.46^{bc}	29.46
Mean	25.66	29.72	30.82	27.40	28.80	28.22^{a}
Control						18.30^{b}
	RxT	Treated vs	Control			
LSD (0.05)	3.346	5.65				
CV (%)	7.0	6.92				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.7.5. Straw nitrogen uptake

Straw nitrogen uptake was highly significantly ($P < 0.01$) affected by N fertilizer rate and timing of application. Likewise, the interaction effect of the two factors also significantly ($P < 0.01$) influenced the nitrogen uptake ($P < 0.05$) (Appendix 5). Straw nitrogen content remained the same across all times of N application for 46 kg N ha^{-1}. The highest uptake of nitrogen for the tef straw was recorded at S2, S3, and S4 for 69 kg N ha^{-1} and at S1, S2, and S3 for 92 kg N ha^{-1} (Table 18). The maximum straw N uptake was, however, obtained at 92 kg N ha^{-1} with the application of full dose at mid-tillering. Straw nitrogen uptake obtained by applying full dose at tillering showed slightly increases as the rate increased. This result is in line with the findings of woldeyesus *et al.* (2004) and Muurinen (2007) who reported significant increase in straw nitrogen uptake with increased N rates. However, the other split-applications did not show significant increment as the rates of nitrogen increased. Full dose applied at sowing and tillering as well as half dose at sowing and the remaining dose at tillering for 92 kg N ha^{-1}, gave no significant straw nitrogen uptake.

Table 18. Mean straw nitrogen uptake (kg ha^{-1}) of tef as affected by rate and timing of nitrogen fertilizer application

N rate	Timing of application (T)					
(kg ha^{-1})	S1	S2	S3	S4	S5	Mean
46	21.71^{d}	23.11^{cd}	22.12^{d}	19.09^{d}	19.72^{d}	21.15
69	20.70^{d}	30.71^{a}	31.80^{a}	32.14^{a}	21.70^{d}	27.41
92	30.63^{ab}	32.95^{a}	28.64^{abc}	24.83^{bcd}	23.31^{cd}	28.07
Mean	24.35	28.92	27.52	25.36	21.57	25.55^{a}
Control						13.21^{b}
	RxT	Treated vs	Control			
LSD (0.05)	5.844	0.62				
CV (%)	13.7	0.91				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.7.6. Total nitrogen uptake

Total nitrogen uptake kg ha^{-1} was highly significantly ($P<0.01$) affected by the N rate and timing of application. The interaction effect of the two factors also significantly ($P < 0.05$) affected the total N uptake (Appendix 5).

In general, total N uptake of tef remained unchanged at the rate of 46 kg N ha^{-1} across all times of application of the nutrient. However, it increased across the increasing frequency split of N application for the application rates of 69 and 92 kg N ha^{-1} except at S4 and S5.

The highest total nitrogen uptake was recorded for full dose at mid-tillering, half dose at sowing and half at mid-tillering as well as at three equal splits of 1/3rd at sowing+ 1/3rd at tillering+ 1/3rd at anthesis for 69 kg N ha^{-1}, and for full dose at mid-tillering, half dose at sowing and the remaining half dose at tillering for 92 kg N ha^{-1} (Table 19). The highest total

N uptake (65.78 kg N ha^{-1} was, however, obtained at 69 kg N ha^{-1} with the application of half of the nitrogen dose at sowing and the other half at mid-tillering. This is because the nitrogen uptake by straw and grain were the highest at this treatment and hence these two grain and straw nitrogen uptake added up to the high total nitrogen uptake. The total nitrogen uptake has a positive association with grain yield. Therefore, the highest grain yield was recorded at the treatment that gave maximum total nitrogen uptake.

Table 19. Mean total nitrogen uptake (kg ha^{-1}) of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kg ha^{-1})	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	46.24^{fgh}	50.72^{defg}	49.24^{efgh}	41.72^{h}	43.40^{gh}	46.26
69	45.94^{fgh}	59.99^{abc}	65.78^{a}	64.73^{ab}	54.95^{cde}	58.28
92	57.84^{bcd}	65.22^{ab}	60.02^{abc}	51.83^{def}	52.77^{cdef}	57.54
Mean	50.01	58.64	58.34	52.76	50.38	53.78^{a}
Control						31.50^{b}
	RxT	Treated vs	Control			
LSD (0.05)	7.867	5.73				
CV (%)	8.7	3.82				

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.8. Nitrogen Use Efficiency

4.8.1. Apparent nitrogen recovery

Apparent nitrogen recovery is a measure of the ability of the crop to extract N from the soil. The main effect of N rate and timing of application as well as the interaction effect of these two factors highly significantly ($P < 0.01$) affected apparent nitrogen recovery (Appendix 5).

Apparent nitrogen recovery by the tef plants generally decreased with the increase in the rate of nitrogen application. The highest amount of apparent nitrogen recovery (about 50%) was obtained when the nutrient was applied in two equal doses at sowing and mid-tillering or at three equal doses at sowing, mid-tillering, and anthesis for 69 kg N ha^{-1} (Table 20). This indicates that tef plants recovered less and less amounts of nitrogen from the soil as rate of application went beyond a certain threshold as well as when the dose applied at sowing was reduced to less than half. The result also indicates that applying nitrogen particularly in two to three equal doses enhanced recovery of the nutrient by the plant from the soil. The results obtained in this study confirm the observations of Lopez-Bellido *et al*., (2005) that recovery of N applied, which is determined based on measurements of N uptake in the aerial plant biomass, is highly affected by timing of N application. Supporting the results of this study, Zafar and Muhammad (2007) stated that about 50% of applied N remains unavailable to a crop due to a combination of leaching, fixation and volatilization.

.Table 20 Mean of apparent nitrogen recovery (%) of tef as affected by rate and timing of nitrogen fertilizer application

N rate (kgha^{-1})	Timing of application					
	S1	S2	S3	S4	S5	Mean
46	34.73^{de}	44.50^{b}	41.27^{bc}	24.93^{gh}	28.57^{fg}	34.8
69	22.73^{h}	43.10^{b}	51.47^{a}	49.97^{a}	35.80^{de}	40.6
92	29.97^{f}	38.03^{cd}	32.33^{ef}	23.47^{h}	24.43^{gh}	29.6
Mean	29.1	41.9	41.7	32.8	29.6	
	RxT					
LSD (0.05)	4.66					
CV (%)	8.0					

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

4.8.2. Agronomic and physiological efficiency

Both agronomic and physiological efficiency were significantly ($P < 0.01$) affected by N rate, timing of application, and by the interaction effect of the two factors. Agronomic efficiency is the amount of additional yield produced for each additional kg of fertilizer applied (Mengel and Kirkby, 2001).

The combination effect which gave the lowest agronomic efficiency (2.31) was recorded at 92 kg ha^{-1} in response of full dose applied at sowing while the highest was obtained from 69 kg N ha^{-1} in split applications of half dose at sowing and the other dose at mid-tillering (Table 21). The agronomic efficiency recorded in the response of split application of full dose at sowing and half dose at sowing and the remaining at mid-tillering, increased as the rate increased 46 to 69 kg N ha^{-1}. However, nutrient applied beyond 69 kg N ha^{-1}, showed reduction in agronomic efficiency across all split applications (Table 21). This might be due to the effect of loss of nutrients that the tef crop did not take the applied fertilizer and hence, caused low grain yield. Craswell and Godwin (1984) asserted that high agronomic efficiency is obtained if the yield increment per unit N applied is high because of reduced losses and increased uptake of N.

As the level of N increased from 46 kg N ha^{-1} to 92 kg N ha^{-1}, physiological efficiency consistently decreased across all split application except 69 kg N ha^{-1} full doses applied at sowing and at S5 which showed slightly increment. The physiological efficiency recorded at 46 and 69 kg N ha^{-1}, showed significantly increment up to the frequency of two split applications but it was decreased beyond two splits (Table 22). The lowest physiological efficiency recorded at the highest nitrogen rate of 92 kg N ha^{-1} in the response of split-applications of ½ dose at sowing and half at mid-tillering and in three equal splits of 1/3rd at sowing+ 1/3rd at tillering+ 1/3rd at anthesis. According to Sowers *et al*. (1994), the application of high N rates may result in poor N uptake and low NUE due to excessive N losses. The ratio of grain N yield to the total N yield provides an estimate of efficiency of N translocation from vegetative tissue to grain and indicated that at low N rate the amount of N traslocated to the grain was high.

Table 21. Mean agronomic efficiency (kg grain yield kg^{-1} N applied) of tef as affected by rate and timing of nitrogen fertilizer application

N rate ($kg\ ha^{-1}$)	Timing of application (T)					
	S1	S2	S3	S4	S5	Mean
46	4.11^{i}	10.453^{e}	12.857^{b}	10.1^{e}	5.927^{g}	6.89
69	6.113^{g}	6.727^{f}	13.663^{a}	9.697^{d}	11.673^{c}	9.57
92	2.31^{j}	5.190^{h}	4.99^{h}	2.65^{j}	6.590^{f}	4.35
Mean	4.18	7.46	10.50	4.48	8.06	
	RxT					
LSD (0.05)	0.429					
CV (%)	3.7					

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

Table 22. Mean physiological nitrogen use efficiency of tef as affected by rate and timing of nitrogen fertilizer application

N rate ($kg\ ha^{-1}$)	Timing of application(T)					
	S1	S2	S3	S4	S5	Mean
46	69.50^{f}	117.78^{cd}	134.85^{a}	130.96^{ab}	92.60^{e}	109.14
69	110.34^{d}	64.22^{fg}	122.67^{bc}	95.80^{e}	126.76^{abc}	103.96
92	69.72^{f}	55.35^{gh}	48.58^{hi}	44.03^{i}	120.96^{c}	67.73
Mean	83.19	79.12	102.03	90.26	113.44	
	R	T	RxT			
LSD (0.05)	4.199	5.421	9.389			
CV (%)	6.0					

Where, R = rate; S1 = full dose at sowing; S2 = full dose at tillering; S3 = ½ dose at sowing + ½ dose at tillering; S4 = 1/3rd at sowing + 1/3rd at tillering + 1/3rd at anthesis, and S5 = 1/4th dose at sowing + $1/_2$ at tillering + 1/4th at anthesis. Means sharing the same superscript letter do not differ significantly at P = 0.05 according to the LSD test

5. SUMMARY AND CONCLUSION

A field experiment was carried out during the 2012 main cropping season from July to November in Habro district at a farmer's filed with the objectives of studying the effects of rates and time of nitrogen fertilizer application on yield and yield components of tef and determining the most economic rate and time of nitrogen fertilizer application for tef production in the study area. The experiment was laid out as a randomized complete block design in a factorial arrangement with three replications. The treatments consisted of entire factorial combinations four levels nitrogen (0, 46, 69 and 92 kg N ha^{-1}) and five split applications (full dose at sowing, full dose at tillering, ½ dose at sowing + ½ dose at tillering, $1/3^{rd}$ dose at sowing + $1/3^{rd}$ dose at tillering + $1/3^{rd}$ dose at anthesis, $1/4^{th}$ dose at sowing + ½ at tillering, $1/4^{th}$ dose at anthesis).

Days to panicle emergence was influenced by the interaction effect of two factors rate and time, but not days to maturity. Increasing the rate of nitrogen application significantly prolonged the days the tef plants to panicle emergence across all application times. Nitrogen rate and timing of application interacted significantly to influence plant height and number of effective tillers. As the rate of N increased from 0 to 69 kg N ha^{-1} days to maturity was significantly delayed. The delay in panicle emergence and maturity of tef plants in response to the increased N rate might be because the high N rate promoted vigorous vegetative growth and development of the plants.

Increases in lodging percentages due to the increased application rates of nitrogen were observed for plants supplied with the nutrient in one full doses at sowing and mid-tillering as well as for those supplied with the nutrient in two-splits of equal doses at sowing and mid-tillering. This might be due to N fertilizer enhances vegetative growth which can lead to easily lodge by high rain-fall and wind.

Panicle length is one of the yield attributes of tef lead to high increment in grain yield. It was affected only by the rate of nitrogen fertilizer. As the rate of nitrogen was increased from 0 to 46 kg N ha^{-1}, the panicle length of tef increased by about 10%. Increasing the rate of nitrogen further from 0 to 69 kg N ha^{-1} markedly increased the panicle length of the plants by about 15%. Beyond this level of N supply, there was no increase in panicle length.

The maximum number of effective tillers was recorded in response to applying nitrogen at the rate of 69 kg N ha^{-1} with two equal split applications (half at sowing and the other half at mid-tillering). While The lowest number of effective tillers was obtained from plots treated with 46 kg N ha^{-1} nitrogen in three split applications (1/4th dose at sowing+ $1/_2$ at tillering+ 1/4th at anthesis).

In general, all the yield and yield components of tef (biomass yield, grain yield, harvest index and straw yield) except thousand seed weight were significantly influenced by the interaction effects of rate and timing of fertilizer application.

Biomass yield increased significantly with the increases in the rate of nitrogen across the increasing frequency of application. The highest biomass yield (9004 kg ha^{-1}) was obtained for plants supplied with 69 kg N ha^{-1} applied in two equal splits at sowing and mid-tillering whereas the lowest biomass yield was obtained for plants grown at 46 kg N ha^{-1} applied full dose at sowing, 1/3rd doses at sowing, mid-tillering, and anthesis Thus, the maximum biomass yield exceeded the minimum biomass yield by about 52%. The highest level of N applied produced less biomass yield compared to 69 N kg N ha^{-1} applied at ½ dose at sowing+ ½ dose at tillering, 1/3rd at sowing+ 1/3rd at tillering+ 1/3rd at anthesis and 1/4th dose at sowing+ 1/2 at tillering+ 1/4th at anthesis. This might be due to the effect of lodging because of the too high amount of N fertilizer enhances vegetative growth and height which can easily be affected by external factors like high rainfall and wind, leading to lodging before the dry matter is able to be translocated to the economic yield since biomass includes the economic yield.

For one time full dose application at both sowing and mid-tillering, tef yield did not increase with the increase in the rate of nitrogen application. This shows that at the sub-optimal rate of 46 kg N ha^{-1}, applying the full dose at any time or in splits in varied doses may not have increased yield, indicating that the rate was too low to cause marked enhancement in growth, development, and yield of the crop plant. Similarly, the result of this study also revealed that applying a full dose even once the highest rate of nitrogen did not increase grain yield of the crop. This might be, because most of the applied nitrogen left over from uptake by the plant from the fully applied dose at sowing or mid-tillering may have been lost due to leaching or volatilization owing to the high rainfall and temperature during the main growing season.

The highest grain yield (2504 kg ha^{-1}) was obtained in response o applying 69 kg N ha^{-1} in two equal split doses at sowing and mid-tillering. This grain yield was, however, in statistical parity with the grain yield obtained in response to applying the same rate of the nutrient in three splits of $1/4^{th}$ at sowing, ½ at mid-tillering and the other $1/4^{th}$ at anthesis. While the lower grain yield of tef obtained at 92 kg N ha^{-1}, particularly in response to applying N as a full dose at sowing and mid-tillering may possibly be attributed to excess supply of the nutrient in the soil. This may be substantiated by the fact that the content of organic carbon in the experimental soil is high, and some of the mineralized N from this carbon may have supplemented the applied N thereby making it more than the quantity desired for optimum yield of tef. Generally, the grain yield obtained from the application of 69 kg N ha^{-1} in two equal splits of half dose at sowing and half at mid-tillering exceeded the grain yield obtained from the application of 46 kg N ha^{-1} full dose at sowing by about 40%.

Apparent nitrogen recovery by the tef plants generally decreased with the increase in the rate of nitrogen application. The highest amount of N (about 50%) was recovered by the plant when the nutrient was applied in two equal doses at sowing and mid-tillering or at three equal doses at sowing, mid-tillering, and anthesis for 69 kg N ha^{-1}. This indicates that tef plants recovered less and less amounts of nitrogen from the soil as rate of application went beyond a certain threshold as well as when the dose applied at sowing was reduced to less than half.

The agronomic efficiency recorded in the response of split application of full dose at sowing and half dose at sowing and the remaining at tillering, increased as the rate increased from 46 to 69 kg N ha^{-1}. However, beyond 69 kg N ha^{-1} applied, showed reduction in agronomic efficiency across all split applications. This might be due to the effect of loss nutrients that the tef crop did not take the applied fertilizer and hence, caused low grain yield.

In general, plots treated with 69 kg N ha^{-1} at two equal splits ($1/_2$ dose at sowing + ½ at tillering) produced high grain and straw yields, coupled with the best economic benefit or profitability. Therefore, this treatment can be suggested for the farmers in the study area instead of using 46 kg N ha^{-1} full dose at sowing or at vegetative growth stage. However, definite recommendation may not be drawn from this research result since it was conducted only for one season. Therefore, the experiment has to be conducted over seasons and locations to make a conclusive recommendation.

6. REFERENCES

Abdo Woyema. 2009. Effect of different rates of nitrogen fertilizer on yield, yield related traits and Quality of durum wheat (*Triticum turgidum* L.var durum). M.Sc. Thesis, Haramaya University, Haramaya, Ethiopia.

Al-Abdul Salam, M. A. 1997. Influence of nitrogen fertilization rates and residual effect of organic manure rates on the growth and yield of wheat. *Arab Gulf Journal of Science Research* 15: 647-660.

Alcoz, M., Frank, M. and Haby, V. 1993. Nitrogen fertilizer timing effect on wheat production, nitrogen uptake efficiency, and residual soil nitrogen. *Agronomy Journal* 85: 1198-1203.

Alizadeh, K, and Ghadeai, J. 2006. Variation of nitrogen uptake efficiency in local landraces of wheat in Mahabad *Iran. Journal of Agriculture and Soc. Sci.,* 18:122–124.

Amanuel Gorfu., Asefa Tana, Tanner, D. G. and Mwangi, W. 1991. On farm research derive fertilizer recommendations for small scale bread wheat production: Methodological issues and technical results. Research Report No. 14. IAR, Addis Ababa, Ethiopia, 37p.

Andrews, M., Lea, P. J., Raven, J. A. and Lindsey, K. 2004. Can genetic manipulation of plant nitrogen assimilation enzymes result in increased crop yield and greater N use efficiency? An assessment. *Annals of Applied Biology* 145:25-40.

Anthony G, Woodard, B and Hoard, J. 2003. Foliar N application timing influence on grain yield and protein concentration of hard red winter and spring wheat. *Agronomy Journal* 95: 335-338.

Arkin, G.F. and Taylor, H.M. 1983. Modifying the root environment to reduce crop stress. *American Society of Agricultural Engineering* 51: 416- 420.

Ashraf, A., Khaid, A. and Ali, k. 1999. Effects of seeding rate and density on growth and yield of rice in saline soil. *Pak. Biol. Sci*., 2(30): 860-862.

Ashraf, M. and Azam, F. 1998. Fate and interaction with soil N of fertilizer ^{15}N applied to wheat at different growth stages. *Cereal Research Communication* 26: 397-404.

Asnakew Woldeab, Tekalign Mammo, Mengesha Bekele and Tefera Ajema. 1991. Soil fertility management studies and wheat in Ethiopia. pp 112-144. *In*: Hailu Gebre-Mariam, D. G. Tanner and Mengistu Hulluka (eds.). *Wheat Research in Ethiopia*. *A Historical Perspective*. IAR, CIMMYT, Addis Ababa, Ethiopia.

Asrat Wondimu and Frew Tekabe. 2001. Utilization of tef in the Ethiopian diet, pp. 239-244. *In*: Hailu Tefera, Getachew Belay and Mark 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.

AUA (Alemaya University of Agriculture). 1994. Forty Years of Research Experience. Debre Zeit Agricultural Research Centre, Debre Zeit, Ethiopia.

Baldock, J., Sadras,V. and Mowat, D. 2003. Nitrogen management for yield and quality.

Bayoumi, TY, El- Demardash. 2008. Influence of nitrogen application on grain yield and end use quality in segregating generations of bread wheat (*Triticum aestivum* L). *Africa. Journal. Biol. Res*., 2: 132-140.

Bekele, HK., Verkuijl, H., Mwangi, W. and Tanner, D. 2000. Adoption of Improved Wheat Technologies in Adaba and Dodola Woredas of the Bale Highlands, Ethiopia. Second National Maize and Wheat Workshop.12-16 November 2000; Addis *Ababa*. International Maize and Wheat Improvement Center) and Ethiopian Agricultural Research Organization (EARO). Addis Ababa, Ethiopia.

Blankenau, K., Olfs, H.W. and Kuhlmann, H. 2002. Strategies to improve the use efficiency of mineral fertilizer nitrogen applied to winter wheat. *Journal Agronomy and Crop. Sci*., 188:146-154.

Borghi, B. 2000. Nitrogen as determinant of wheat growth and yield. *In*: Satorre, E.H., Slafer, G.A. (Eds.), *Wheat Ecology and Physiology of Yield Determination. Food Products* Press, New York, 67-48.

Botella, M.A., Cerda, A.C. and Lips, S.H. 1993. Dry matter production, yield and allocation of carbon-14 assimilate by wheat as affected by nitrogen source and salinity. *Agronomy Journal* 35(5):1044-1049.

Brady, N. C. and Weil, R.R. 2002. The Nature and Properties of Soils. 13th ed. Person Education Ltd, USA.621 pp.

Bruce, R.C., and Rayment, G.E. 1982. Analytical Methods and Interpretation Used by the Agricultural Chemistry Branch for Soil and Land Use Surveys. Queensland Department of Primary Industries. Bulletin QB8, 2004, Indooroopilly, Queensland.

Campbell, C.A., R. P. Zenter, F. Selles and McConkey, B. G. 1993. Available water and nitrogen effects on yield components and grain nitrogen of zero-till spring wheat. *Agronomy Journal* 85: 114-120.

Cassman, K.G. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proc. National Acad. Sci*. (USA) 96: 5952-5959

Cassman, K. G., Dobermann, A. and Walters, D.T. 2002. Agro-ecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* 31(2): 132-40.

Channabasavanna, A. S. and Setty, R. A. 1994. Response of broadcast rice (*Oryza sativa*) to level of nitrogen, phosphorus and potassium and time of N application, *Indian Journal Agronomy* 39(3):457–459.

Charman, P.E.V., ans Roper, M.M. 2007. Soil organic matter. *In soils, Their Properties and Management. 3rd ed.* P.E.V. Charman and B.W.Murphy (eds.) pp 276-285. Oxford University Press, Melbourne Australia.

Chichester, F.W. 1970. Transformation of fertilizer nitrogen in soil. Total and ^{15}N-labelled nitrogen of soil organic mineral sedimentation fractions. *Plant and Soil* 33: 437-456.

CIMMYT. 1988. From Agronomic Data to Farmer Recommendations: An Economics Training Manual. Completely Revised Edition, Mexico, DF.79 pp.

Clark, R. B. 1982. Plant response to mineral element toxicity and deficiency. *In*: *Breeding plants for less favourable environments*, M. N. Christiansen and C. F. Lewis, 71–142. New York: John Wiley & Sons.

Collins, H. P., Delgado, J. A., Alva, A. K. and Follett, R. F. 2007. Use of nitrogen-15 isotopic techniques to estimate nitrogen cycling from a mustard cover crop to potatoes. *Agronomy Journal 99*: 27–35.

Costanza, S.H., DeweJ, M. T. and Harlan, J.R. 1979. Literature review and numerical taxonomy of *Eragrostis tef* (Tef). *Economic Botany* 33 (4): 413-424.

Costanza, S.H., DeWet, J.M.J. and Harlan, J.R. 1980. Literature review and numerical taxonomy of *Eragrostis tef* (tef). *Economic Botany* 33(4):413-424.

Craswell, E. T. and Godwin D. C. 1984. The efficiency of nitrogen fertilizers applied to cereals in different climates, pp.124-140. *In*: Mengel, K. and E.A. Kirkby, 1996. Principles of Plant Nutrition. Panama Publishing Corporation, New Delhi, India.

CSA. 2012 Central Statistic Authority. Agricultural Sample Survey: report on Area and production of major Crops (Private peasant holdings ''*meher*'' season), Volume I Addis Abeba, Ethiopia.

Damene Darota. 2003**.** Yield response of bread wheat (*Triticum aestivum L.*) to applied levels of N and P Fertilizers. M.Sc. Thesis, Alemaya University, Alemaya, Ethiopia.

Deckers, J., Spaargaren, O. and Nachtergaele, F. 2001. Vertisols: Genesis, Properties and Soils Cape Management for Sustainable Development, FAO, Rome, Italy, 20 pp.

De Datta, S.K. and Patrick, Jr. W. H. 1986. Nitrogen Economy of Flooded Rice Soils. Martinus Nijhoff, The Netherlands. PP. 186.

Dekking, L.S. and Koning, K.F. 2005. The Ethiopian cereal tef in celiac disease.*The New England Journal of Medicine* 353:16.

Desai, R.M. and Bhatia, C.R. 1978. Nitrogen uptake and nitrogen harvest index in durum wheat cultivars varying in their grain protein concentration. *Euphytica* 27:561-566.

Donald, L.S. 2004. Understanding and reducing lodging in cereals. *Advances in Agronomy 84*: 217–271.

El-Karamity, A.E. 1998. Response of some wheat cultivars to seeding and nitrogen fertilization rates. *Environment*. 22: 859-866.

Evans, L.T. 1997. Crop Evolution, Adaptation and Yield 1st ed. Cambridge University Press, New York, Porchester.

Fageria, N. K. and Baligar, V. C. 2001. Lowland rice response to nitrogen fertilization. *Commun. Soil Sci. Plant Anal*. 32:1405–1429.

Fageria, N. K. 2003. Plant tissue test for determination of optimum concentration and uptake of nitrogen at different growth stages in lowland rice. *Commun. Soil Sci. Plant Anal.* 34:259 270.

Fageria, N. K. and Baligar, V. C. 2003. Methodology for evaluation of lowland rice genotypes for nitrogen use efficiency. *Journal Plant Nutrient* 26:1315–1333.

Fageria, N. K. and Baligar, V. C. 2005. Enhancing nitrogen use efficiency in crop plants. *Advanced Agronomy*. 88:97–185.

FAO. 2000. Fertilizers and Their Use 4th ed. International Fertilizer Industry Association, FAO, Rome, Italy.

FAO. 2006. Soil Fertility and Crop Production. Plant Nutrition and Food Security, Rome, Italy 43 pp.

Freney, JR., Smith, Cj. and Mosier, AR. 1992. Effect of a new nitrification inhibitor (Wax Coated Carbide) on irrigated wheat. *Fertilizer Res.* 32: 1-11.

Fufa Hundera. 1998. Variations of morph-agronomic characters and grain chemical composition of released varieties of tef [*Eragrostis tef* (Zucc) Trotter]. *Journal. Genet. & Breed*, 52: 307-311.

Fufa Hundera, Tesfa Bogale, Hailu Tefera, Kebebew Assefa, Tiruneh Kefyalew, Abera Debelo and Seyfu Ketema. 2001. Agronomy Research in tef. *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, pp 167-176

Genene Gezu. 2003. Yield and quality response of bread wheat varieties to rate and time of nitrogen fertilizer application at Kulumsa, southern Ethiopia. MSc Thesis, Alemaya University, Alemaya Ethiopia.

Getachew Fisseha. 2004. Soil characterization and bread wheat (*Triticum aestivum* L.) response to N and P fertilizatoin. MSc Thesis, Alemaya University, Alemaya, Ethiopia.

Gobeze Loha. 1999. Effect of special arrangement and nitrogen fertilizer application on (*Sorghum binocular* L. Moench) and ground nut (*Arachis hypogeal*) intercrop system in Eastern Ethipopia. MSc Thesis, Alemaya University of Agriculture, Alemaya, Ethiopia.

Gomez, K.A. and Gomez, A.A. 1984. Statistical Procedure for Agricultural Research, 2nd ed. John Willey and Sons, New York.

Gooding, M.J., and Davies, W.P. 1997. Wheat Production and Utilization. CAB Int., Wallingford, UK pp. 202-210.

Haftom Gebretsadik, Mitiku Haile and Yamoah, CH. 2009. Tillage frequency, soil compaction and N-fertilizer rate effects on yield of tef (*Eragrostis tef (Zucc.) Trotter). Ethiopia Journal of Science* 1(1): 82-94.

Hailu Tefera, Kebebew Assefa, Fufa Hundera, Tiruneh Kefyalew and Tesfaye Teferra. 2003. Heritability and genetic advance in recombinant inbred lines of tef (*Eragrostis tef*). *Euphatica*, 131: 91-96.

Hailu Tefera and Seyfu Ketema. 1990. Variability and genetic advance in tef *(Eragrostis tef)* cultivars. *Tropical Agriculture* (Trinidad) 67:317-320.

Hailu Tefera and Peat, W.E. 1996. Evaluation of selection methods for grain yield in the F_2 and F_3 generations of tef (*Eragrastis tef*). *Ethiopian Journal of Agricultural Science* 15: 20 –32.

Hansen, KA., Martin, JM, Lanning, SP. and LE, Talbert. 2005. Correlation of genotype performance for agronomic and physiological traits in space-planted versus densely-seeded conditions. *Crop Sci*. 45:1023- 1028.

Hesselbach, D. and Westphal, A. 1976. Effects of fertilization on development, dry matter production and nutrient uptake of tef. pp. 214-225 *In: Proceedings of the Sixth Annual Research Seminar,* 12-14 Nov. 1975, Addis Ababa, Ethiopia, Institute of Agricultural Research (IAR), Addis Ababa, Ethiopia.

Hirel, B., Gouis, J. Le, Ney, B. and Gallais, A. 2007. The challenge of improving nitrogen use efficiency in crop plants: towards a more central role for genetic variability and quantitative genetics within integrated approaches. *Journal of Experimental Botany* 58: 2369-2387.

Huber, D. M. and Thompson, I. A. 2007. Nitrogen and plant disease. *In*: *Mineral Nutrition and Plant Disease*, L. E. Datnoff, W. H. Elmer, and D. M. Huber (eds) 31–44. St. Paul, MN: The American Phytopathological Society.

IAEA. 2000. International Atomic Energy Agency. Optimizing Nitrogen Fertilizer Application to Irrigated Wheat, IAEA-TECDOC-1164, IAEA, Vienna.

IAEA. 2003. International Atomic Energy Agency. Integrated soil, water, and nutrient management in conservation agriculture (Rep. Cons. Mtg, Foz de Iguaçu, Brazil), IAEA-311-03CT06055, IAEA, Vienna.

IAR . 1975. Institute of aIAgricultural Research. Hand book on crop production in Ethiopia. IAR, Addis Ababa, Ethiopia.

Ingram, A. L. and Doyle, J. J. 2003. The origin and evolution of *Eragrostis tef* (Poaceae) and related polyploids: Evidence from the nuclear *waxy* and plastid *rps*16. *American Journal of Botany* 90: 116-122.

IRRI. 1990. Annual report. International rice research institute, Lose Banos, Philippines.

Jackson, M. L. 1973. Soil Chemical Analysis. Prentice Hall Grice. Englewood Cliffs, USA. 284pp.

Jeremy, L. 2007. Nitrogen management for wheat protein and yield in the Esperance Port Zone. State of Western Australia, p 14-20.

Johnston, A. E. 1994. The efficient use of plant nutrients in agriculture. IFA, Paris, France.

Kebebew Asefa. 1991. Effects of some synthetic plant growth regulators on lodging and other agronomic and morphological characters of tef [*Eragrostis tef,* (Zucc.) Trotter]. M.Sc. Thesis, Alemaya University of Agriculture, Alemaya, Ethiopia.

Kebede Hankasa, Johnson Nur and Ferris, D.M. 1989. Photosynthetic response of tef [*Eragrostis tef* (Zucc) Trotter] to temperature. *Physiol. Plant* 77: 262-266.

Kenea Yadeta, Getachew Ayele and Workneh Negatu. 2001. Farming Research on Tef: Small Holders Production Practices. *In*: Hailu Tefera, Getachew Belay and M. Sorrels (eds.), *Narrowing the Rift: Teff Research and Development. Proceeding* of the International Work shop on tef genetics and improvement, 16-19 October, 2000, Addis Ababa, Ethiopia, pp 9-23.

Kumar, K. and Rao, K. V. P. 1992. Nitrogen and phosphorus requirement of upland rice in Manipur. *Oryza*. 29:306-309.

Landon, J.R. 1991. Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Sub-tropics. Longman Scientific and Technical, Essex, New York. 474 pp.

Legesse Amsalu. 2004. Response of tef [*Eragrostis tef* (Zucc.) Trotter] to applied nitrogen and phosphorus in Sirinka, North Eastern Ethiopia. MSc Thesis, Alemaya University, Alemaya, Ethiopia.

Legg, J.O. and Meisinger J.J. 1982. Soil nitrogen budgets Nitrogen balance, and cycle. *Agronomy ASer Monogr Am Soc Agron, Madison*, 566p.

Limaux, F., Recous, S., Meynard, J.M. and Guckert, A. 1999. Relationship between rate of crop growth at date of fertilizer N application and fate of fertilizer N applied to winter wheat. *Plant Soil Nutrition* 214: 49–59.

Limon-Ortega, A., Sayre, KD. aand Francis, CA. 2000. Wheat nitrogen use efficiency in a bed planting system in Northwest Mexico. *Agronomy Journal* 92: 303-308.

Lopez-Bellido, L., Lopez-Bellido, R.J. and López-Bellido, F.J. 2005. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. *Field Crops Res.* 94: 86-97.

Lory, J. A., Randall, G. W. and Russelle, M. P. 1995. Classification system for factors affecting crop response to nitrogen fertilization. *Agronomy Journal 87: 869-76.*

Marschner, H. 1995. Mineral Nutrition of Higher Plants. 2nd ed. Academic Press, London.783p.

Mekonnen Asrat. 2005. Response and uptake of barley (*Hordem Vulgarae L*.) to different rates of ORG- Pand N fertilizer. MSc Thesis, Alemaya University, Alemaya, Ethiopia.

Melesse Harfe .2007. Response of bread wheat (*Triticum aestivum* L.) varieties to N and P fertilizer rates. M.Sc. Thesis, Haramaya University, Haramaya, Ethiopia.

Mengel, K. and Kirkby, E. A. 1996. Principles of Plant Nutrition, Panimo Publishing Corporation, New Delhi, India. 314pp.

Mengel, K. and Kirby, E.A. 2001. Principles of Plant Nutrition. 5thed. Kluwer Academic Publishers, Dordretcht, the Netherlands. 849 pp.

Michael, J., Ottman, T., Doerge, A., Edward, C. and Martin, E. 2000. Durum grain quality as affected by N-fertilizer near anthesis and irrigation during grain fills. *Agronomy Journal* 92: 1035-1041.

Miller, R.W. and Donahue, R.L. 1995. Soils In Our Environment. 7th ed. Prentice-Hall Englewood Cliffs, New Jersey, USA.

MoARD. 2008. Ministry of Agriculture and Rural Development. Crop Variety Register, Animal and Plant Health Regulatory Directorate, Addis Ababa, Ethiopia, June 2008.

Mohammad, T. MD., Jamal Khan, Khan, AD., Arif MD., DD. Jan,. Saeed MD and Zahir Afridi, MD. 2011. Improving wheat productivity through source and timing of nitrogen fertilization. *Journal Bot*. 43(2): 909 -911, Pakistan.

Murage, E. W.; Karanja, N. K.; Smithson, P. C. And Woomer, P. L. 2000. Diagnostic indicators

of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands, *Agriculture, Ecosystems and Environment* (79): 1-8.

Muurinen, S. 2007. Nitrogen dynamics and nitrogen use efficiency of spring cereals under Finnish growing conditions. *Yliopistopaino*, 29: 1-38.

National Academy of Sciences. 1996. Lost crops of Africa Volume 1, Grains. Bostid National Research Council. National Academy Press. Washington, D.C, USA.

Newbould, P. 1989. The use of nitrogen fertilizer in agriculture. Where do we go practically and ecologically? *Plant Soil* 115:297–311.

Okamoto, M. and Okada K. 2004. Differential responses of growth and nitrogen uptake to organic of nitrogen four gramineous crops. *Journal. Exp. Bot.* 55 (402): 1577 – 1585.

Olsen, S. R., Cole C. W., Watanabe, F.S. and Dean, L.A. 1954. Estimation of available phosphorous in soils by extraction with sodium bicarbonate Circular 939, US. Department of agriculture.

Ortiz-Monasterio, J.I., Sayre, K.D., Rajaram, S. and McMahon, M. 1997. Genetic progress in wheat yield and nitrogen use efficiency under four N rates. *Crop Sci*. 37(3): 898-904.

Ozen, H.C. and Onay, A. 2007. Plant Physiology. Nobel Press, p. 1220. Pollmer WG, Eberhard D, Klein D, Dhillon BS. 1979. Genetic control of nitrogen uptake and translocation maize. *Crop Sci*. 19: 82-86.

Page, A.L. 1982. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. Madison, USA.

Panda, S. C., Panda, P. C. and Nanda, S. S. 1995. Effect of level of N and P on yield and nutrient uptake of rice. *Oryza*, 32:18-20.

Pinthus. 1973. Lodging in wheat barley, and oats: The phenomenon, it causes, and preventive methods. *Advances in Agronomy* 25:209-263.

Prasad, R. and Power, JF. 1995. Nitrification inhibitors for agriculture, health and the environment. *Advanced Agronomy* 54: 233-281.

Reddy, M.S. and Kidane, G. (eds.).1991. Development of Technologies for the Dry Land Farming Areas of Ethiopia, Nazret, Ethiopia.

Reinke, R. F., Lewin, L. G. and Williams, R. L. 1994. Effect of sowing time and nitrogen on rice cultivars of differing growth duration in New South Wales. Yield and yield components; *Australian Journal of Experimental Agriculture* 34(7):933–938.

Ren, L, J. Ma, Zhang, R. 2003. Estimating nitrate leaching with a transfer function model incorporating net mineralization and uptake of nitrogen. *Journal Environ. Qual*. 32:1455-1463.

Sage, RF. and Pearcy, R.W. 1987. The nitrogen use efficiency of C3 and C4 plants. *Plant Physiol.* 84: 954-958.

Samtsevich, S.A. 1968. Methods of productivity studies root systems and rhizosphere organisms. *Acad. Sci*., USSR, 200p.

SAS. 2002. SAS/STAT User's Guide, Version 9.1.3. SAS institute Inc., Cary, NC.

Schmied, B., Abbaspour, K, and Schulin, R. 2000. Inverse estimation of parameters in a nitrogen model using field data. *Soil Sci. Soc. Am. Journal* 64:533–542.

Semenov, M.A., Jamieson, P.D. and Martre, P. 2007. Deconvoluting nitrogen use efficiency in wheat: *A simulation study. Eur. Journal Agronomy* 26:283-294.

Sewnet Ashebir. 2005. Effects of nitrogen and seed rates on grain yield components and nitrogen uptake of rain-fed rice (*Oryza sativa*) in Fogera, South Gonder. MSc Thesis, Alemaya University, Alemaya, Ethiopia.

Seyfu Ketema. 1983. Study of lodging, floral biology and breeding techniques in tef [*Eragrostis tef* (Zucc) Trotter] PhD Thesis. University of London, London, United Kingdom.

Seyfu Ketema. 1991. Germplasm evaluation and breeding work on tef in Ethiopia. Cambridge University of press. Cambridge, England.

Seyfu Ketema. 1993. Phenotypic Variations in Tef (*Eragrostis tef*) Germplasm-Morphological and Agronomic Traits. A catalog. Technical manual No. 6. Institute of Agricultural Research.Addis Ababa, Ethiopia.

Seyfu Ketema. 1993. Tef [*Eragrostis tef (Zucc.)* Trotter]. 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. Biodiversity institute Addis Ababa, Ethiopia

Singh, A. K., Thakur, S. and Singh, S. K. 1995. Response of rice to nitrogen and zinc application in calcareous situation; *International Rice Research Institute Notes* 20(2):16–17.

Slanger, J.H.G. and Kerkhoff, P. 1984. Nitrification Inhibitors in agriculture and horticulture. *Fertilizer Res*., 5: 77-98.

Sowers, KE., Pan WL, Miller, BC and Smith, JL. 1994. Nitrogen use efficiency of split nitrogen applications in soft white winter wheat. *Agronomy Journal* 86: 942-948.

Stanford, G., Legg, J.O. and Chichester, F.W. 1970. Transformation of fertilizer nitrogen in soil. Interpretations based on chemical extraction of labeled and unlabelled nitrogen. *Plant and Soil* 33: 425-435.

Stevenson, F. J. 1982. Origin and distribution of nitrogen in soil. *In*: *Nitrogen in agricultural soils*, F. J. Stevenson 1–42. Madison, WI: ASA, CSSA, and SSSA.

Tadesse Ebba. 1975. Tef (*Eragrostis tef*) cultivars: Morphology and Classification, Part II. Experimental Station Bulletin 66, Addis Ababa University, College of Agriculture, Dire Dawa, Ethiopia. 73pp.

Talawar, S. and Rhoades, R.E. 1998. Scientific and local classification and management of soils. *Agriculture and Human Values* 15: 3-14.

Tams, A. R., Mooney, S. J, and Berry, P. M. 2004. The effect of lodging in cereals on morphological properties of the root-soil complex. Super Soil, 3rd Australian New Zealand Soils Conference, 5-9 December 2004, University of Sydney, Australia.

Tanaka, K., Kasai, Z. and Ogawa, M. 1995. Physiology of ripening. pp.97-118. *In*: T. Matsuo, K. Kumazawa, R. Ishii, K.Ishihara, and H. Hirata, (eds) .*The Science of the Rice Plant*. Vol. 2. Food and Agriculture Policy Research Center, Tokyo.

Tekalign Mammo, Teklu Erkossa and Balesh Tulema. 2001. Soil Fertility and Plant Nutrition Research on Tef in Ethiopia. pp. 199-200. *In:* Hailu Tefera, Getachew Belay and Mark 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, pp 167-176.

Temesgen Kassahun. 2001. Effect of sowing date and nitrogen fertilization on yield and related traits of tef [*Eragrostis tef* (Zucc.) Trotter] on Vertisols of Kobo area, Northern Wollo. MSc Thesis, Alemaya University, Alemaya, Ethiopia.

Tenaw Werkayehu. 2000. Effect of nitrogen fertilizer rates and plant density on grain yield of maize. *African Crop Sci. Journal* 8:273-282.

Tilahun Geleto, Tanner, D.G., Tekalign Mamo and Getinet Gebeyehu. 1996. Response of rainfed bread and durum wheat to source, level and timing of nitrogen fertilizer at two Vertisol sites in Ethiopia. pp. 127-147. *In: Proceeding the Ninth Regional Wheat Workshop for Eastern, Central and Southern Africa*. Addis Ababa, Ethiopia, CIMMYT.

Tisdale, S.L., Nelson, W.L., Beaton, J.D. and Havlin, J.L. 1995. Soil Fertility and Fertilizers. 5th ed., Macmillan, New York,USA.

Tolessa Debele, Gemechu Gedeno and Melakeselam Leul. 1994. Response of maize to split application of nitrogen fertilizer at Bako. *Sebil* 6:56-60.

Vavilov, N.I. 1951. The origin, variation, immunity and breeding of cultivated plants. *Chronica Bot*.13:1-351.

Warraich, EA, Ahmad, N. S.M.A Basra, and Afzal, I. 2002. Effect of nitrogen on source–sink relationship in wheat. Int. *Journal*. *Agri. Biol*. 4: 300–302.

Woldeyesus Sinebo., Gretzmacher, R. and Edelbaue, A. 2004. Genotypic variation for nitrogen use efficiency in Ethiopian barley. *Field Crops Res.* 85: 43-60.

Wuest, S. B. and Cassman, K.G. 1992. Fertilizer nitrogen use efficiency of irrigated wheat. Uptake efficiency of pre-plant versus late season application. *Agronomy Journal* 84:682-688.

Yang, J., Zhang, Z., Huang, Q. and Zhu L. 2000. Remobilization of carbon reserves is improved by controlled soil-drying during grain filling of wheat. *Crop Sci*. 40: 1645-1655.

Yildirim, M., Akinci, C; Koc, M. and Barutcular, C. 2009. Applicability of canopy temperature depression and chlorophyl content in durum wheat breeding. *Anadolu Journal Agric. Sci*. 24(3):158.

Zafar, J. and Muhammad, F. C. 2007. Effects of soil and foliar application of different concentrations of NPK and foliar application of $(NH_4)_2so_4$ on growth and yield attributes in wheat (*Triticum aestivum*. L). *Pak. Journal. Pl. Sci.* 13 (2): 119-128.

Zahran, M., Mosalem, M. E., El-Menofi, M.M. and Moussa, A. M. 1997. Effect of sowing date, seeding rate and nitrogen level on wheat production: growth and growth attributes. First Annual Conference. September 1-3, NRC, Egypt.

Zeidan, M.S., Amany, A., Baher M.F. El-kramany. 2006. Effect of N fertilizer and plant density on yield and quality of maize in sandy soil. INS Inet Publication. 2(4):156-161.

Zhao, RF., Chen, XP; Zhang, FS; Zhang, H; Schroder, J. and Romheld, V. 2006. Fertilization and nitrogen balance in a wheat-maize rotation system in North China. *Agronomy Journal* 98: 935-945.

7. APPENDICES

Appendix 1. Soil physical and chemical properties of the study area

pH H_2O (1:2.5)	EC (mS/cm)	CEC & Exchangeable Bases (cmol (+)/Kg Soil)					Total N (%)	Organic (%)	Available P (mg/Kg)	Texture			
		CEC	Ca	Mg	Na	K				Clay (%)	Silt (%)	Sand (%)	Soil Class
7.16	0.14	69.22	39.80	15.92	0.47	1.64	0.15	2.82	55.78	65	32	3	Clay

Appendix 2. Mean square values of phenology, lodging and growth parameters of tef as influenced by N rate and timing of application

Source of variation	Degrees of freedom	Days to panicle emergence	Lodging percentage	Plant height	Number of effective tillers
Replication	2	6.0222ns	12.183ns	14.132*	4.067ns
Rate	2	5.9556*	148.292**	67.385**	94.867**
Timing	4	8.1333**	85.318**	15.600*	21.278*
Rate*Timing	8	6.4833**	34.639**	11.256*	18.478*
Error	28	0.9508	5.716	4.222	4.329

Where, ** = highly significant; * = significant; ns = Non-significant

Appendix 3. Mean square values of yield and yield components of tef as influenced by N rate and timing application.

Source of variation	Degrees of freedom	Grain yield	Biomass yield	Straw yield	Main panicle Seed weight	Harvest index
Replication	2	139485*	1550441*	784043*	7.6222*	0.0001093ns
Rate	2	438163**	5765525**	3059350**	12.0222**	0.0002351ns
Timing	4	226330**	1724878**	1069550**	4.8556*	0.0004541*
Rate*Timing	8	65704*	2005114**	1209641**	5.4389**	0.0006784**
Error	28	16626	162133	98321	0.9079	0.0001057

Appendix 4. Mean square values of days to maturity, panicle length and thousand seed weight of tef as influenced by N rate and timing of application

Source of variation	Degrees of freedom	Days to maturity	Panicle length	Thousand seed weight
Replication	2	12.067ns	5.02ns	0.000635*
Rate	3	978.017**	120.36**	0.003903**
Timing	4	5.642ns	5.64ns	0.000933**
Error	38	5.084	3.159	0.000159

Where, ** = highly significant; * = significant; ns = Non-significant

Appendix 5. Mean square values of shoot N concentration and nitrogen uptake of tef as influenced by N rate and timing of application.

Source of variation	Degrees of freedom	GN%	SN%	GNU	SNU	TNU	APRN	AE	PE
Replication	2	0.010702*	0.005496ns	37.143*	35.63ns	145.47*	33.931*	0.09954ns	51.81ns
Rate	2	0.101882**	0.086709**	134.860**	218.99**	679.71**	451.549**	102.54629**	7636.00**
Timing	4	0.016928**	0.033764**	36.602**	73.17**	159.84**	360.854**	62.76747**	1786.79**
Rate*Timing	8	0.016129**	0.014039*	16.969*	40.44*	85.86*	183.125**	22.95065**	2681.18**
Error	28	0.001581	0.003817	4.003	12.21	22.12	7.775	0.06582	31.52

Where, GN = nitrogen concentration in grain at physiological maturity

SN = nitrogen concentration in straw at physiological maturity

GNU = grain nitrogen uptake

SNU = straw nitrogen uptake

TNU = total nitrogen uptake

APRN = apparent nitrogen recovery

AE = agronomic efficiency

PE = physiological efficiency

** = highly significant, * = significant, ns = Non-significant