Optimization of productivity and quality of irrigated tomato (*Solanum lycopersicum* L.) by smallholder farmers in the Central Rift Valley area of Oromia, Ethiopia

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Thesis

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Abstract

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Tomato (*Solanum lycopersicum* L.) is a vegetable crop with high potential to contribute to poverty reduction via increased income and food security. It is widely grown by smallholders, has high productivity and its demand is increasing. Ethiopia produced about 30,700 Mg of tomatoes on 5,027 ha annually in 2014/2015. Average yields are only 6.1 Mg ha^{-1}, below the world average yields. There is both a need and a potential to increase tomato production per unit area.

The aim of this thesis is to analyze the irrigated tomato production systems of smallholder farmers in Ethiopia, to survey and characterize the tomato in selected ecoregions and seasons, and to identify yield-limiting or yield-reducing factors and opportunities to enhance yield by using a combination of surveys and field experiments. Field experiments on optimization of yield and quality of field-grown tomato were carried out at Ziway, Ethiopia, for two seasons to study the impact of different irrigation practices applied, based on local empirical practices, deficit irrigation, or crop water requirement.

This thesis begins with a survey of tomato production systems. The survey details the area and production in various zones and for each of these zones yield-determining, yield-limiting, and yield-reducing factors and opportunities for improving yield and quality are indicated. It also avails area, production and yield data for each growing season and typifies the production systems in these zones. Low temperature (cold) from October-January and shortage of improved seeds are recognized as yield-determining factors, whereas insufficient water and nutrient (fertilizer) supply proved to be yield-limiting factors across zones. Late blight (*Phytophthora infestans*), Fusarium wilt (*Fusarium oxysporum*) and different pests and weeds are identified as yield-reducing factors in the zones. Experienced growers who have access to extension service recorded significant yield increment. Farmers Research Groups improved actual average yield with the use of improved technology

(improved varieties and quality seed), and better efficiencies of water and fertilizer use. This study quantified influences of irrigation systems and strategies on growth-determining tomato features. Variation in irrigation systems and strategies accounted for variation in growth and dry matter accumulation. Greater performance for yield-related traits was obtained with drip irrigation based on crop water requirement for tomato varieties. Examination of plants showed also that local empirical irrigation is responsible for the occurrence of Phytophthora root rot, whereas deficit irrigation proved cause for occurrence of Fusarium wilt (*Fusarium oxysporum*), blossom end rot and broome rape (*Orobanche ramosa*) on roots or leaves, stems or fruits.

The experiments on irrigation scheduling with different irrigation systems and strategies gave useful indications on the possibility to improve commercial yield (CY) and water use efficiency. Promising results on CY and agronomical water use efficiency of tomato were achieved with drip irrigation based on crop water requirement, while for the biological water use efficiency higher value was obtained with deficit drip irrigation in both seasons. The findings indicate that the CY was decreased significantly for deficit by 50% in drip irrigation and deficit by 50% in furrow irrigation in both seasons. Mean CY for drip irrigation according to crop water requirement increased by 51% and 56% compared with deficit drip irrigation, whereas furrow irrigation based on crop water requirement increased by 52% and 54% compared with deficit furrow in Experiments 1 and 2, respectively. However, water use efficiency decreased with the increasing water volume.

Simultaneous measurements of rate of photosynthesis based on gas exchange measurements and the thylakoid electron flux based on chlorophyll fluorescence were used to investigate physiological limitations to photosynthesis in leaves of deficit irrigated tomato plants under open field situations. Combined leaf gas exchange/chlorophyll fluorescence measurements differentiated the treatments effectively. Reduction in rate of photosynthesis, stomatal conductance and the maximum quantum efficiency of photosystem II varied across seasons of all varieties, whereas leaf temperature was increased by deficit irrigation in all varieties. Among varieties studied, Miya was found relatively tolerant to deficit irrigation. Stomatal limitation of rate of photosynthesis increased significantly as a result of water stress suggesting a strong influence of the stomatal behaviour.

We also determined the influence of irrigation systems and strategies on water saving and tomato fruit quality. Using deficit drip irrigation was the best management strategy to optimize water use and tomato quality. Fruit dry matter content, acid content and total soluble solids were significantly higher with deficit drip irrigation than with other treatments.

From this thesis it appeared that agro-climatic conditions, access to resources and culture all contribute to the relatively low yields of tomato in the Central Rift Valley of Ethiopia. The thesis also proved that significant advances can be made in yield, quality and resource use efficiency.

Keywords: Chlorophyll fluorescence, Ethiopia, gas exchange, irrigation, photosynthesis, quality, smallholders, survey, tomato, water use efficiency, yield.

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Chapter 1

General introduction

Agriculture is the mainstay for growth of the economy and food security of Ethiopia. It directly supports 80% of the population's livelihoods, provides 47% of the Gross Domestic Production, and accounts for more than 80% of the country's export value (AfDB, 2009; FAOSTAT, 2009). Ethiopia has a surface water potential of 104,300 million m^3/ha with a total irrigable area of 3.7 million ha. The estimated number of smallholders engaged in irrigated crop production in Ethiopia is about 6 million (Joosten *et al*., 2011). The irrigated crop production by smallholders accounted for 0.38 million ha (10.8%) of the total irrigable land (Awulachew *et al*., 2007; Hagos *et al*., 2009). During 2006 over 790 smallholders' irrigation schemes existed in Ethiopia (Awulachew *et al*., 2007). Smallholders' irrigation schemes in Ethiopia are defined as traditional irrigation users which share a main or a branch canal, grouped into 20-30 growers each possessing a farm size of 0.25 to 0.50 ha. Other growers using rain water harvesting, treadle or small diesel driven pump water diversions, a small bucket or drip systems, or small sprinkler systems are all categorized under this scheme (MoWR, 2002; Awulachew *et al*., 2005).

Smallholder production is based on low-input/low-output production systems; it is constrained by limited use of improved seed, chemical fertilizers, biocides, irrigation, new production technology and credit facility. As a result, average yields realized by these smallholders are well below that of the medium and large-scheme producers. Irrigation is one way by which productivity can be improved to meet the increasing food demand of Ethiopia (Van den Berg and Ruben, 2006). The country cannot assure food security for the increasing population with rain-fed crop production alone; it needs a substantive contribution from irrigated agricultural production (Tesfaye *et al*., 2008). Although abundant rainfall and water resources are present in some parts of the country (with 24% of the area and 43% of the population), larger parts (with 76% area and 57% of the population) show moisture-deficit with low productivity (Awulachew *et al*., 2010). These areas are limited by less or no access to production technology, poor rural infrastructure and market access, lack of technological innovations, persistent rural poverty, and increasing population pressure resulting in a vicious circle of poverty and environmental degradation (Van den Berg, 2006; Awulachew *et al*., 2005). These constraints are also valid for smallholder tomato growers in Ethiopia despite the fact that there is some regional export of tomato (cf. Wiersinga and De Jager, 2009). This thesis presents the results of survey work and field experimentation that aimed at identifying actual yield-limiting or yield-reducing factors and opportunities to enhance crop yield and quality.

Irrigation and food insecurity

Irrigation continues to expand globally because the growing global economy and world population are placing greater demands on irrigated agriculture to provide food, feed, fuel and fibre (FAO, 2012). Global warming and resulting drought are important constraints affecting crop production in water-scarce regions (Sezen *et al*., 2010). In Ethiopia, lack of irrigation infrastructure and a lack of institutional capacity limit food security (Stokes *et al*., 2010). Nevertheless, Ethiopia's Gross Domestic Production is strongly connected to agricultural exports. Consequently the country's economy is tightly dependent on rainfall. In most parts of Ethiopia, production from rain-fed agriculture strongly fluctuates due to erratic rainfall which is unpredictable both in amount and distribution causing crop failure and chronic food insecurity.

In Ethiopia, climate change and population growth may pose additional stressors to water availability. Webb and Von Braun (1994) estimated that a 10% decline in rainfall below the long-term national average would result in a fall in all cereal yields by an average of 4.2%. Besides, about 76% of the area inhabiting 57% of the population has been identified as moisture deficit and food insecure zones (Awulachew *et al*., 2010).

Ethiopia with a population of 84.7 million and an economic growth rate of 3.2% per year (AfDB, 2011), faces a food deficit of up to 6.5 million Mg annually. The food deficit is even present if the rain-fed seasons are at their best (Yenesew *et al*., 2010). To sustain this alarmingly growing Ethiopian population, agricultural production will need to increase. Yet the proportion of fresh water available for agriculture is decreasing as the allocation of water to hydropower, industry and domestic uses increases (Keller *et al*., 2000).

Irrigation is a means by which productivity can be increased to meet the increasing food demand (Van den Berg and Ruben, 2006). The goal of irrigated agriculture is to increase household income via diversified agricultural livelihoods and enhancing the contribution of crop production to the livelihood of the people. Irrigated crops of smallholders provide cash income for the growers (IFAD, 2005; Tesfaye *et al*., 2008). Properly managed irrigation can increase crop yields, reduce risks associated with agriculture, increase product quality, minimize pest pressures, and correctly deliver and manage nutrients as irrigation management is specific to each crop (USDA, 2001). However, lack of efficient use of available water amplifies food insecurity (Yenesew *et al*., 2010). Ethiopia has not adopted irrigation and storage of water techniques on any significant scale, and is therefore struggling with economic water scarcity (Stokes *et al*., 2010). To cope with the decreasing water resources it seems crucial to look for options in optimal use of the available water. Successful irrigation implementation is recommended as a means to overcome food insecurity. Effective management of irrigation water resources is of paramount importance in optimizing crop yield and quality.

Irrigated tomato production by smallholders in Ethiopia

The cultivated tomato (*Solanum lycopersicum* L.), originally confined to the Peru-Ecuador area, was transported from Peru to Europe in 1535 (Humboldt, 1811; Sabine, 1819; de Candolle, 1884; Muller, 1940a, b; Luckwill, 1943a, b; cf. Jenkins, 1948). After spreading north possibly as a weed in pre-Columbian times it was not extensively domesticated until it reached Mexico, and from there the cultivated forms were disseminated to Europe and other parts of the world (Jenkins, 1948). Tomato is among the top list of major, most popular vegetable crops with a role in food security, human nutrition and national economy of a large number of countries (Benton, 2008), with a yearly production of over 145.8 million Mg on over 4.3 million ha (FAOSTAT, 2010). It is very versatile and the crop can be divided into fresh market and processing (canning industry and mechanically harvested) tomatoes. Tomatoes are a good source of lycopene, vitamins A and C. Lycopene is a very powerful antioxidant which can help prevent the development of many forms of cancer (Trinklein, 2010).

Tomato production has a long history in Ethiopia; it dates back to the period of Italian exploration from 1935-1940 (Samuel *et al*., 2009). Yet, average yield of tomato is low ranging from 6.5 to 24.0 Mg ha^{-1} and varying across production zones (Gemechis *et al*., 2012). Reported average farmer yields ranged from 7.0 until 14.6 Mg ha^{-1} for the years 2001-2010 (CSA, 2001-2010), whereas the average yields were 51, 41, 36, 20 and 34 Mg ha^{-1} in America, Europe, Asia, Africa and the entire world, respectively (FAOSTAT, 2010). The crop is grown between 700 and 2000 m a.s.l. experiencing warm and dry days and cooler nights for optimum growth and development (Dessalegn, 2002). However, because of their livelihood needs, growers are forced to grow the crop in marginal (arid and semi-arid) areas where shortage of water is common (Cherinet, 2011).

In Ethiopia, the area cropped with tomato has increased to about 5,027 ha with a production of 30,700 Mg until 2014. The production takes place by smallholder farms and medium and large-scale farms (CSA, 2014/2015). The crop provides both food and income.

Tomato is used in a variety of dishes in raw, cooked and processed form. Tomato products include tomato paste, juice, ketchup, and whole peel tomatoes. The latter are produced for both export and local markets for salad and local sauce (Dessalegn, 2002).

Table 1.1. Land use and area and production of different crops in Ethiopia

Land use[a]		**Area**
Total area		1,104, 300 km^2
Land area		1,000,000 km^2
Water area (Swamp and marsh, Lakes and rivers, etc.)		104,300 km^2
All crop area		13,574,721 ha
Fallow land		615,139 ha
Grazing land		1,708,624 ha
Wood land		231,965 ha
Other land use		1,310,055 ha
All land use		19,721,352 ha
Crop[b]	**Area (ha)**	**Production (Mg)**
Cereals	10,152,015	23,607,662
Pulses	1,558,422	2,671,834
Oil seed crops	855,763	760,099
Root & tuber crops	216,971	5,461,554
Vegetables	139,717	595,400
Perennial crops (fruits, coffee)	651,833	1,126,629
Tomato	5,027	30,700

Data (a) from (CSA, 2014/2015: Vol. IV; CSA, 2014/2015) and (b) from (CSA, 2014/2015: vol. III, V, VII).

Irrigation management and irrigated tomato production by smallholders

Proper use of irrigation water is increasingly crucial for increasing productivity and saving water in areas of water scarcity. Because irrigation and fertilizer application are linked in tomato production systems, efficient irrigation management is needed in order to avoid nitrate leaching, groundwater pollution and wastage of water (Hochmuth and Cordasco, 2000). In Ethiopia, semi-modern smallholder irrigation development started several decades ago in response to droughts and food insecurity. However, furrow irrigation is the most widely used system in Ethiopia and is characterized by low efficiencies and high labour and pumping costs (Yohannes and Tadesse, 1998). In furrow irrigation, loss of applied irrigation water during the transport from reservoir to the field under unlined irrigation system is 71% (Navalawala, 1991). Such a huge water loss causes abundant nutrient loss via seepage or percolation. Assessment of irrigation efficiencies in the Central Rift Valley of Ethiopia showed an irrigation efficiency of 35% implying high conveyance losses throughout the conveyance network. Smallholders usually use a furrow irrigation system with unlined canals or with unlined storage ponds resulting in higher water loss via percolation (Bekele and Tilahun, 2006).

Growth and development of fleshy fruit vegetables including tomato are largely dependent on water (Jones and Tardieu, 1998), their yield and quality greatly influenced by water (Amjad *et al*., 2007). Low yields have been recorded in most tomato growing areas of Ethiopia due to its low efficiency, for example, a deep percolation loss of 70% in tomato fields argued in Dire Dawa area, Eastern Ethiopia (Bekele and Tilahun, 2006). Contrary to this, drip irrigation is rarely used although considered to have merits over the former systems by increasing yield up to 19%. This is because of reduced evaporation and deep percolation, controlled soil water content and eliminated effects of wind (Theodore, 1980; Sanders *et al*., 1989; Pruitt *et al*., 1989; Kadam, 1993; Tan, 1995), and increased water use efficiency of tomato by 20% over furrow (Pruitt *et al*., 1989).

Nowadays, smallholders are faced with poverty and food insecurity largely related to climate changes. The longer the irrigation period practised by smallholder growers, the greater is the irrigation water distribution variability due to underlying soil characteristics, variations in land use and in cultivation practices and poor irrigation technology. Growers have been using furrow irrigation at 3-4 and 7 days interval during vegetative and fruit ripening stages, respectively, in Batu (Ziway) while 3-5 days interval until three weeks after planting and every week subsequently in Awash Malkassa (Dessalegn, 2002). Such variable irrigation management in the same ecology may contribute to the poor and varied yield levels.

Deficit irrigation as a means to save water and improve tomato quality

Deficit irrigation (DI) is an irrigation practice by which the amount of supplementary water applied as irrigation is reduced to only a fraction of potential evapotranspiration from well-watered reference crop (ETcrop). DI is an optimizing strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction (English and Raja, 1996). It is a feasible water-saving irrigation strategy for areas with limited water supply (Zegbe-Domínguez *et al*., 2003; Kang and Zhang, 2004). The saved water can be used in irrigating other crops, and such an innovative concept has been named DI (English *et al.*, 1990). DI will play an important role in farm-level water management strategies, with consequent increases in the output generated per unit of water used in agriculture (Geerts and Raes, 2009).

The increasing shortage of water resources worldwide requires optimization of irrigation management in order to improve water use efficiency (WUE) (Liu *et al*., 2006). Water management strategy during growing period can influence savings of water, quality as well as yield of irrigated tomatoes. Although subsurface drip irrigation is used on processing tomato acreage, Chan *et al*. (2001) ascribed this technology as useful for fine and coarse textured soils that are difficult to irrigate with furrow and sprinkler systems. The challenge tomato growers are facing is to optimize WUE, yield and fruit quality through proper water management strategy. However, it is unclear which way of water management strategy would optimize WUE, yield and quality of fruit using drip and furrow irrigation in Ethiopia. Although optimum yields have been obtained by drip irrigation (Phene, 1999), the gain in yield can be offset by lower fruit quality than is obtained with furrow and sprinkler irrigation. Many studies have shown that the quality of fruit increases when irrigation is terminated early (May and Gonzalez, 1999, 1994; May *et al*., 1990; Lowengart-Aycicegi *et al*., 1999; Murray, 1999).

The most important factor for improving fruit quality is to apply less water than the ETcrop during the growing period. Product quality may increase with proper deficit irrigation management. Several researchers have argued that total soluble solid and acidity content of tomato (Birhanu and Tilahun, 2010), protein content and baking quality of wheat (*Triticum aestivum* L.), fibre length and strength of cotton (*Gossypium hirsutum* L.) and sugar concentration of sugar beet (*Beta vulgaris* L.) and grape (*Vitis vinifera* L) increase under deficit irrigation (Kirda and Kanber, 1998).

Published reports indicate that deficit irrigation strategies can be successfully applied to various vegetable crops, especially to those tolerant to water deficit in order to improve WUE and save water. Nevertheless contrasting results described for the same species suggest that a better understanding is required on how variety, or soil features affect plant responses to water deficit. Better knowledge on the vulnerability of each trait of plants to water deficits is also crucial in order to set adequate deficit irrigation scheduling. Research on the effects of deficit irrigation on plant performance are also important for tomatoes.

Problem statements

Irrigation management affects both yields and quality (soluble solids) of tomato (Cahn *et al*., 2001; Lowengart-Aycicegi *et al*., 1999; May and Gonzales, 1999; Murray, 1999; Renquist and Reid, 2001). Water shortage is a serious problem threatening agricultural development (Liu and He, 1996). In the coming decades, increasing food production in countries with limited water and land resources is the greatest challenge. Thus, sustainable use of water for agriculture has become a national/global priority, requiring urgent and immediate solutions (FAO, 2012). Water shortage and the increasing competition for water resources between agriculture and other (domestic, industrial, environmental and recreational water) sectors will compel adoption of water saving strategies such as DI concurrently contributing to environmental preservation (Reina *et al*., 2005; Costa *et al*., 2007).

Ethiopian smallholders are exercising more than two tomato growing periods per annum during different seasons of the year, a wet season (high humidity) and a dry season (higher temperatures) resulting in an unbalanced moisture stress with consequent yield-reducing factors. The yield-reducing factors during the dry season often reported include parasitic weed, Fusarium wilt disease, insect pests, and blossom end rot (MARC, 2000; Dessalegn, 2002; Abebe *et al*., 2005; Gebremariam, 2005). The main challenges during the wet season to tomato production in Ethiopia are fungal diseases, non-parasitic weeds and nutrient stresses. These factors are affecting the photosynthetic organs of plants (most often leaves), cause stunted growth and reduced yield and quality (Abate and Ayalew, 1985; Prior *et al*., 1994; Zemichael and Gebremariam, 1994; Hull, 2001; Sahle, 2001; Asgedom *et al*., 2009).

The mean yields of tomato in Ethiopia ranges from 6.5 to 24.0 Mg ha^{-1} (Figs 3.2 and 3.3) which is below the average yields of 51, 41, 36 and 34 Mg ha^{-1} in North America, Europe, Asia and the entire world, respectively (FAOSTAT, 2010). Besides, several researchers reported that blossom end rot resulted from moisture stress combined with poor calcium assimilation and partitioning into fruits (Dekock *et al*., 1979; Tromp and Wertheim, 1980; cf. Dekock *et al*., 1982). Due to the above problems the prevailing tendency in recent years has been towards conversion of surface irrigation to improved irrigation systems and strategies to improve crop yield and quality. However, presently, most growers are not sure about which irrigation system, when and how much water they should apply, and they tend to base irrigation scheduling and amount on empirical experience with the furrow irrigation system. Therefore, it is important to assess the current irrigation management status of irrigated tomato production by smallholders to better understand and determine water management for sustainability of the production system and its economic viability to the growers.

Research questions, objectives and approach of this study

This thesis aims to identify actual yield-limiting or yield-reducing factors and opportunities to enhance crop yield and quality by combined use of survey work and field experimentation. Based on this approach, suitable and specific strategies can be developed to improve tomato WUE, yield and quality. Although other researchers have worked on factors affecting tomato yield and quality, their researches were focused on specific sites in the country (usually the Central Rift Valley). Thus, no attempts have been made to analyse contrasting tomato growing ecoregions' conditions that may limit or reduce yield and quality as well.

The specific research questions are:

1. Are current status and constraints of irrigated tomato by smallholder growers in growing ecoregions of Ethiopia properly characterized for future research and development intervention?
2. Is tomato productivity in growing ecoregions mostly limited by weather conditions or by inadequate management or by both?

3. Do empirical irrigation practices by smallholder growers result in suboptimal yield and quality in tomato growing zones of Ethiopia?
4. How do varying ways of water supply impact on tomato physiological processes and yielding ability in the Central Rift Valley of Ethiopia?
5. Do combinations of irrigation systems and strategies in producing processing or fresh market tomatoes affect yield and quality? Which of the alternative strategies (i.e. based on local empirical knowledge, according to crop water requirement, deficit irrigation) give the optimal combination of yield, quality and water use?

These research questions were related to the following research objectives:

1. To analyze irrigated crop production by smallholders with emphasis on tomato in selected tomato growing zones using published and unpublished sources to identify constraints and opportunities (Chapter 2).
2. To describe the current status and yield constraints of irrigated tomato production systems by smallholders in Ethiopia (Chapter 3).
3. To assess in a mechanistic way which irrigation system and strategy would be best in terms of growth and dry matter partitioning of field-grown tomatoes. (Chapter 4).
4. To compare drip and furrow irrigation practices for their impact on yield-related characteristics and growth components, and the development of disease, blossom end rot and weeds and their effects on fresh market and processing tomatoes (Chapter 5).
5. To design irrigation schedules and assess volume of water used for optimum commercial yield and water use efficiency of tomato by smallholders in the Central Rift Valley area (Chapter 6).
6. To identify the effects of irrigation management practices on physiological changes of fresh market and processing tomatoes in the open field in a semi-arid area of Ethiopia (Chapter 7).
7. To evaluate the deficit irrigation strategy as a means to save water and improve fruit quality under drip and furrow irrigation in fresh market and processing tomatoes (Chapter 8).

Area and production data were obtained from the Central Statistics Agency (CSA, 2001-2010), Ethiopian Institute of Agricultural Research at different locations, Ministry of Agriculture at regional and national levels or were offered by several sources from different zones, and Bureaus of agriculture belonging to each zone (FARC, 2011; SARC, 2011; BARC, 2010; MARC, 2011). These are presented in tables and figures, and when important, differences between sources are discussed.

Soil data was obtained from Ethiopian Geomorphology and soils map (FAO, 1984) and the suitable soils map was obtained from the Digital Soil and Terrain Database of East Africa developed by Food and Agriculture Organization of the United Nations (FAO, 1997). The soil units known to be suitable for tomato production were first identified through literature review. Then the polygons representing those suitable soils were extracted from the whole dataset being constrained within the boundaries of the study zones. The administrative boundaries of the five study zones have been adopted from EthioGIS. The data extraction, area calculation and mapping were done using ArcGIS 9.3 software. The identification of various factors affecting yield was based on either local and current information or previous publications as quoted in the following sections.

During the survey work qualitative and quantitative data were collected from 400 randomly selected farm households which were equally distributed among five different study zones where tomato was co-staple (Fig. 1.1). In this thesis, a ‘household’ is defined as a ‘family-based co-residential unit’ sharing daily activities, most resources and caring for the primary needs of its members (Niehof, 2004:323). Surveys and Focus Group Discussions (FGDs) were held with smallholder tomato growers and staff of Ministry of Agricultural during 2011. Qualitative and quantitative data were gathered by employing a structured questionnaire. Before launching the survey, the questionnaire was pre-tested and improved accordingly. Primary data gathered were used to describe the actual tomato production management practices and to quantify the distribution of crop area and production in relation to agro-ecological conditions in the different growing zones.

Field experiments were conducted on fresh market and processing tomato varieties to determine the influence of volume of water, irrigation systems and strategies on the plant growth and development, dry matter partitioning (DMP), yield-related characteristics, gas exchange (GE) and chlorophyll fluorescence (Fv/Fm), yield and quality traits. Initially, the same irrigation volume to all irrigation treatments for 14 days (plant establishment period) was used.

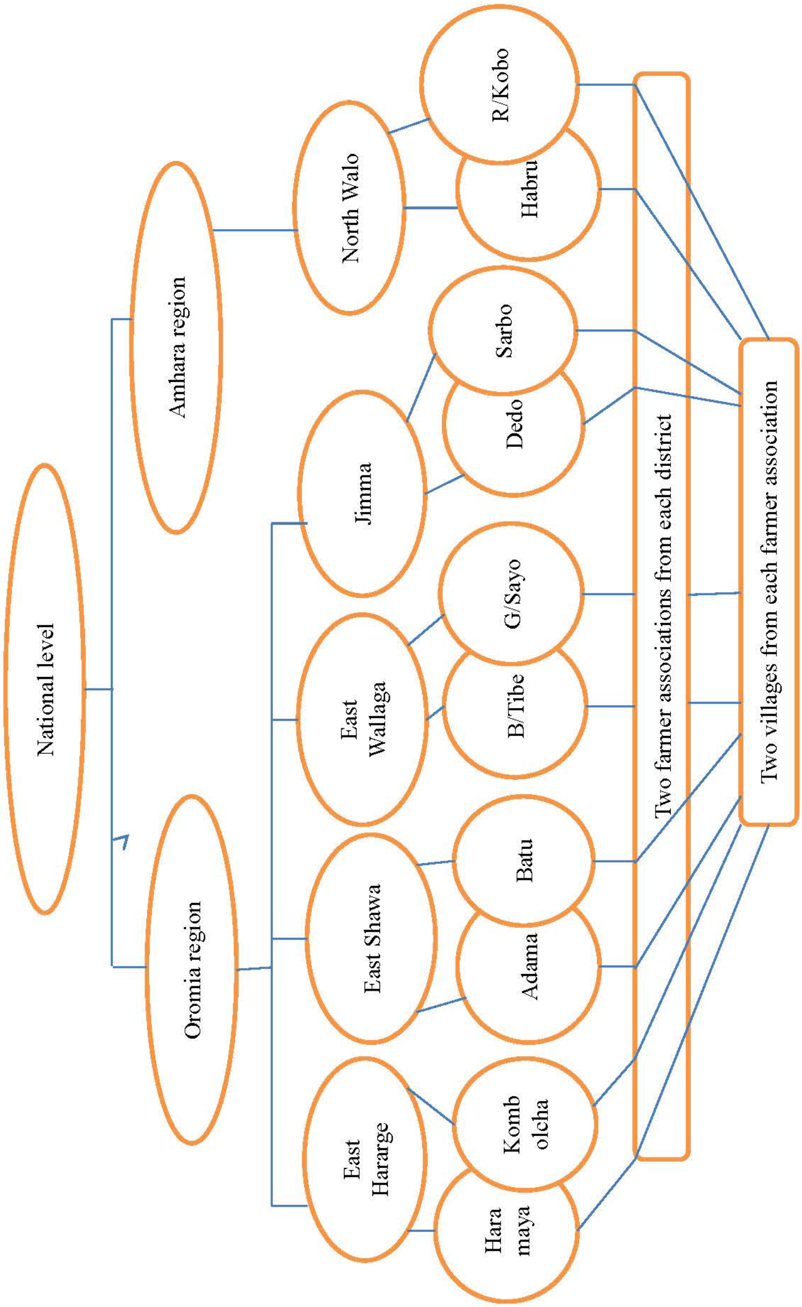

Fig. 1.1. Frame work of survey at farm household level

Organization of the thesis

This thesis is organized in nine main chapters (Fig. 1.2). After this introductory chapter, Chapter 2 reviews the literature aiming to understand the current status of smallholder irrigation and challenges related to the research topic. It explains irrigation development and current status of smallholders irrigation in Ethiopia, discusses land use rights and holding size, irrigation policy and strategy, and finally challenges and opportunities for irrigation development in Ethiopia.

The following chapter will deal with survey of tomato production and possible yield constraints in Ethiopia. This Chapter 3 begins with a presentation of area, production and yield in growing ecoregions and seasons; it also describes production characteristics of sample zones and discusses production or yield constraints.

Chapters 4, 5, 6, 7 and 8 are based on the results of field experiments carried out in the Central Rift Valley, Oromia region, Ethiopia. Chapter 4 starts with growth analysis of the tomato plant, development of nodes and average node development rate, dry matter accumulation and dry matter partitioning.

Chapter 5 compares fresh market and processing tomatoes performance of plant yield related characteristics and growth components, effects of local empirical, full- and deficit-drip and furrow irrigation on occurrence of Blossom end rot, *Phytophthora* root rot, *Fusarium oxysporum* and *Orobanche ramosa*.

Chapter 6 reports influence of irrigation system, volume and scheduling on commercial yield, agronomical and biological water use efficiency of fresh market and processing tomatoes.

Chapter 7 discusses photosynthetic rate (A), stomatal conductance (gs), maximum quantum efficiency of photosystem II (Fv/Fm), photosynthetically active radiation ($PAR_{absorbed}$), leaf temperature (Tl) and leaf transpiration rate (E).

Chapter 8 presents water savings and tomato yields under deficit irrigation in the Central Rift Valley, water use efficiency, average fruit weight, fruit dry matter content, pH, titratable acidity and total soluble solid of deficit- and full-irrigated tomatoes.

Chapter 9 discusses achievements of research questions and objectives, and analysis of the findings of the study. It starts with features of irrigated tomato by smallholders in different ecoregions and general highlights of production (yield) constraints, followed by an overview of main findings in relation to research questions. This chapter includes suggestions on implication of deficit irrigation strategy for water-limited areas and improvement of fruit quality.

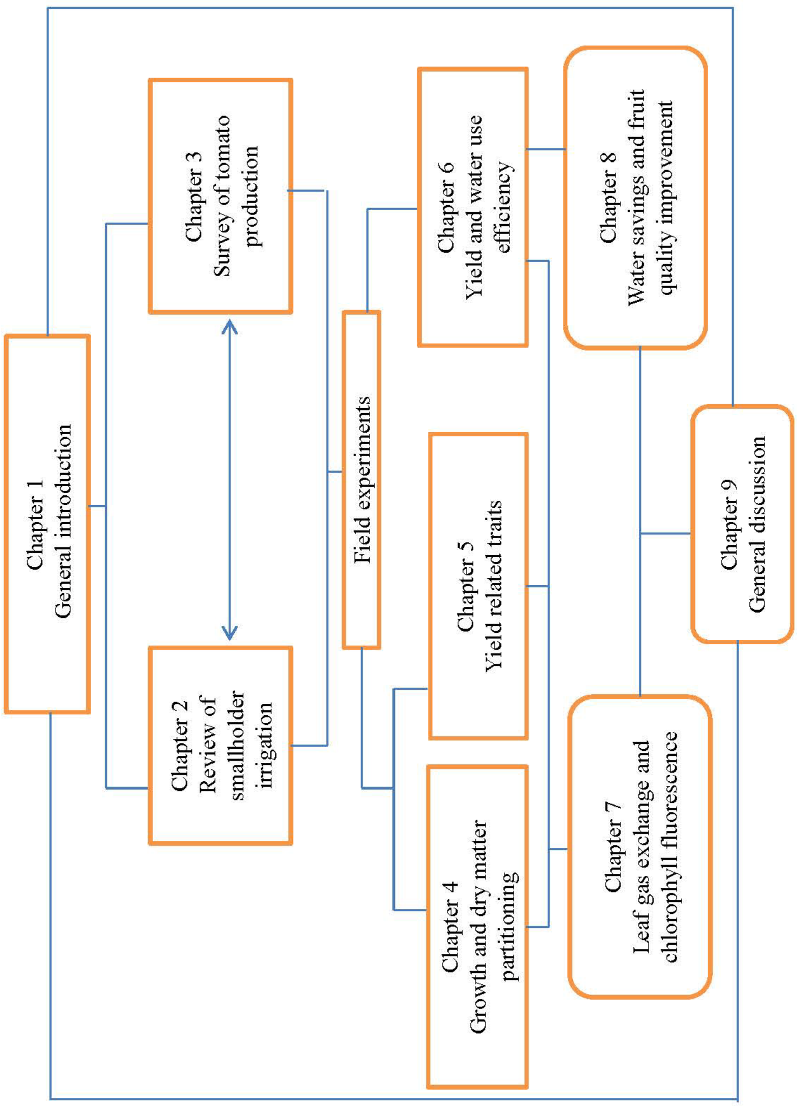

Fig. 1.2. Organization of the thesis

Chapter 2

Review of smallholders' irrigated crop production with emphasis on tomato in selected tomato growing zones of Ethiopia

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Abstract

The history of irrigated crop production in Ethiopia dates back to the 1960s when Ethiopia started with the production of industrial crops on large-scale farms by private investors in the Awash basin, with subsequent initiation of smallholders in the 1970s. Since then, semi-modern smallholder irrigation development and management started by the Ministry of Agriculture in response to major droughts, which caused wide-spread crop failures and food insecurity. Moisture deficit areas, where productivity remained low, constitute over three-fourths of the area inhabiting about 57% of the population of the country. Despite semi-modern smallholders' irrigation development started several decades ago, the gross irrigated smallholders farm is small whereas only10.8% of the total irrigable area is actually irrigated. Smallholders could not benefit from irrigation to the extent expected because of weak institutional and smallholders 'diverse income' behaviour, unsolved physical factors influencing irrigation efficiency and lack of research and independent, high quality, support services. There is increasing consensus that the sustainability of these smallholders' irrigated crops or tomato production is being questioned because of constraints related to extension, credits, inputs supply, technical capacity, lack of national irrigation policy, inadequate planning, and lack of research focus. Thus, emphasizing on tomato in selected tomato growing zones of Ethiopia, this review discusses and analyzes smallholders' irrigated crops or tomato production, challenges, impacts and opportunities using country-specific research and support services and irrigation project reports, case and empirical studies, workshop proceedings and working papers and draws conclusions and forwards recommendations for future improvements.

Keywords: Extension, Ethiopia, irrigation, smallholder, tomato.

Introduction

The purpose of this review is to collect literature on smallholder irrigated crop production with emphasis on tomato, to analyse and reflect on the status and to contribute to literature on smallholders irrigated tomato in growing zones of Ethiopia. It presents and discusses irrigation potential and development in Ethiopia, status and challenges and impacts relating with empirical evidences from different countries.

Irrigation potential and development in Ethiopia

The rationale for the development of irrigation and water management was to increase yields and productivity of land and labour, reduce vulnerability to climatic variability, reduce natural resources degradation, increase exports and job opportunities (Dessalegn 1986; Tesfaye *et al.*, 2008; Assefa, 2008; Salami *et al.*, 2010).

There have been different estimates of the irrigation potential of the country (Assefa, 2008). The country has also a number of lakes and ground water resources with a potential use for irrigated agriculture. The water resource was estimated to be 2.6-13.5 billion m^3 (Awulachew *et al.*, 2010). One of the previous estimations was made by the World Bank (1973), which suggested a figure of between 1.0 and 1.5 million ha of potential irrigable land. Recent estimates, however, somewhat overestimate the figure. There is variation in the estimated 12 river basins potential (an estimated annual runoff of ~125 billion m^3) due to lack of standard criteria to estimate across regions of Ethiopia (Assefa, 2008), estimating the minimum irrigation potential between 1.0 and 1.5 million ha and the maximum potential at 4.3 million ha (Tilahun and Paulos, 2004). The same authors reported that there is also a potential of 6.5 billion m^3 ground water sources with the capacity of developing 1.16 million ha across Ethiopian zones in the future. According to the MoWR (2001), the total irrigable land in the country measures 2.3 million ha. The International Fund for Agricultural Development (IFAD, 1987), on the other hand, gives a figure of 2.8 million ha, while the Office of the National Committee for Central Planning's 1990 figure, which is based on Water Resource Development in Africa (WRDA's) estimations, is 2.7 million ha. The Indian engineering firm Water and Power Consulting Services' 3.5 million ha is the highest estimate so far and Ethiopian Water Resource Management Policy (EWRMP) accepted the figure and was using it in the early 1990s (Tahal Consulting Engineers, 1988).

On the other hand, the Awash River basin attracted a good deal of local and international investment, and was the subject of numerous studies and surveys in the 1960s and 1970s (Dessalegn, 1986). By the beginning of the 1970s, 100,000 ha of land was under modern irrigation in the country of which about 50% was located in the Awash Valley (cf. Assefa, 2008). According to the Ministry of Water Resources' sector report, the area under irrigation is only about 197,250 ha (3% of the potential irrigable land estimated before the year 2001), of which smallholders' irrigation accounts about 85,000 ha (MoWR, 2001). However, the potential estimated was uncertain. The medium and large scheme irrigation potential ranges between 200,000 and 400,000 ha and between 2 and 3 million ha, respectively (MoWR, 2001).

The history of modern irrigated agriculture in Ethiopia dates back to 1960 when it started with the production of industrial crops (sugarcane and cotton) on large scale farms by private investors in the Awash valley. However, local farmers had already been practising traditional irrigation during the dry season using water from river diversions for subsistence crop production (Awulachew, 2006). Semi-modern smallholder irrigation development and management started in the 1970s initiated by the MoA in response to major droughts, which caused wide-spread crop failures and food insecurity. After the rural land proclamation in 1975, the government nationalized the large irrigated farms and the smallholders' irrigation schemes were transformed into cooperatives. The government began to focus on the potential of smallholders' irrigation to improve food insecurity and started promoting farmers and community based smallholders' irrigation through giving assistance and support to adopt modern technologies, rehabilitation and upgrading of traditional schemes after major famines in 2000/2001 (Habtamu, 1990).

Status of smallholders' irrigation in Ethiopia

Ethiopia is endowed with rich water sources. Yet these are mainly untapped. They could largely contribute to the overall national economic development on a sustainable basis. Ethiopian agriculture is mainly based on rainfall, which is erratic and low in amount. As a result of recurrent drought and famine during the years 1972/1973, 1983/1984 and 2002/2003 which cost many lives (Awulachew *et al.*, 2005 cf. Assefa, 2008), shortage of food and malnutrition became the main features of the country.

Current agricultural strategy and policy of the government promotes irrigated agriculture in all potential river basins. The modern small scale irrigation schemes and traditional irrigation are sustainable and are easily manageable by farmers. Smallholder irrigation (those schemes under the direct management of smallholders) will also enable farmers to increase crop intensities through double cropping, through supplementary watering during drought as well as crop growth in dry areas (crop expansion). The gross irrigated area has also increased between 1995 and 2003 from 75,000-200,000 ha (Diao and Nin Pratt, 2007), and in 2009 increased to 640,000 ha out of which 128,000, 129,000 and 383,000 ha accounted for rain water harvesting, (medium + large) scheme and smallholders' irrigation, respectively (Hagos *et al.*, 2009). To cope with the decreasing water supply in the Central Rift Valley which however appears difficult to resolve in short-term, and the occurrence of drought events, it appears important to look for options in optimal use of the available water.

Smallholder irrigation in Ethiopia is characterized by low levels of efficiency, lack of finance, inadequate marketing and weak extension services. Most smallholders' irrigation systems are based on river diversions, small reservoirs, bore holes and diesel-operated motorised pumps. Irrigated vegetable production during the dry season, usually in areas close to town centres, is getting attention in the farming community. Smallholder community irrigation projects are financed either by the government or by non-governmental organizations (NGOs), although beneficiaries contribute about 10% of the investment cost in the form of labour or by providing local materials such as sand, stone and wood. The beneficiaries also cover minor organization and management costs. However, maintenance works (e.g. pumps and head works) are carried out with government assistance in some regions (Tafesse, 2003).

Marketing is one of the constraints for smallholder irrigated crop production. Most growers produce vegetables (tomatoes, onions, carrots and cabbages). However, due to the perishable nature of these crops, prices fluctuate frequently and growers are often forced to sell at low prices. Besides, the absence of access to markets is also another constraint. In principle, after the construction of Smallholder Irrigation system (SHI), Water User Associations (WUAs) are established in which all beneficiaries become members. The WUA is a legally recognised body responsible for the management of the scheme, facilitation of water distribution, and maintenance and operation of the scheme. Because of weak WUA constrained with finance and technical know-how, water management and infrastructure maintenance were found to be main challenges affecting the sustainability of SHI development (Dejene *et al*., 2005). Women growers are not participating to the extent they are expected in irrigated farming because of access to resources, cultural barriers and in some cases their engagement in home-based activities (Kinfe *et al*., 2011).

Land holding size in the sample zones

According to the CSA (2011) database, total (irrigated + rainfed) plot size per household was less than 0.1 to 1.0 ha for over 60%, 78%, 36%, 32%, 40% and 58% of the growers in North Wollo, East Hararghe, Shewa, Wollega and Jimma zones and at national level, respectively (Table 2.1). Moreover, Gemechis *et al.* (2013) reported that from the overall samples in these five survey zones, proportions of households which do not have land, rent in land, use share cropping and gift were 51%, 14%, 29% and 6%, respectively.

Other researchers (Hagos *et al*., 2009; Assefa, 2008; Dejene *et al*., 2005) on smallholders' irrigated crop production holding size argued for 0.25-0.50 ha on communal field. Tesfaye *et al.* (2008) conducted a study on the Filtino and Godino irrigated vegetable production (Ada Liban district, Oromia) and reported that size of cultivated land and household food security are positively related. Households with larger holding size improved food security compared to households with smaller farm size implying farm size was one of the production constraints. In the growing zones, smallholder producers who work on small plots are pursuing the 'diverse-income' of depending on a variety of sources to earn a livelihood (Gemechis *et al*., 2012).

In East Shewa over 36% of growers work on land of less than or equal to 1.0 ha growing a much larger number of small plots of tomatoes and other vegetables, whereas in North Wollo about 60% of the households owned holding size of less than or equal to 1.0 ha for cropping (Tables 2.1 and 2.2). In East Wollega's river diversion irrigation schemes, about 32% of the farmers operate on less than or equal to 1.0 ha plots; it was observed that irrigated farming on these plots was just one of the several livelihood activities growers pursue, including rain-fed cropping, animal production, grain trading and government jobs. In East Hararghe, about 35% are small plots of tomato and root vegetables (potato, carrot and beet roots) plot cultivators, most often women growers. Because of higher income from khat (*Catha edulis*) cropping compared to tomato crops, smallholders rely less frequently on

Table 2.1. Land holding size (ha), number and percentage of households in sample tomato growing zones and at national level

Land holding size (ha)	Sample zones										National level	
	North Wollo		East Hararghe		East Shewa		East Wollega		Jimma		No	%
	No	%	No	%	No	%	No	%	No	%		
Less than 0.1	28994	9.0	33880	5.8	21832	8.4	13285	6.0	23393	4.2	891,008	6.4
0.1-0.5	82369	25.7	250400	43.2	26184	10.1	21734	9.9	81269	14.6	3,695,894	26.6
0.51-1.0	81647	25.4	169388	29.2	46194	17.8	35488	16.0	121300	21.8	3,455,009	24.8
1.01-2.0	83119	25.9	100282	17.3	69020	26.6	59972	27.2	179146	32.2	3,498,910	25.2
2.01-5.0	42437	13.2	25813	4.5	80518	31.0	72184	32.7	131448	23.6	2,099,754	15.1
5.01-10.0	2404	0.8	0	0	13620	5.3	14945	6.8	18695	3.6	241,672	1.7
Greater than 10	0	0	0	0	2011	0.8	3031	1.4	0	0	27,114	0.2
All	**320970**	**100**	**579763**	**100**	**259380**	**100**	**220639**	**100**	**557002**	**100**	**13,909,361**	**100**

Source: (CSA, 2011)

Table 2.2 Cropped area and number of holders of tomatoes and some major crops at National level during the year 2010

Crop	All cropped area (ha)	Numbers of holders	Cropped area (ha) per household head
Tef	2588661	1740658	1.49
Maize	1772253	3799402	0.47
Wheat	1683565	1983764	0.85
Sorghum	1618677	1222580	1.32
Barley	1129112	2194613	0.51
Faba bean	512067	1530774	0.33
Haricot bean	244013	822141	0.30
Field peas	226533	475244	0.48
Pepper	97712	1227989	0.08
Potatoes	69784	931197	0.07
Sweet potatoes	53465	591575	0.09
Taro	52201	475231	0.11
Cabbages	35344	2076330	0.02
Onion	17588	298187	0.06
Tomatoes	4953	98679	0.05

Source: (CSA, 2010)

irrigated tomato crop production for their livelihood needs. Less frequent irrigated tomato cultivation was observed among growers in the Jimma area who depended on a variety of livelihood strategies such as irrigated cropping, rain fed cultivation, coffee and khat growing, and timber wood trading.

Land is a public resource that cannot be sold and exchanged by smallholders by law, it is usually government-owned and crop growers have user rights. In his review, Rukuni (1997) suggested that communal ownership of land and the present tenure arrangements would promote productivity and efficiency enhancement if only the communal ownership was secure. In his assessment, problems of tenure security arise primarily when communal land tends to be viewed as government-owned. Land owners may lease land for limited period for a productive purpose in Ethiopia.

Technical capacity

Ethiopian smallholders like those in other African countries (Shah *et al*., 2002) have got more expenditure than their fair income from pump irrigation schemes, which are more costly and difficult to operate and maintain than gravity schemes. This cost is usually less than 5% of farm gross income, however, 20-25% due to lack of technical know-how for most African smallholders including those in Ethiopia (Shah and van Koppen, 1999).

The organisation of smallholders with respect to irrigation infrastructure differs from place to place. For instance, in the Central Rift Valleys the Haleku irrigation scheme has two motor pumps (diesel and electric pump) which are alternatively used depending on the availability of fuel and electricity, whereas Dodicha has two diesel pumps of which one is working, with a too small capacity for the irrigated area in which there is no standby pump when the pump fails which happens frequently. The condition of many smallholder irrigation schemes is poor which contributes to inefficient use of water and high irrigation costs (Scholten, 2007). Pumps are broken or not working at desired capacity and pipes and diversion canals are leaking. Rodents are a major problem along the main canals and are causing water losses in most irrigation schemes (Assefa, 2008).

Many irrigation schemes are constructed with governmental or non-governmental support, but operational and maintenance support is often lacking or only partly received. Water Users Associations (WUAs) lack the know-how for proper maintenance of irrigation equipment and infrastructure and lack the financial skills to manage irrigation systems adequately over longer periods (Scholten, 2007). Instead they use two water distribution systems, i.e. free irrigation and scheduled distribution. The choice between free irrigation and scheduled distribution systems depends on the availability of water. The former distribution system is used when there is sufficient water available whereas the latter is used when water is scarce.

Irrigation policy and strategy and rules ensuring equity

In 1998, the MoWR issued Water Resources Management Policy, by setting guidelines for water resources planning, development and management. The aim of the irrigation policy was to develop the irrigation potential for food crops production and raw materials for agro-industries, on efficient and sustainable basis without degrading soil fertility and water resources. Similarly, irrigation development strategy was also aimed to exploit the production potential to achieve food self-sufficiency, export earnings and supply of raw material to industries without affecting fertility and productivity of land and water (Cherie, 2001). According to this author main aims in the irrigation strategy were to help growers in the aspects of strengthening technical capacity, including institutional, financial and economic, engineering, social and environmental aspects. Government gives emphasis to develop irrigation to assist growers to improve irrigation management practices and the promotion of modern irrigation systems to reduce household risks that are associated with crop failures resulting from droughts.

Smallholder growers, however, had been facing problems in irrigation development during dry seasons for food crops production. Mismanagement of agricultural water, environmental degradation, inadequate inputs and recurrent drought have affected household food insecurity (Awulachew *et al.*, 2010).

Penov (2004) indicated that WUAs are the most frequently suggested organizational form for management of irrigation schemes. WUAs are legal entities which are expected to have full control over the irrigation facility in their scheme. Establishing a sustainable irrigation organization is one of the main aspects for a successful and sustainable irrigation management (Boelens, 1998). Sustainable management of growers-managed irrigation systems needs well established rules that ensure the interest of all growers. Certification is important to get legal access to credit services from governmental and non-governmental organizations. They can also legally enter into different agreements with different unions, governmental and non-governmental organizations. Uncertified WUAs have not such legal rights.

Rules ensuring equity

The main activities of WUAs are repair, maintenance of canals, supervision of water distribution, settling any conflicts and raising internal resources to sustain the WUA. Where growers cultivate on adjacent plots using common pumps, certain tasks and activities should be properly coordinated to smoothly run the irrigation scheme and avoid possible conflicts (Stern, 1988). Inequity of water distribution, untimely water deliveries, and insufficiency of irrigation water with consequent loss of agricultural productivity and livelihood for the poor were among the constraints observed in tomato growing zones. Irrigation would even harm women and other disadvantaged groups (Smith, 2004). Amacher *et al.* (2004) in his study in Tigray attributed that larger irrigation structures are associated not only with productivity increases but also with health costs: people living in villages close to dams spend more time being ill or caring for ill relatives.

Jayne *et al*. (2003) in his assessment of smallholders income and land distribution found a Gini coefficient for income as high as 0.59 for Ethiopian smallholder households alone; only 3% of the variation in per capita incomes is between districts and 36% between villages; the Gini coefficient for land is 0.55, with 78% of the variation within villages. This local inequality may have a large impact on the distribution of the benefits of irrigation: local communities, with their own internal power structure, are responsible for allocation of irrigated land and for water distribution (Van den Berg and Ruben, 2006) resulting in the allocation of irrigation to relatively rich and powerful people, despite the original government aim of irrigation for poverty alleviation. Van Halsema *et al*. (2011), examining the over-abstraction of water and the poor irrigation performance of both Halaku and Dodicha schemes, suggested that policy should focus on improving existing schemes instead of further developing new ones.

Implementation

FDRE (2002) reported that the Tigray region initiated an ambitious plan in 1995. During this year plan the government intended to construct 500 dams with a capacity of irrigating 50,000 ha within 10 years (Hagos *et al.*, 1999). Although this is well below the irrigation potential of 0.32 million ha (Tesfay*et al.*, 2000), the plan proved to be highly unrealistic. Experience in Sub-Sahara has shown that smallholder irrigation can succeed if growers participate in design and management during planning (FAO, 2000). A smallholder irrigation far from input and output markets or in a catchment (an area with a common outlet for its surface runoff), where there are too many competing water users, will fail. A scheme which is designed to improve traditional irrigation, but in which growers' views are not heard, will fail. Also the failure to formally recognise the need for on-going support to farming communities is likely to lead to shortages of funds for maintenance, and so to irreparable breakdowns.

In Ethiopia, most NGO-based irrigation projects were constructed without prior consultation of growers (Awulachew *et al.*, 2010). The planned capacity for high rainfall, moisture deficit and pastoralist (marginal) zones was 0.64 million ha whereas total under-performance by all categories was 0.23 million ha (Awulachew *et al.*, 2010). Ambitious irrigation planning without securing sufficient skilled manpower, local capacity to run the schemes (management, financial, and technical capacity) was observed almost in all regions as a source of failure (Awulachew and Merry, 2006). The OIDA (2000) report showed that 15 smallholders' irrigation schemes have been completely abandoned due to inadequate operations and maintenance resulting in sedimentation. Moreover, Makombe *et al.* (2011) in their analysis on smallholder irrigation in Ethiopia, recommend that the existing traditional irrigation systems be upgraded to modern schemes before, or concurrently with, new small-scale irrigation development plans.

Physical factors influencing irrigation efficiency

Irrigation efficiency (IE) is defined as the ratio of the volume of water that is taken up by the crop to the volume of irrigation water applied (ASCE, 1978). Whatsoever the irrigation system, water management is of prime importance and surface run-off, infiltration and leaching must be avoided to save water but also to reduce the degradation of water quality and the risk of salinity increase in the water table (Bieche, 1999). Al-Jamal *et al.* (2001) stated that smallholders can adopt either drip irrigation for yield maximization or sprinkler irrigation for yield increase and high IE instead of furrow system. Van Halsema *et al.* (2011), on Halaku and Dodicha IE assessment, reported an IE of 35% implying the combined effect of the varying medium to high conveyance losses throughout the conveyance network and the low to high application efficiencies at field level. The excess water amount that leaves the farm at the end of the furrows is termed as run-off. Run-off is inherent to furrow irrigation and in some cases to drip irrigation in sloping farms and/or if irrigation application exceeds the soil infiltration rate. Furrow irrigation is the most widely used irrigation by smallholders. Furrow irrigation is featured by low efficiency, high labour and pumping cost requirement, compared to drip irrigation, which is used rarely due to high installation cost (Yohannes and Tadesse, 1998).

On-farm evaluation in Eastern Ethiopia showed deep percolation loss of 70, 32, 57 and 70% in tomato, sorghum, maize and potato fields, respectively (Bekele and Tilahun, 2006). For deep-rooted crops and soils without excessive permeability, surface irrigation delivery strategy can be appropriate; however, for shallow-rooted crops and/or soils with small water holding capacity, percolation losses can be substantial and crops may become highly stressed by waterlogging. Under rigid delivery schedules, it is extremely difficult, both to modernize the irrigation methods and to implement irrigation scheduling programs (Pereira, 1999).

The longer the irrigation period practised by growers, the greater is the distribution variability. As the frequency of irrigation increases and the period decreases, the distribution variability decreases. With drip irrigation, water is applied directly to the root zone thus reducing the soil infiltration variability. Assessment of irrigation efficiencies on Haleku scheme, Central Rift Valley of Oromia showed that the conveyance losses in the main, secondary and tertiary canals accounted for conveyance losses of 13.3-19.9 L S^{-1} in the upstream and an increase to 70.8 to 82.0 L S^{-1} in the downstream part of the scheme (Van Halsema *et al.*, 2011). The same assessment argued extremely high conveyance losses at various places in the scheme due to overtopping and leakages, especially in the main, secondary and the majority of the tertiary canals serving plots, resulting in a very low overall conveyance efficiency, implying that only 17% of the pumped water from the source river reaches the plots.

A study on socio-economic performance of Gibe-Limu and Gambella Tarre irrigated vegetable production (GobuSayo district, West Oromia) indicated that poor performances of schemes resulted from scarcity and unreliability of water, poor management and socioeconomic problems (Dejene *et al.*, 2005). The same study evidenced lack of well empowered institutions of water rights, technical problems in design and construction, and inadequate institutional capacity of the local administrative irrigation agency to coordinate and support management of irrigation. Nevertheless, evaluation based on over 300 irrigation projects has shown that smallholders' irrigated crop production can be cost-effective and can give high returns in sub-Saharan Africa (Inocencio *et al.*, 2005).

Scholten (2007) ascribed that smallholder producers in the Dodicha irrigation scheme in the Central Rift Valley was not cost-effective. He also disclosed that WUAs lack know-how on maintenance of irrigation equipment and financial skills (for example, WUAs do not have sufficient savings in case of unforeseen expenditure) to manage irrigation schemes adequately over longer periods. Consistent with this, Van Halsema *et al.* (2011) on the same schemes disclosed that various problems over water distribution and management reflected a general problem in the functioning of the WUA, which is perceived to be affected by ineffectiveness of the irrigation pumps, conflicts of inequity, lack of adequacy and reliability in irrigation water resulting from weak WUAs, local bureaucracy, uncomfortable relationship between committees working on irrigation management and poor irrigation handling, all leading to poor yield and often crop failure. Dejene and his co-workers (2005) in their evaluation on Gibe-Limu and Gambella Tarre smallholders irrigation (Gobu Sayo district, West Oromia) disclosed that weak enabling legal system of land and water rights, poor local administrative irrigation agency, poor water distribution management in terms of performance indicators (i.e. adequacy, reliability and equity), and water related conflicts were rampant and unsettled resulting in poor performance.

Challenges of irrigation development in Ethiopia

Challenges related to institutional issues

According to the organizational structure, irrigation planning and development of large- and medium-scale irrigation projects are the responsibilities of the Ministry of Water Resource (MoWR), whereas the smallholder irrigation and water harvesting schemes are planned, implemented and governed under the Ministry of Agriculture (MoA) at the Federal level. The institutional set-up and accountability issues vary from one region to the other region, and are not sustainable. Consequently, there was a confusion on mandate, resulting in scheme failure because of inadequate accountability (Awulachew *et al.*, 2005). The regional water development bureaus' mandates involve planning, design and construction of small-scale irrigation schemes and transfer to Commission for Sustainable Agriculture and Environmental Rehabilitation Bureau for management, operation and maintenance in Amhara, Southern Nations and Nationalities People (SNNP) and Tigray regions. This institutional form usually led to unsustainable development in many instances. In other region, like Oromia, irrigation schemes are fully implemented by the Oromia Irrigation Development Authority (OIDA), which has its own extension coordinating team (Awulachew *et al.*, 2005).

Challenges related to inadequate research and support services

Smallholders are faced with poverty and food insecurity largely related to climate changes, poor access to agricultural technologies, soil and environmental degradation, weak institutional support services and no economic incentives for sustainable smallholder irrigated crop production.Very limited research on smallholders' irrigated crop production is conducted (Gemechis *et al.*, 2013). The country's soil database has not been handled systematically, and the total area covered by different soil types is an extrapolation from a large scale map (FAO, 1984; 1997). Production challenges in terms of soil are high phosphorus fixing, poor soil conservation viz., erosion in the heavy rainfall areas, leaching in the humid areas, moisture stress and salinity in drier areas, poor drainage of vertisols and fluvisols, low organic matter and nutrient depletion for which no research is addressed (DARD, 2000). These gaps led to limited information, risk and uncertainty of smallholders' irrigated production including tomato, thus resulting in poor performances.

Irrigation can only work if other components of the agricultural system are also effective for example the seed system or extension (Tesfaye *et al.*, 2008). International experience indicates that with adequate access to smallholders' support services, smallholders can increase productivity and production significantly. For instance smallholders in Zimbabwe with average farm size between 2 and 3 ha doubled maize and cotton production in the 1980s when extension, marketing and credit services were provided (Rukuni and Eicher, 1994). Sustainable smallholders' irrigated crop production is only possible if the production levels attained make it affordable (Crosby, 2000). This implies favorable land, water, knowledge, motivation, management and smallholders gain access to reliable and good quality support services such as essential extension, credit and marketing access.

Smallholders' irrigated tomato production constraints in Ethiopia include inputs (Woldeab, 2003; Tesfaye *et al.*, 2008), sub-optimal agricultural practices and diseases and pest damages (Yaynu *et al.*, 1999; Wondirad and Tesfamariam, 2002; Shih *et al.*, 2005; and Etagegnehu, 2005). For example only 12% of the growers use chemical fertilizers, while improved seeds and biocides are used by 25% of Tigray smallholder farmers (Hagos *et al.*, 1999). Poor infrastructure and institutional arrangements for input supply, poor extension service support and output marketing were reported in several smallholder irrigation areas such as Weyibo, Bissare, and Lebuof SPNNR (Tafesse, 2002); Gibe Limu and Gambella Tarre of Oromia (Dejene *et al.*, 2005); Halaku and Dodicha of Oromia (Scholten, 2007; Assefa, 2008; Van Halsema *et al.*, 2011), Aradumi of North Walo (Gemechis *et al.*, 2013) and Filtino and Godino schemes of Ada Liben, Oromia (Tesfaye *et al.*, 2008).

These authors reported that rural institutions such as growers' cooperatives and credit associations either do not exist or if they exist are very weak in supporting the smallholder growers. According to the 2011 National Agricultural Sample Enumeration (NSE), inputs and credits are not available at reasonable rates for the majority of smallholders. They experience difficulty in obtaining credit for production inputs (Table 2.3). In these selected areas about 26-59% of the households did not use package of inputs due to shortage of money and 8-35% due to unavailability of packages of inputs (CSA, 2011).

Credit service is not available for 4-27%, inadequate for 11-66% and prohibited for 14-58% of the households because of failures to pay previous loan due to shortage of money. This indicates that due priority is not given to the smallholder growers in credit provision in spite of their size in the population, cultivated land size and contribution to national agricultural income. On top of this, in these zones for 4-42% advisory service was not available, for 17-68% no adequate advisory services were available and 3-43% were not aware. The share of commercial banks' loans to agriculture has been very low compared to manufacturing, trade, and other services sectors, hampering expansion and technology adoption. Scholten (2007) in his assessment on Haleku and Dodicha irrigation reported that smallholders' schemes lack operation and maintenance support resulting in inefficient water use due to malfunctioning pumps, pipes and diversion canals, and working at under-capacity. Access to formal credit in Ethiopia is mainly confined to large urban centers, where collateral requirements are high (Salami *et al.*, 2010). Furthermore, Tesfaye *et al.* (2008) on their study

Table 2.3. Reason for not using services, number and percentage of households in selected tomato growing zones and at national level

Reason for not using services	North Wollo		East Hararghe		East Shewa		East Wollega		Jimma		National level	
	No	%	No	%	No	%	No	%	No	%	No	%
Shortage of money	77999	25.8	217969	48.6	65877	30.6	81142	59.2	131504	29.2	3644914	34.3
Lack of land	26059	8.6	47119	10.5	32794	15.2	17798	13.0	53139	11.8	1744194	16.4
Unavailable	84915	28.0	35310	7.9	48679	22.6	0	0	155094	34.5	1788619	16.8
Not aware	68809	22.7	70133	15.6	37267	17.3	13099	9.5	31005	6.9	1408009	13.2
Efficacy suspicion	26223	8.7	42358	9.4	0	0	19219	14.0	12314	2.7	1018843	9.6
Others	18566	6.2	35693	8.0	30917	14.3	6078	4.3	66869	14.9	1037439	9.7
Package of inputs not used (total)	**302571**	**100**	**448582**	**100**	**215534**	**100**	**137336**	**100**	**449925**	**100**	**10642018**	**100**
Unavailable	9530	4.0	61748	12.3	35128	16.6	24922	12.8	145424	27.0	1884195	16.2
Inadequate	27259	11.4	329148	65.8	68721	32.5	37746	19.3	142496	26.4	2908900	25.0
No return	15768	6.6	4201	0.9	0	0	10800	5.5	18520	3.4	429900	3.7
Failure to pay previous loan	138519	58.0	70959	14.2	82322	38.9	97930	50.1	151666	28.0	4530934	38.9
Not aware	22700	9.5	10694	2.0	11941	5.6	7045	3.6	16466	3.0	728437	6.3
Others	24929	10.5	23774	4.8	13549	6.4	16972	8.7	64373	12.2	1151523	9.9
Credit not used (total)	**238705**	**100**	**500524**	**100**	**211661**	**100**	**195415**	**100**	**538945**	**100**	**11633889**	**100**
Unavailable	22504	40.2	46088	18.6	22271	15.4	3942	3.8	88618	32.0	1208102	20.4
Inadequate	9345	16.7	168749	68.2	69687	48.3	50850	49.0	174322	63.0	2827899	47.8
No return	0	0	0	0	0	0	7249	7.0	0	0	201885	3.4
Not aware	24185	43.1	26072	10.5	34121	23.6	31717	30.6	6965	2.5	1186401	20.0
Others	0	0	6682	2.7	18267	12.7	10046	9.6	6883	2.5	495439	8.4
Advisory not used (total)	**56034**	**100**	**247591**	**100**	**144346**	**100**	**103804**	**100**	**276788**	**100**	**5919726**	**100**

Source: *(CSA, 2011 Vol. III)*

on two irrigation schemes disclosed that the institutional credits usually give priority to rainfed agriculture instead of irrigated crop production.

Impact of irrigation development

Household food security and forest conservation

The World Bank (1986) provides a definition of "food security" as 'access by all people at all times to enough food for an active and healthy life'. A study conducted in 10 Indian villages in different eco-regions reveals that increasing irrigation by 40% was equivalently effective in reducing poverty, that is decreasing food insecurity, as offering a pair of bullocks, improving educational level and wage rates (Singh *et al.* 1996). Kumar (2003) also ascribed that irrigation has significantly added to boosting India's food production and creating grain surpluses used as drought buffer. A review by Hussain and Hanjra (2004) suggests that access to reliable irrigation can enable growers to adopt new technologies and intensify cultivation, leading to increased productivity, overall higher production, and greater returns from farming. This in turn opens up new employment opportunities; both on-farm and off-farm, and can improve incomes, livelihood, and the quality of life in rural areas. The same study revealed that access to irrigation contributed to socioeconomic uplift of rural communities via improved production, income and consumption, employment, food security, and other social impacts contributing to overall improved welfare. In Zimbabwe, irrigated crop production was found to serve as source of food security for the growers and the community nearby via improved productivity, sustainable production and incomes (Mudima, 2002), and growers involved in irrigated crops production never run out of food unlike their counterparts who depended on rain-fed agriculture. Ngigi (2002) in his study in Kenya, concluded that irrigation can assist in agricultural diversification, enhance food self-sufficiency and increase rural incomes under limited water conditions.

Smallholders irrigated vegetable crops production increased production, cropping diversity, income and diet diversification in Oromia, Southern People Nations and Nationality Region (SPNNR) and Tigray regions (IFAD, 2005; Woldeab, 2003). The shift from cereal-livestock to cereal-vegetable-livestock system also improved the household nutrition as a consequence of vegetables becoming part of smallholders' daily diet. Tesfaye *et al.* (2008) reporting on Godino and Filtino smallholders irrigated vegetable production (Ada Liben district) of Oromia region, ascribed that irrigated vegetable production enabled households increased cropping intensity, insured increased and sustainable production, income and consumption thereby improving food security of the household; consistent with the work of Abebaw (2003). Shimelis *et al.* (2005) on Gibe Limu and Gambella Tarre irrigated vegetable and maize production (Gobu Sayo district) of West Oromia also reported that it improved smallholders' livelihoods in terms of diversification and intensification of crop production, household income, housing and employment generation. Tafesse (2002) reported similar findings regarding Weyibo, Bissare, and Lebu, irrigated vegetables production (SPNNR).

Average tomato yield is 45 Mg ha^{-1}from irrigated land, considerably more than the 18 Mg ha^{-1}from rain-fed production on research fields (Dessalegn, 2002). In other reports 22.4 and 8.9 Mg ha^{-1} in East Shewa (ESZBoA, 2011) and 20 and 8.27 Mg ha^{-1} in East Hararghe zones (EHZBoA, 2011) were reported under irrigation and rain-fed production, respectively, on farmer's field. Smallholders irrigated cropping area, including tomato, increased countrywide from 134,545 to 186,413 ha during the last five years (CSA, 2006-2010; Joosten *et al.*, 2011) supported with multiple cropping practices to cope with the problem of food security.

Irrigated crop production and watershed management can reverse soil degradation by conserving soil and water, reducing flooding, and increasing recharge and base flow (Rockstrom *et al.*, 2003). Assefa (2008) in the Central Rift Valley of Oromia argued that smallholders involved in irrigated tomato and onion production in a way contributed towards forest conservation unlike their counterparts who depended on charcoal making to earn livelihood needs. Consequently, the pressure on surrounding Acacia tree has been decreasing because of smallholders' engagement in irrigated vegetable production for living.

Gender equality, and labour and growers' productivity

Irrigation activities that started targeting women farm decision-makers have been very successful (Zwarteveen, 1997; Hulsebosch and Van Koppen, 1993; Merrey and Baviskar, 1998). Women's share in irrigated smallholder agriculture in the region is increasing from time to time because of men migration from rural to urban areas in search for lucrative employment (OBoA, 2011). While over 55% of the agricultural labour force in Ethiopia are women (Awulachew *et al.*, 2010), irrigated smallholder agriculture gives equal chance to women engagement in irrigated crops production to earn income for livelihood needs. Kinfe *et al.* (2011) in Laylay Michew district of Tigray reported that special consideration for female headed households was taken into account while selecting participants in accessing irrigable land.

Irrigation is highly beneficial to those households directly involved, and enabled to absorb the household abundant labour, increases expenditures and decreases dependence on income from public programs (food for work) in Tigray and Oromia regions (Van Halsema *et al.*, 2011; Tesfaye *et al.*, 2008). The benefits of irrigated production can spread to non-irrigation households through local markets for labour, food and other goods (Van den Berg and Ruben, 2006). Irrigation promoted crop intensification through which small plots of land yielded more per capita and increased labour productivity, that is, the abundant household labour engaged in job opportunities via the forward and backward linkages between irrigation and commodity value chains in the SPNNR region (Tafesse, 2002). Chamber (1994), based on empirical studies, confirmed that reliable and adequate irrigation increases employment, i.e., migrant labourers as well as small and marginal growers have more work on more days of the year, which ultimately contributes to food security. Kinfe *et al.* (2011) also stated that irrigated tomato and maize production increased labour productivity throughout the season and motivated self-employment offsetting full-time and part-time off-farm or non-farm employment due to efficient labour utilization.

Delgado (1998) in his study in sub-Saharan Africa concluded that smallholder irrigated crop production is important to provide employment, human welfare, and political stability. Smallholders' irrigated crop production could moderate the rural exodus, create growth linkages and enlarge the market for industrial goods (Eicher and Rukuni, 1996). Smallholders' irrigated crop production is also considered to be both a major cause of and potential solution for poverty reduction and economic growth (Jazairy *et al.*, 1992; DFID, 2002). Smallholder irrigated crop production can be cost-effective and give high returns in sub-Sahara Africa (Inocencio *et al.*, 2005) and smallholders that are doing well on their irrigation have assets.

Opportunity for irrigation development

Rainfall variability needs irrigation development for crop production. Research in semi-arid tropical regions shows that the occurrence of dry spells, that is short periods of 2-4 weeks with no rainfall, by far exceeds that of droughts. Stewart (1988), based on research in East Africa, reported that severe yield reductions due to dry spells occur once or twice in 5 years. Sivakumar (1992) also reported that the frequency of seasonal dry spells lasting 10-15 days was independent of long-term seasonal averages, which range from 200 to 1200 mm in West Africa. Barron *et al.* (2003), studying the frequency of dry spells in semi-arid locations in Kenya and Tanzania, reported a minimum probability (based on statistical rainfall analysis) of 0.2–0.3 for a dry spell lasting more than 10 days at any time of the growing season of a crop, and a probability of 0.7 for such a dry spell to occur during the sensitive flowering stage of maize.

Conclusions and summary

Semi-modern smallholder irrigation development started over several decades in response to droughts and food insecurity. Although there were constraints, evaluation conducted so far on several smallholders irrigated crop production has also shown that smallholder irrigated crop production can be cost-effective and give high returns, increase land and labour productivity and contribute to forest conservation via reduced reliance on charcoal production in the Central Rift Valley. Empirical evidences from different countries also argued that access to reliable irrigation water supported with new technologies and intensification, led to improved productivity, overall higher production, and greater returns from farming thereby enhanced employment opportunities, both on-farm and off-farm, and improved incomes, livelihood, and quality of life in rural areas.

Despite these impacts, Ethiopian smallholders could not benefit to the extent expected from irrigation due to the low performance of smallholder irrigation related to constraints of policy and strategy ensuring equity and physical factors influencing irrigation efficiency. Second, inadequate research support and lack of improvement of smallholders' access to good quality support services (extension, credits and inputs supply) and poor market access are also major constraints. Analytical and empirical research in the field is still scanty and more effort is needed to address smallholders' irrigated tomato production.

There is a necessity for research on irrigation water management technologies and crop water requirement research, thus growers may engage in how to successfully improve traditional small-scale into modern ones including organizational issues linked to water user association formation. Enhancing water availability for production and modernization of existing irrigation schemes that can lead to security and intensification of cropping via increasing cropping intensity is crucial to reduce food insecurity.

Chapter 3

Survey of tomato production and possible yield constraints in Ethiopia

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Abstract

Tomato is a widely grown vegetable crop in Ethiopia. It is consumed in almost every household in different ways. In certain areas, such as Wollo, Hararghe, Shewa, Jimma and Wollega, it is also an important co-staple food. Primary data were collected from 400 randomly selected smallholder producers who were equally distributed among five study zones where tomato was a co-staple food. These data were used to describe the actual tomato production and management practices and to quantify the distribution of crop area and production in relation to agro-ecological conditions in the different administrative zones (North Wollo, East Hararghe, East Shewa, Jimma and East Wollega) and growing seasons. Qualitative and quantitative data were gathered by carrying out a survey among growers and staff of the Offices of Agriculture during 2011, employing a structured questionnaire. Before launching the survey, the questionnaire was pre-tested and improved. Focus group discussions and key informant interviews were held for triangulation. Based on the survey of 400 smallholder producers important yield constraints were identified. These included lack of resources such as irrigation water, nutrients and high-quality seed, but also adverse weather conditions including drought and cold. Yields were also reduced by several major weeds, insect pests and diseases including late blight and Fusarium wilt. Crop production management varied significantly among study zones because of differences in agro-climatic conditions, access to resources and culture. Average fruit yields ranged from 6.5 to 24.0 Mg ha^{-1} and were different for the five survey zones. According to the results of the survey and the focus group discussions, about 32-40% of the growers used irrigation. Supplementary irrigation was required in most of the production regions to sustain food security and tomato production. Possibilities for yield improvement are discussed and recommendations are made to further improve tomato yield in the different growing zones.

Key words: Biocides, diseases, Ethiopia, improved seed, irrigation water, nutrients, pests, tomato.

Introduction

The introduction of cultivated tomato (*Solanum lycopersicum* L.) into Ethiopian agriculture dates back to the period of the Italian invasion from 1935 until 1940 (Asgedom *et al*., 2011). The Ethiopian Institute of Agricultural Research (EIAR) was established in 1966 (Setotaw, 2006) and tomato became recognized as a commodity crop and secured research fund. Since 1969, 300 tomato varieties were tested (Cherinet, 2011). However, most varieties tested showed susceptibility to late blight, powdery mildew and mosaic virus (Tindall, 1970). The first record of commercial tomato cultivation is from 1980 with a production area of 80 ha (Dessalegn, 2006) in the upper Awash by Merti Agroindustry for both domestic as well as export markets. The total area increased to 833 ha by the year 1993 and later on the cultivation spread towards other parts of the country. Since 1994 up to the year 2011, tomato acreage increased to 5,338 ha with a total production of 55,635 Mg (CSA, 2011). Currently tomato is one of the regional export crops of the country (Joosten *et al.*, 2011).

In Ethiopia, the crop is grown between 700 and 2000 m above sea level, with about 700 to over 1400 mm annual rain fall, in different areas and seasons, in different soils, under different weather conditions, but also at different levels of technology (e.g., with furrow, drip or spate irrigation) and yield levels (Gemechis *et al.*, 2006; Birhanu and Tilahun, 2010).

Smallholders have grown tomato for a long time for their livelihood needs since the start of its commercialization. Yet, average yield of tomato in Ethiopia is low, ranging from 6.5-24.0 Mg ha^{-1} compared with average yields of 51, 41, 36 and 34 Mg ha^{-1} in America, Europe, Asia and the entire world, respectively (FAOSTAT, 2010). Moreover, growers have been challenged by production fluctuation and low yields. Improving smallholders' tomato production would contribute to enhancing food security and alleviating poverty. The few surveys carried out so far on tomato production were broad and covered also all other horticultural crops. Such surveys were crude and did not identify production status and constraints at the level of the individual crop. Moreover, the limited information available at the crop level is site-specific (Abebe *et al.*, 2005; Dessalegn, 2002) and no attempts have been made to assess for each tomato growing eco-region conditions that may limit or reduce yield.

Thus, a survey at household farm level was carried out to identify the status, constraints and opportunities of tomato production in the country, and to explain the low yield levels in tomato production. In this survey, emphasis has been given to the impact of education level of household head, seed type, irrigation, chemical fertilizers, use of biocides, diseases, drought and cold on tomato yield.

Materials and methods

The survey work was undertaken in five selected tomato growing zones of Ethiopia to represent different eco-regions and production systems where tomato was a co-staple food. East Hararghe, Jimma, East Shewa, North Wollo and East Wollega were selected representing warm humid lowlands to cool humid mid-highlands, cool moist mid-highlands, tepid semi-arid dry land, tepid moist mid-highlands, and warm sub-humid lowlands to tepid sub-humid mid-highlands, respectively, to assess actual crop management practices followed by growers and possible yield constraints.

Primary data were collected from 400 randomly selected farm households who were equally distributed among the five different study zones (Fig. 3.1). Survey, focus group discussions (FGDs) and key informant interviews (KIIs) were held with growers and staff of the Offices of Agriculture during 2011. Qualitative and quantitative data were gathered by employing a structured questionnaire. Before launching the survey, the questionnaire was pre-tested and was improved accordingly. FGDs and KIIs were guided by checklists prepared for the study purpose. The data on cropped area, production and yield were obtained from CSA (CSA, 2001-2010), the Ethiopian Institute of Agricultural Research (EIAR) at different locations, Offices of Agriculture at different levels, and Experimental stations belonging to each zone (BARC, 2011; FARC, 2011; MARC, 2011; SARC, 2011). These are presented in tables or figures, and, when important, differences between sources are discussed.

The variables that have been hypothesized as factors most likely influencing tomato yield were analyzed using SPSS software (SPSS, 1999) and fitted to linear multiple regression models to determine the effects of these variables on tomato yield in the study areas.

As presented in Equation 1, the yield response model for the sample tomato growers considered inputs of production and other farm-specific characteristics:

$$Y=\beta0+ \beta1\ E+ \beta2GE+\beta3S+\beta4I+ \beta5B+ \beta6CF+ \beta7L+\beta8DE+ \beta9D+ \beta10CE+e \qquad [1]$$

where: Y = yield of tomato (dependent variable in kg $plot^{-1}$) for this study; β0-β10 =

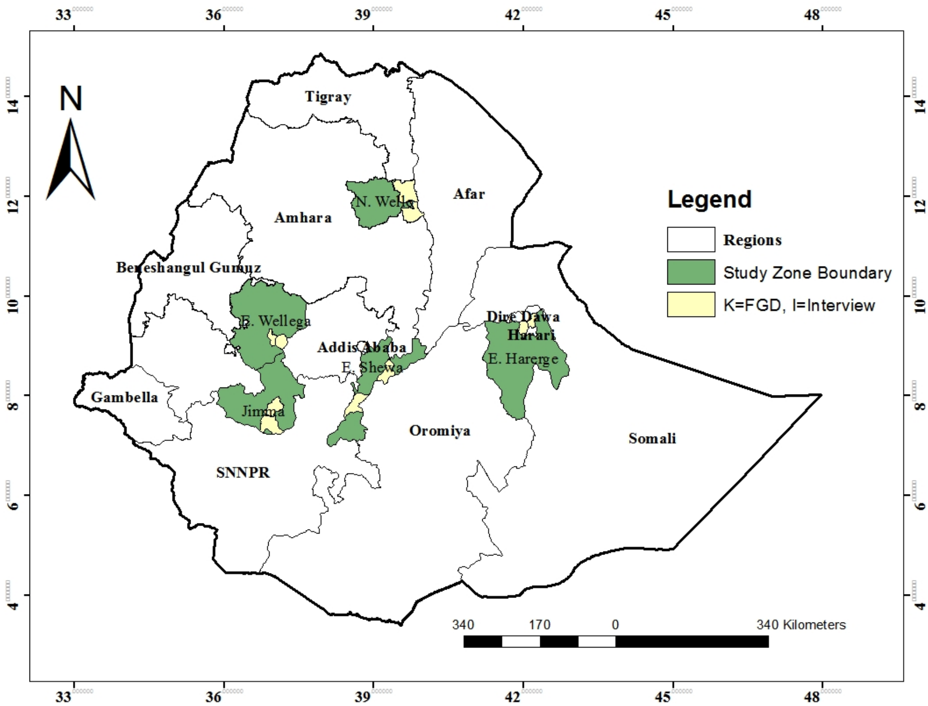


Fig. 3.1. Location of sample tomato growing zones in Ethiopia

constants; E = level of education; GE = year of tomato growing experience; S = Seed cost (ETB plot^{-1}); I = irrigation use (1 = user and 0 = otherwise); B = biocide use in litre plot^{-1}; CF = commercial fertilizer use in kg plot^{-1}; L = land size in hectare; DE = disease effect (1 = affected by disease and 0 = otherwise); D = drought (1 = drought effect due to lack of timely water supply on demand throughout the growing period and 0 = water supply on demand throughout growing period); CE = cold effect (1 = cold damage and 0 = otherwise); and e = error term.

Results and discussion

Area, production and yield in the country

Since the start of tomato production in Ethiopia, the cropped area increased to about 5342 ha during 2008. Between 2001 and 2003, the cropped area and production increased by 73% and 75%, respectively, but there was a sharp decrease in both cropped area (22%) and production (34%) in the following year (Fig. 3.2a). In 2005 the cropped area increased by

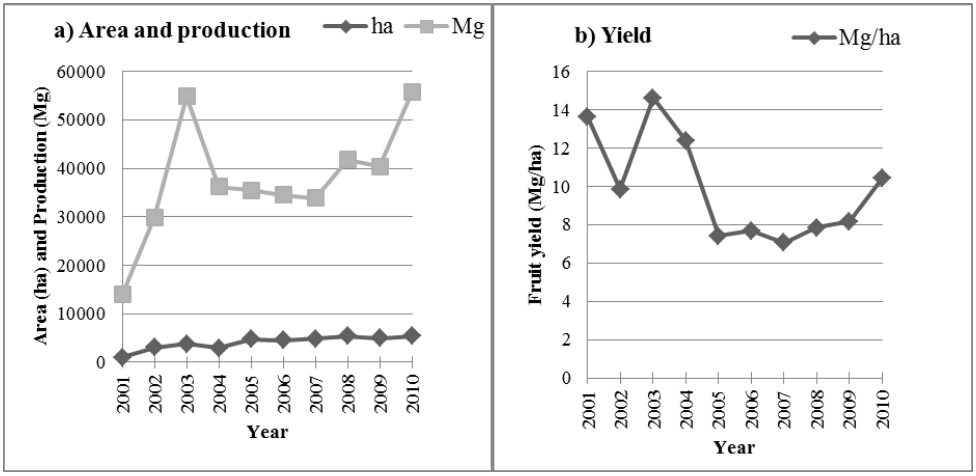


Fig. 3.2. (a) Area of tomato(♦), tomato production (■) and (b) tomato yield (♦) at national level in Ethiopia

39%, but production decreased by 2% because of poor access to fertilizer or low use intensity in most areas, which may have an influence on the yield levels (Fig. 3.2a). This was also affirmed by KIIs. Moreover, Setotaw (2006) also reported similar problems in his study in the same country.

During 2006, both cropped area as well as production dropped by 6% and 2.5%, respectively. In 2007, tomato area increased by 6% while production appears to fall by 2% because of damage by diseases. By 2008, increments of about 10% in cropped area and of 19% in production were observed due to good climate. Nevertheless, in the following year there was a decrease of 7.3% and 3.3% in both cropped area and production as a result of growers facing significant shortage of seeds and shortage of inputs due to exorbitant input prices accentuated by a cut-down in fertilizer subsidy and non-availability of credit facility (Emana *et al*., 2010); then the values went up again because of good market demand (Own Survey, 2011). Average fruit yields varied between 7.05 and 14.6 Mg ha^{-1} during 2001-2010 (Fig. 3.2b).

Area, production and yield in the selected major tomato growing zones

The cropping area varied from 379-1489 ha in different zones with average fruit yields ranging from 6.5 to 24.0 Mg ha^{-1} (Table 3.1). The largest tomato production comes from the late cycle (November-March), due to the large area cropped during that cycle, whereas

Table 3.1. Actual growing period, area, production, average yield and tomato varieties used in selected growing zones in Ethiopia

Zone	Actual growing period (Month)												Area (ha)	Production (Mg)	Actual yield (Mg ha^{-1})	Attainable yield (Mg ha^{-1})	Varieties[6]
	J	F	M	A	M	J	J	A	S	O	N	D					
North Wollo[1]	—	—	—	—	—								91	1429	15.7	23.6	Chali, Roma VFN, Kochoro, Malkashola, Sirinka1, Mersa, Wayno
			—	—	—	—	—						136	1822	13.4		
					—	—	—	—	—				152	1436	9.5		
East Hararghe[2]			—	—	—	—	—						269	2241	8.3	20.2	Kochoro, Kurfa, Chali, Malkashola, Roma VFN
		—	—	—	—	—							376	4775	12.7		
							—	—	—	—	—		251	1619	6.5		
East Shewa[3]	—	—	—	—	—								26	572	22.0	42.2	Bishola, Chali, Eshet, Fetan, Kochoro, Malkashola, Malkasalsa, Miya, Metadel, Roma VFN, Malkassa Marglobe, Heinz-1350, Riogrande, Rossel, Floradade, etc.
		—	—	—	—	—							325	4550	14.0		
				—	—	—	—	—					337	4280	12.7		
					—	—	—	—	—				144	1699	11.8		
							—	—	—	—	—		49	519	10.6		
								—	—	—	—	—	67	1608	24.0		
	—	—								—	—	—	301	6923	23.0		
	—	—	—								—	—	240	5400	22.5		
Jimma[4]	—							—	—	—	—	—	255	1647	6.5	28.7	Chali, Kochoro, Malkashola, Cherry tomatoes
	—	—							—	—	—	—	383	2712	7.1		
	—	—	—							—	—	—	637	6071	9.5		
East Wollega[5]			—	—	—	—	—	—					78	523	6.7	30.0	Chali, Kochoro, Malkashola, Cherry tomatoes
		—	—	—	—	—							117	1112	9.5		
	—	—							—	—	—	—	195	1482	7.6		
	—	—	—								—	—	389	4279	11.0		
	—	—	—	—								—	518	7045	13.6		
Total area, Total production, Average yield													5336	63744	12.0		

Source: (Own survey, 2011); (5, 6) BARC, 2011; (2, 6) EHZBoA 2011; FARC, 2011; Gemechis *et al.*, 2006; (4,6) JZBoA, 2011; (3,6) MARC, 2011; (1, 6) SARC, 2011; SARC, 2006.

highest productivity is from the intermediate late (February-June) cycle followed by the late cycle in East Shewa zone (Table 3.2), because of suitable agro-climatic conditions compared with the other cycles. During 2001-2010, the cropped areas in the sample zones were inconsistently increasing and decreasing. In North Wollo (Fig. 3.3a), cropped area and production increased (2001-2007), but from 2007 onwards the cropped area decreased because of scarcity of irrigation water associated with extended drought for some growers, whereas production increased as a consequence of adoption of fertilizers and use of irrigation by resource-rich growers (Table 3.3).

In East Hararghe (Fig. 3.3c), there were remarkable increases in cropped area and production (2001-2005) because of good climate and market opportunities. However, in 2006, cropped area and production decreased by 19% and 16%, respectively, as a result of poor access to irrigation water and biocides to control diseases (Table 3.3). In East Shewa (Fig. 3.3e), cropped area and production increased by 64% and 70% over the period 2001-2003, but the cropped area declined by 40% in 2004 as a consequence of poor market access during 2003 and shortage of improved seeds (Dessalegn, 2006). Cropped area and production also decreased by 34% and 27%, respectively, in 2006 because of poor access to credit and fertilizer supply. In 2007, the cropped area (24%) and production (30%) increased as a result of good market opportunities. In East Wollega (Fig. 3.3g), cropped area and production increased over the period 2001-2003 as a result of suitable climate and market opportunities, but in 2004 both declined, by 11% and 10%, respectively, because of poor control of late blight. There was a gradual increment in cropped area and production due to poor access to credit and irrigation water and inputs (2005-2008). A decrease of 12% and 9% in cropped area and production, respectively, occurred in 2009 as a consequence of soaring input prices and low product price. In 2010 there was a slight increase in cropped area (5%) and production (6%) as a result of good climate and market. In Jimma (Fig. 3.3i) cropped area and production increased during the period 2001-2003. However, they decreased by 37% and 36% between 2004 and 2005 because of damage by late blight (Ocho, 2006; JZBoA, 2011). From 2005-2008, increases in cropped area (18%) and in production (20%) were observed as a consequence of access to input. These increases were followed by a decrease in cropped area (2%) and in production (3%) in 2009. In 2010 cropped area and production increased by 5% and 6%, respectively.

According to the results from the KIIs and FGDs, about 32-40% of the smallholders

Table 3.2. Crop cycle, growing zones, actual growing period, area, production, average yield and tomato varieties used in sampled growing zones in Ethiopia

Crop cycle	Growing zones	Actual growing period (Month) J F M A M J J A S O N D	Area[1] (ha)	Production[1] (Mg)	Yield (Mg ha^{-1})	Varieties[2]
Early	East Wollega		518	7045	13.6	Kochoro, Malkashola, Chali
Intermediate early	East Hararghe		376	4775	12.7	Kochoro, Chali, Malkashola
	East Shewa		325	4550	14.0	Kochoro, Chali, Fetan
	North Wollo		91	1429	15.7	Kochoro, Marsa, Roma VFN
	East Wollega		117	1111	9.5	
Intermediate late	East Shewa		67	1608	24.0	Malkashola, Kochoro, Chali
	East Hararghe		251	1619	6.5	Roma VFN, Malkashola
Late	East Shewa		240	5400	22.5	Kochoro, Roma VFN, Fetan
	East Wollega		389	4279	11.0	Kochoro, Malkashola, Chali
	Jimma		637	6071	9.5	
Total area, Total production, Average yield			3011	37887	12.6	

Source: (Own survey, 2011); (1) from EHZBoA, 2011;, ESZBoA, 2011; EWZBoA, 2011;, JABoA, 2011 and NWZBoA, 2011; and (2) from BARC, 2011; FARC, 2011; MARC, 2011 and SARC, 2006.

Table 3.3. Determinants of tomato production (yield) in sample ecoregion zones

Explanatory variables	Overall		Sample eco-region zones									
			East Hararghe		Jimma		East Shewa		North Wollo		East Wollega	
	Beta (t value)	Sign.	Beta (t value)	Sign.	Beta (t value)	Sign.	Beta (t value)	Sign.	Beta (t value)	Sign.	Beta (t value)	Sign.
Household education	-0.26 (-1.21)	0.23	0.11 (1.91)	0.06	0.08 (1.86)	0.06	-0.26 (-0.92)	0.36	0.08 (1.19)	0.24	0.01 (0.19)	0.85
Growing experience	0.16 (5.92)	0.00	0.15 (2.75)	0.01	0.14 (3.38)	0.00	0.28 (4.33)	0.00	0.11 (1.31)	0.19	0.17 (3.78)	0.00
Seed cost	-0.25 (-7.86)	0.00	-0.06 (-1.34)	0.18	-0.04 (-0.56)	0.58	-0.04 (-0.53)	0.60	-0.73 (-5.92)	0.00	-0.03 (-0.74)	0.46
Irrigation use	0.06 (3.40)	0.00	0.10 (2.22)	0.03	0.27 (9.06)	0.00	0.08 (2.04)	0.05	0.13 (2.53)	0.01	0.09 (3.37)	0.00
Biocide use	-0.02 (-0.99)	0.32	0.20 (4.34)	0.00	0.16 (3.71)	0.00	0.18 (2.11)	0.04	0.20 (3.53)	0.00	0.17 (4.42)	0.00
Commercial fertilizer use	0.42 (15.82)	0.00	0.30 (6.10)	0.00	0.12 (2.12)	0.04	0.16 (2.91)	0.00	0.26 (5.16)	0.00	0.59 (12.30)	0.00
Land size	0.67 (18.57)	0.00	0.36 (9.93)	0.00	0.48 (6.54)	0.00	0.45 (6.11)	0.00	1.07 (8.74)	0.00	0.36 (8.96)	0.00
Diseases effects	-0.01 (-0.78)	0.43	0.10 (2.19)	0.03	-0.12 (-3.20)	0.00	-0.02 (-0.45)	0.65	-0.24 (-2.41)	0.02	-0.02 (-0.54)	0.60
Drought effects	0.07 (4.14)	0.00	-0.01 (-0.42)	0.64	-0.03 (-0.41)	0.68	0.094 (1.49)	0.14	0.12 (1.21)	0.23	0.07 (2.14)	0.04
Cold effects	0.02 (1.18)	0.24	-0.18 (5.31)	0.00	0.11 (1.95)	0.06	0.02 (0.30)	0.76	0.10 (2.05)	0.05	0.05 (1.08)	0.28
R^2	0.92		0.97		0.95		0.96		0.94		0.97	

R^2= Adjusted coefficient of multiple determination. **Source**: (Own survey, 2011).

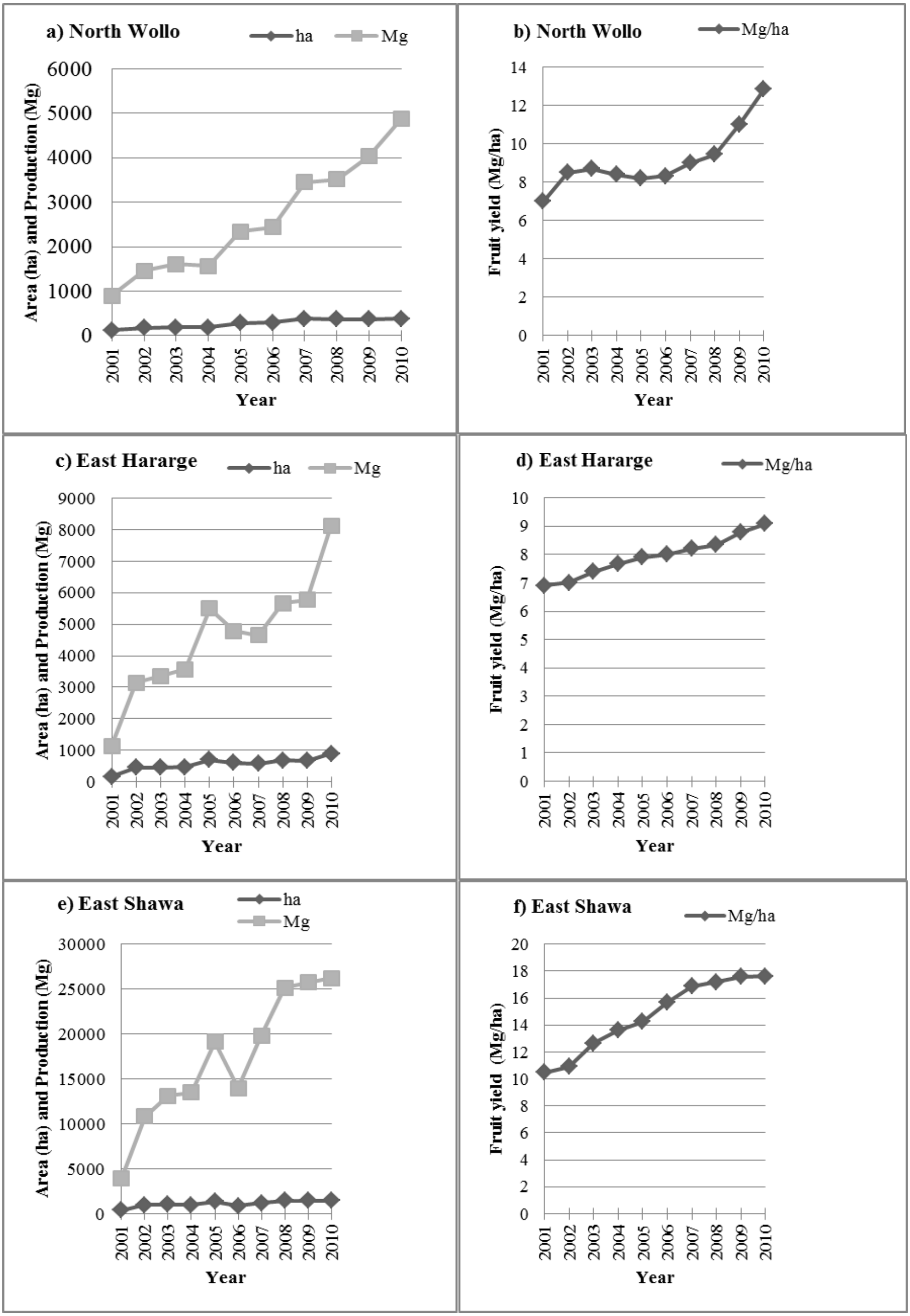
used irrigation (entirely furrow). The study also indicates that various socio-technical problems resulting from inappropriate technology and poor irrigation handling might lead to crop failure. Lack of clear water rights de-motivated growers from participating in irrigation activities which in turn affected the yield (Tables 3.1, 3.2 and 3.3). Although the amount of water needed for irrigation depends on farm size, there are various sources of conflicts in inequitable water distribution due to poor scheme coordination, water theft, water shortages and corruption.

At overall zones level, the significant determinants of yield are number of years of growing experience, seed cost, use of irrigation, amount of commercial fertilizers, land allocated to production and drought effects (Table 3.3). For each unit increment in the number of years of growing experience we observed an estimated yield increase by 0.16 units whereas for every unit increase in improved seeds cost we estimated a yield decrease by 0.25 units keeping all other variables constant. This is because of an increase in costs of improved seed probably made growers tend to use recycled seed or to purchase low quality seed. Similarly, for each unit increment in the level of use of irrigation, commercial fertilizers and land size, we estimated a yield increase by 0.06, 0.42 and 0.67 units, respectively, holding all other variables constant. Likewise, for each unit improvement in drought management there may be a yield increase by 0.07 units keeping other variables constant. However, household education level, amount of biocides, diseases and cold effects were found to be insignificant in constraining yield in our data set. The influence of cold damage was significant only in the East Hararghe, Jimma and North Wollo zones (Tables 3.1 to 3.3). Disease did not seem to affect yield in East Shewa and Wollega sample zones.

The largest tomato production comes from the late cycle, due to the large area whereas the highest productivity is from the intermediate late cycle followed by late cycle in East Shewa zone (Table 3.2) because of suitable agro-climatic conditions compared to other cycles.

Factors affecting tomato production

A diverse range of constraints (Table 3.3) hindered consistent tomato production across the country. Crop production management varied significantly across the zones as it is affected by agro-climatic conditions and culture (Table 3.3).


a) North Wollo
ha
Mg
Area (ha) and Production (Mg)
Year
b) North Wollo
Mg/ha
Fruit yield (Mg/ha)
Year
c) East Hararge
ha
Mg
Area (ha) and Production (Mg)
Year
d) East Hararge
Mg/ha
Fruit yield (Mg/ha)
Year
e) East Shawa
ha
Mg
Area (ha) and Production (Mg)
Year
f) East Shawa
Mg/ha
Fruit yield (Mg/ha)
Year

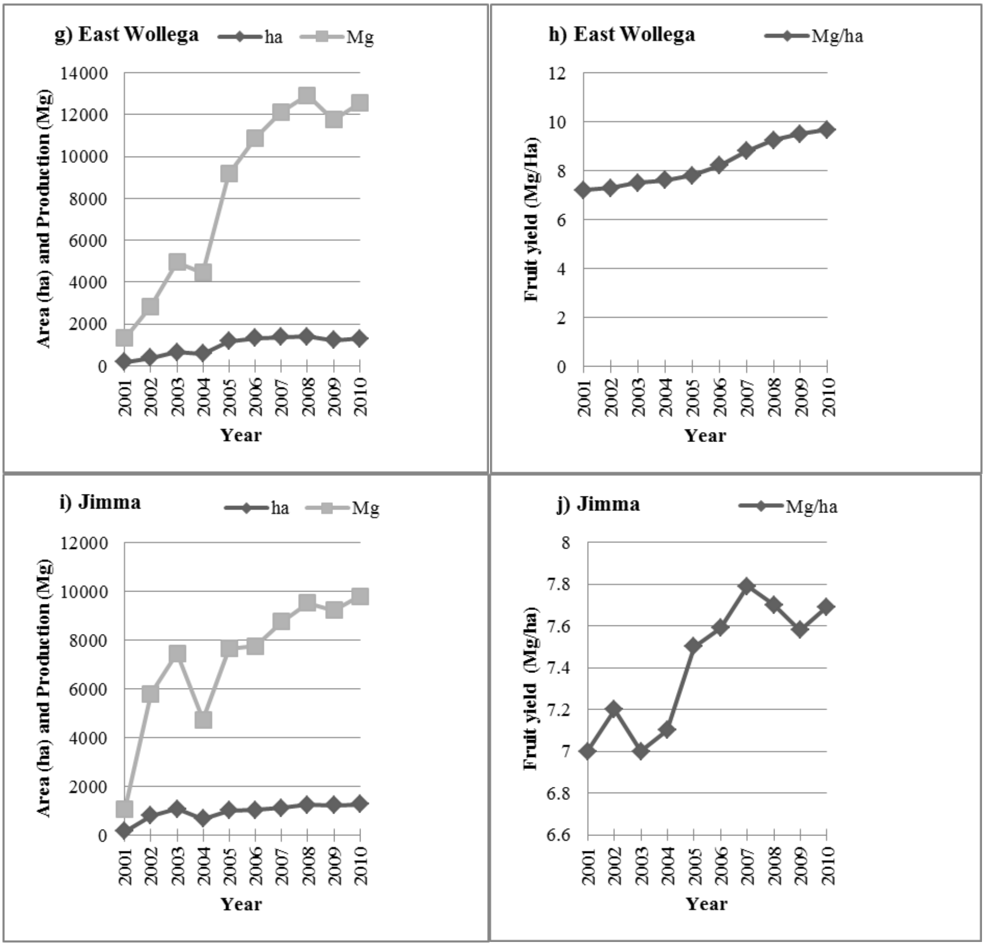


Fig. 3.3. Area (♦), production (■) and fruit yield (♦) in the major tomato growing areas during the period 2001-2010 for North Wollo (a and b); East Hararghe (c and d); East Shewa (e and f); East Wollega (g and h); and Jimma (i and j).

The five survey zones showed significant differences in management practices having influence on productivity.

Insignificant effect of improved seed cost on yield increase was observed in all zones except in North Wollo, probably due to the fact that majority of the growers in these zones used unreliable seed sources or purchased seeds from local traders. Besides low quality seed, other seed- or seedling-related factors could reduce yield including seed ageing, low viability and germination rate due to improper temperature (Perry, 1984), water availability and aeration (Finch-Savage, 1995), poor emergence rates resulting in subsequent reduced growth and yield (Benjamin and Hardwick, 1986; Benjamin, 1990), poor tolerance to sub-optimal conditions, and low seedling growth rates (Powell *et al.*, 1984), many of which might be related to the fact that growers apply sub-optimal management practices. Dias *et al.* (2006) reported for tomato that the lowest percentages seed germination and seedling emergence were obtained from seeds produced on primary branches.

The negative t values in Table 3.3 for seed cost (in all zones), biocides (pooled data), education level (in East Shewa and pooled data), disease (almost in all zones) and drought effects suggest that as these variables increase the yield declines. With regard to biocides, perhaps some growers apply biocides below the recommended dose to be able to spray their entire farm with available biocide while others spray after the tomato has already been affected by diseases.

Explanations on the differential responses of explanatory variables on the output results (Tables 3.1 and 3.3; Fig. 3.3) for the different survey zones are presented in the following section.

North Wollo

Highly significant yield differences were obtained between either amount of biocides or commercial fertilizers users and the non-users. For each increment in litre of biocides, kg of commercial fertilizers and hectare of land size, there was an increase in the amount of yield often highly significantly by 0.20 kg, 0.26 kg and 1.07 kg, respectively, keeping other factors constant. An increase in 1.00 Ethiopian birr of seed cost decreased yield by 0.73 kg of tomato, whereas for each unit increment in use of irrigation and selecting appropriate growing season (or cold effect management) we estimated an increase in yield by 0.13 kg and 0.10 kg, respectively, holding other variables constant. For each unit occurrence of disease we estimated a significant yield decrease of 0.24 kg. The fact that we did not detect a significant yield difference among the numbers of years of experience in growing tomato or a drought effect could be attributed to lack of knowledge on irrigation management practices for obtaining greater returns to irrigation via improved water management and use. Some growers in this zone used uncontrolled flooding irrigation which probably caused lower yield as it was associated with NO_3-N leaching.

East Hararghe

An increase in the education level of household head, use of irrigation, each kg of biocides, each kg of commercial fertilizers and each hectare of land size was associated with an yield increase by 0.11, 0.10, 0.20,0.30 and 0.36 kg per unit, respectively, keeping other variables constant (Table 3.3). The very low increase in yield with each hectare of land size might be because of a tiny plot size (≤ 0.5 ha) for the majority of the household heads in this zone combined with cold effects (Table 3.3). The significant effect of education level indicates that education is a major driving force in tomato productivity in this zone (Table 3.3), corroborating with the report of Asfaw and Admassie (2004) on adoption of chemical fertilizer in Ethiopia. For each unit of disease management there could be a yield increase of 0.10 kg holding other variables constant; growers abandoned tomatoes due to *Phytophthora infestans* and shifted to growing other crops in Haramaya district since 2004 (EHZBoA, 2011) and diseases were identified as yield-reducing factors (YRF) (Table 3.1). Non-significant difference was observed for seed cost and drought effect (Table 3.3). Even though the effect of drought was non-significant, shortage of water mainly occurred in the lowland areas during growing seasons as a yield-limiting factor (YLF) (Own survey, 2011). Growers in this zone entirely used furrow system and relied on boreholes and river/spring lifting for irrigation. Consistent with the report of FARC (2011), we observed that for each unit increase in cold effect there was a probability of yield decrease by 0.18 units in this zone (Table 3.3).

For each year increase of the number of years of growing experience, there is an estimated increase in yield of 0.16 units (Table 3.3), similar to the increase reported for cotton (Bakhsh *et al*., 2005).

East Shewa

For each year increase in the number of years of growing experience, each unit of irrigation, each kg of biocide, each kg of fertilizer and each hectare of land size there may be a probability of yield increment by 0.28 kg, 0.08 kg, 0.18 kg, 0.16 kg and 0.45 kg, respectively, holding other variables constant. The low increase in yield with each hectare of land size in this area is probably associated with a small plot size per household head (< 1.0 ha) and household education level which contributed to low productivity (Table 3.3). Non-significant difference was recorded for education level contrary to findings of Appleton and Mackinnon (1993) and Asfaw and Admassie (2004). This is probably because of uneducated growers' long growing experiences and access to information from the nearby research. Consistent with the reports of Shimelis (2003) and Tesfaye *et al.* (2008), experienced growers who have access to extension service registered significant yield increment. This valley is the leading area regarding tomato production; technological progress was enhanced during 2005-2009 as a result of the JICA-MARC collaborative work (Own survey, 2011), in establishing a Farmers Research Group (FRG) with regard to the use of improved technology including new varieties and biocides (Gelato and Dessalegn, 2011). Better efficiencies of water and fertilizer use may improve actual average yield (Table 3.1). Even though a yield difference was observed among the variables (seed cost, disease, drought and cold), these did not contribute to significant yield differences (Table 3.3), perhaps due to poor quality seed, the occasional presence of diseases and pests and because of favourable agro-climatic conditions for crop production (Own survey, 2011).

Jimma

For each level or grade increase in education level, number of years of growing experience, use of irrigation unit, each litre of biocide, each kg of fertilizer and each hectare of land size might be associated with a yield increase of 0.08 kg, 0.14 kg, 0.27 kg, 0.16 kg, 0.12 kg and 0.48 kg, respectively (Table 3.3); possibly the most important YLF in this area was nutrient depletion caused by soil erosion. The small increase in yield with each hectare of land size in this zone is very likely due to a tiny plot size per household head (0.25 - 0.50 ha), combined with disease effects (Table 3.3). Similarly, the effect of diseases was significant; significant differences between amount of biocides users and non-users might support that YRF might include severe damage of late blight (*Phytophthora infestans*) and bacterial wilt (*Ralstonia solanacearum*), as earlier reported (Ocho, 2006) during heavy rains and highly humid months of July and August and due to the over flooding of irrigation water. Growers in this ecoregion cultivated tomatoes under rain-fed conditions supplemented with irrigation. Non-significant effect of improved seed cost on yield may be attributed to use of recycled seed by most growers which was already explained earlier. Also insignificant differences were recorded due to drought; probably this indicates that external influences like those of agro-climatic fluctuations on tomato production are important. Significant effect of cold on yield was also noted in tomato grown under sub-optimal growing conditions during the months of October to January; for each unit of cold occurrence during such growing months we estimated a yield decline of 0.11 kg (Table 3.3).

East Wollega

For each year increment in number of years of growing experience, use of irrigation unit, each litre of biocide, each kg of commercial fertilizer and each hectare of land size we estimated a yield increment of 0.16 kg, 0.09 kg, 0.17 kg, 0.59 kg and 0.36 kg, respectively (Table 3.3). The low increase in yield with each hectare of land size is because of a tiny plot size for most household heads (< 0.5 ha) in combination with disease effects (Table 3.3). Most growers had access to improved seeds, purchased seeds from local traders were not true-to-type; some growers kept their own source and selected from the 2nd or 3rd generation of their harvests to use it during the subsequent years. A significant difference due to drought possibly implies that the most important YLF was less access to water during growing period of dry years. Although no significant differences were recorded for the factor diseases, the highly significant difference observed for amount of biocides use (Table 3.3) implies the presence of disease and pests including late blight (*Phytophthora infestans*) as YRFs. The explanation given elsewhere for the insignificant effect of cold also applies to this zone.

Conclusions

Tomato cultivation is usually undertaken under full or supplemental irrigation and the crop is grown in various eco-regions during different growing periods with different levels of technology. The majority of growers in some zones are uneducated. Yields varied across eco-regions but were generally low because of constraining agro-climatic conditions, poor access to resources and specific cultural reasons. Growers are attempting to control these constraints, however, most constraints are beyond their capacity requiring due attention from research, extension and policy officials.

While the same variety was in use by the majority of growers across the eco-regions, yields varied among eco-regions and within eco-regions because of differences in seasonal climate and management practices. Education and extension services are crucial for smallholder producers to adopt new technologies. They lack training or adequate knowledge on use of biocides, irrigation, fertilizers, and diseases and drought management in most zones.

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Chapter 4

Growth and dry matter partitioning of field-grown tomatoes (*Solanum lycopersicum* L.) as influenced by irrigation systems and strategies

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Abstract

Effects of different irrigation practices on growth and biomass allocation in fresh market and processing type tomatoes (*Solanum lycopersicum* L.) were studied. Detailed measurements on growth and dry matter partitioning of field-grown tomato were carried out at Batu (Ethiopia) for two seasons under furrow and drip irrigation with three strategies, i.e. according to local empirical practices, according to crop water requirement and deficit irrigation strategy. Growth determining tomato features were quantified for three cultivars. Maximum rate of node appearance was 0.49 nodes d^{-1} and maximum green leaf area index (GLAI) was attained 77 days after planting (DAP), with values of 5.23 and 6.64 for furrow- and drip-irrigation based on crop water requirement (DETc), respectively. Lower maximum GLAI values were observed under deficit irrigation treatment. Highest values of root depth (36.6 cm), plant height (80.6 cm), leaf area (6465 cm^2 $plant^{-1}$), specific leaf area (883 cm^2 g^{-1}), leaf area ratio (499 cm^2 g^{-1}), leaf weight ratio (0.57 g g^{-1}), crop growth rate (1.93 g m^{-2} d^{-1}) and net assimilation rate (1.25 mg cm^{-2} d^{-1}) were recorded for DETc. Fruit dry matter accumulation (fruit DMA) was 38.1 g DM $plant^{-1}$ and fruit dry mass harvest index was 40.7% under DETc. Peak DMA by roots, stems and leaves under DETc were 10.02, 7.74, and 17.98 g $plant^{-1}$, respectively. DMA by roots accounted for 16-20% of total biomass for Chali and Malkashola (processing type), and for 16-18% for Miya (fresh market type) during 47-57 DAP, but accounted for 11, 10 and 11% for Chali, Miya and Malkashola between 57 and 77 DAP. DMA by stems accounted for 31-20, 31-19 and 30-19% of total biomass for Chali, Miya and Malkashola, respectively between 47-77 DAP, but decreased to 22-16 % afterwards. DMA by leaves accounted for 53-69, 53-70 and 54-70% of total biomass for Chali, Miya and Malkashola, respectively from 47-67 DAP, but decreased to 39% (Chali and Miya) and 38% (Malkashola) from 77 DAP onwards. Likewise, fruit dry mass harvest indices (FDMHI) were 39-55, 38-55 and 35-54% (Experiment 1) and 39-45, 38-44 and 38-46 % (Experiment 2) from 87-97 DAP for Chali, Miya and Malkashola, respectively. Variation in irrigation systems and strategies accounted for variation in growth and dry matter accumulation. Using different irrigation systems and strategies and tomato cultivars suitable irrigation practices were identified and discussed and options for improvement are forwarded.

Key words: crop growth rate, dry matter partitioning, Ethiopia, green leaf area index, irrigation, leaf area ratio, net assimilation rate, root depth, specific leaf area, tomatoes.

Introduction

Growth is an irreversible increase in plant size accompanied by a *quantitative* change in biomass. Development is a more subtle phenomenon and implies an additional *qualitative* change in plant form and function (Atwell *et al*., 2003). The dry matter partitioning over component plant parts is a function of the pattern of development of that plant. Thus, factors influencing development also modify the distribution of dry matter. For better yield and quality production of irrigated tomato (*Solanum lycopersicum* L.), detailed knowledge on crop growth and development under a range of irrigation conditions is crucial. Growth studies of the plant should emphasize the level of underlying changes such as rate of organ formation, leaf area development, dry matter accumulation and dry matter partitioning of the crop.

Tomato is a major horticultural plant in Ethiopia. For Ethiopian conditions, data on growth, dry matter accumulation and dry matter partitioning are very scanty for tomato. Frequently, only the fresh fruit yield is registered without details on growth, dry matter accumulation and dry matter partitioning (Birhanu and Tilahun, 2010; Dessalegn, 2002; Yohannes and Tadesse, 1998). Measuring plant productivity helps to improve the efficiency of production in agriculture. Plant dry matter and leaf area development are the spatial and temporal integration of plant processes and, thus plant dry matter and leaf area are relevant variables in explaining plant growth components and plant canopies (Echarte *et al.*, 2008; Sinclair and Muchow, 1999). To address the concern that proper irrigation strategy provides sufficient water to match the plant needs, while not hampering oxygen availability to the roots, we carried out experiments to develop suitable irrigation practice(s) for field-grown tomatoes. The study was conducted using a fresh market tomato type (Miya) and processing tomato types (Chali and Malkashola) with germination of over 85% obtained from Malkassa Agricultural Research Centre. These are featured by semi-determinate and determinate growth having compact branching habit, very good field establishment, high yielding capacity, early fruit set, and firm fruits; they are relatively tolerant to leaf diseases (Dessalegn, 2002).

Dry matter accumulation rate varies across growth phases of a plant. Dry matter, leaf area and other plant traits were measured at 10-day intervals and at harvesting time to quantify effects of different irrigation practices or to analyze differential response of tomato cultivars. In this study, we analyze growth and dry matter accumulation of field-grown fresh market and processing tomatoes based on experiments in which drip or furrow irrigation was applied adopting three different strategies. These three strategies included: i. according to local empirical practices, ii. according to crop water requirement, and iii. deficit irrigation practices. The purpose of this study was to assess in a mechanistic way which irrigation system and strategy would be best in terms of growth and dry matter partitioning of field-grown tomatoes.

Materials and methods

Experimental site, design and set-up

The experiments were carried out in Adami Tullu Jido Kombolcha District (07º 96’ N and 038º 72’ E), on the technology testing site of the International Development Enterprise (IDE) in the open field from August 2010 to March 2011. The experimental design was a split-plot design with three replications assigning cultivars to main plots and the combination of irrigation systems and strategies to sub-plots. Seedlings were transplanted in seven rows of 3.0 m long with 0.7 m between adjacent rows and 0.3 m distance between seedlings within the row. The individual plot area was 14.7 m^2 (4.9 m × 3.0 m) and the average planting density was ca. 4.73 plants m^{-2}. Spacing between plots was 1.0 m.

The two irrigation systems (drip and furrow) were used as follows. The drip irrigation system was designed as the one used by IDE in tomato production farms in the open field in the Central Rift Valley (using 16 mm tubes, with drippers delivering 2 L/h, set 0.3 m apart). Also, the irrigation water was delivered to furrow-irrigated plots by watering cans. Irrigation water was abstracted from ground water by a diesel driven pump to a water tank near the experimental farm. From this tank 15 L capacity watering cans were used to apply the irrigation water according to the three irrigation strategies described below. For the drip irrigation plots water was applied to a 20 L capacity drip kit hanged at 1.5 m while for furrow plots water was directly applied to the furrow between adjacent tomato plants throughout the growing season. Currently, because of water shortages, growers are encouraged to adopt drip irrigation by IDE in Ethiopia. Drip and furrow irrigation were used according to the three strategies described below.

1. According to local empirical practices: Despite noticeable developments, irrigation practice is still based on ancestral skills and characterized by sub-optimal irrigation schedules. Water application is done at intervals based on the growers’ judgment, not necessarily backed

by scientific principles (Ayele Kebede, personal communication, 2008; Jansen *et al*., 2007). The drip and furrow irrigation systems were compared based on this irrigation strategy which maintains a high soil moisture level at all time. Growers variably use scheduling for furrow flooding with 3-5 or even 7 days intervals with too much water while those adopting drip irrigation, irrigate daily 1-2 time(s) depending on growth stages. Accordingly, growers' averaged amount and irrigation scheduling conditions were used to represent local empirical practices.

2. According to crop water requirement: The amount of water and the frequency of irrigation were determined based on criteria derived from the calculated maximum allowable depletion (MAD) and the total available soil water (TAW). These were applied (for both drip and furrow) from two weeks after transplanting (47 days after planting (DAP) or days of vegetative growth) to fruit ripening or fruit picking periods.

3. Deficit irrigation strategy (50% MAD): Crops are deliberately under-irrigated during growth stages that are relatively insensitive to water stress with regard to the quality and quantity of harvestable yield. This strategy allows evapotranspiration (ET) stresses to the plant resulting in yield reduction. As the agricultural sector accounts for over 85% of water usage worldwide, even a relatively small decrease in irrigation water could substantially increase the water available for other purposes.

Except for irrigation all standard management practices were applied throughout the course of the experiments.

Plant material

Fresh market type (Miya) and processing types (Chali and Malkashola) tomato cultivars obtained from Malkassa Agricultural Research Centre were used as planting materials. The cultivars and irrigation treatments were assigned randomly using a lottery method to the main plots and sub-plots, respectively.

Growing conditions

Experiment 1: Average seasonal maximum daily temperature was 26.7 ^{o}C with a corresponding average minimum daily temperature of 13.4 ^{o}C. Average seasonal sunshine was 8.6 hours per day.

Seeds of cultivars Chali, Miya and Malkashola were sown on the 3rd of August 2010 in a seedbed under grass shade conditions (to protect seedlings from hot and cold weather). After hardening, seedlings were transplanted on the 4th of September, 2010, on sandy clay loam soils (NMSA, 2011; ZSLTC, 2011). These seedlings were then grown under open-field conditions subjected to two irrigation systems (furrow and drip) along with three strategies (local empirical practice, according to crop water requirement, and deficit irrigation). Differential water application started 2 weeks after transplanting.

Experiment 2: Average seasonal maximum daily temperature was 27.8 ^{o}C with a corresponding average minimum daily temperature of 13.1 ^{o}C. Average seasonal sunshine was 9.5 hours per day.

Seeds of cultivars Chali, Miya and Malkashola were sown on the 4th of November, 2010, under similar nursery conditions as in Experiment 1, and the seedlings were transplanted on the 4th of December, 2010, in similar soils as in Experiment 1. Tomato plants were cultivated under open-field situations with two irrigation systems (furrow and drip) along with three strategies (according to local empirical practice, based on estimated crop water requirement, and deficit irrigation). Differential water application started as in Experiment 1.

Sampling

From the middle rows of each plot two representative plants were sampled destructively on each sampling date every ten days during Experiment 1 and Experiment 2 growing seasons to assess growth and dry matter partitioning (DMP). After selection, plant height and main stem node numbers were recorded and, subsequently, plants were uprooted with care (from 47-77 DAP) or severed at the ground surface (from 77 DAP onwards root measurements were no longer feasible). During the same growing season root measurements were taken, from 47-77 DAP, by excavating plants to a soil depth of about 0.3 m using a spade and by washing all the soil away from roots in bulk samples taken from prescribed sections of the plot. Development of meristems, leaves and root depth were measured prior to measurement of fresh weights of roots, leaves (leaf blades plus petioles), stems and fruits. A representative leaf subsample (100 g) was taken, leaf blades were separated from petioles, and blades were run through a leaf-area meter to assess GLAI. Subsamples of roots, leaves, stems, and fruits were dried at 65.8 ^{o}C to a constant weight for 48 hours prior to dry weight determinations and grinding. Sampling procedures for both drip- and furrow-irrigated crops were identical as briefed earlier, and plants planted later to fill gaps were excluded from sampling.

Growth measurements

For growth analysis of tomato specific leaf area was calculated as the ratio of total leaf area $(plant)^{-1}$ to total leaf DM $(plant)^{-1}$, whereas leaf area ratio was calculated by dividing the total leaf area $(plant)^{-1}$ to total plant DM $(plant)^{-1}$ and GLAI was derived from the ratio of total leaf area $(plant)^{-1}$ to ground area occupied by a plant stand (Thomas *et al*., 2003). Crop growth rate was calculated according to Poorter (1991), skipping one harvest using destructive measurement each time. Hence, for the second harvest interval, growth rate was calculated as the average of the increase in total dry matter accumulated (TDMA) day^{-1} between the first and third harvest, for the third harvest interval as the increase between second and fourth and so forth. Leaf weight ratio is the ratio between total leaf DM $(plant)^{-1}$ and total DM $(plant)^{-1}$. Net assimilation rate was calculated as the increase of plant DM accumulation per unit of assimilatory material per unit of time i.e.,

$$NAR = \left(\frac{1}{A}\right) * (dW|dt)$$

where A is total LA of the plant, and W is total DM of individual plant.

Relative growth rate (RGR) is the product of net assimilation rate (NAR) and leaf area ratio (LAR).

Specific root length (SRL) is defined as the ratio of total root length to total root biomass.

Specific leaf area (SLA) is a variable that describes the allocation of leaf biomass per unit of leaf area.

Statistical analysis

All data were subjected to Analysis of Variance (ANOVA) to determine the significance of the difference between treatments using the SAS statistical software version 9.2 (SAS Institute Inc., 2008). Mean separations for two-way and three-way interactions were computed by using the Method of Least Squares Means (lsmeans) for variables that showed significant difference among treatment combinations. Least Significant Difference (LSD) test was also performed on significant ANOVA for the comparison of means where main factor was found significant ($p<0.05$). Pearson's correlation test was used to analyze the relationships between growth and development variables.

Results and discussion

Growth analysis of the tomato plant

Green Leaf Area Index (GLAI)

GLAI is linked to processes like photosynthesis, evapotranspiration, plant water status and respiration (Malone *et al*., 2002b), thus quantifying this variable enables to get insight about the plant status.

Generally, a reduction in GLAI leads to a reduced light interception and thus reduced dry matter production (Alarcon *et al.*, 1994; Li and Stanghellini, 2001; Kutuk *et al.*, 2004).

Maximum GLAI values were observed for drip irrigation based on crop water requirement (DETc) followed by local empirical drip irrigation (DLE). Such high GLAI corresponded to a higher rate of dry matter accumulation (DMA) since light interception is directly related to GLAI. This is in line with Echarte *et al.* (2008) and Sinclair and Muchow (1999) that an increase in leaf area (LA) leads to an increase in the rate of DMA via increased light interception. The peak GLAI values of 5.23 and 6.64 obtained from FETc and DETc ,respectively, were high in Experiment 1, but lower (3.28 and 5.53) in Experiment 2 (Table 4.1) due to high temperature and incidence of Fusarium wilt. The first season values were similar to the work of Jones *et al.* (1989) and Marlowe *et al.* (1983), who reported GLAI values of 5.50-6.50 and 7.0 to 8.0 for sub irrigated field-grown and drip irrigated greenhouse-grown tomatoes, respectively. Small GLAI values were observed in the deficit irrigated crops ranging from 1.98-2.60 in both seasons. These lower GLAI values with FDI and DDI crops might have been attributed to induced water stress used in these studies. In line with this finding, Scholberg *et al.* (2000) also elucidated that peak GLAI values below 2.00 or 3.00 in tomato could be ascribed to poor crop growth due to induced water or N stress. GLAI values observed at 77 DAP for FETc and DETc were 4.90 and 5.61, respectively (Fig. 4.1a). The

Table 4.1. Growth and development of field-grown tomatoes as influenced by combinations of irrigation systems and strategies in 2010 (Experiment 1) and 2010/2011 (Experiment 2). PH = plant height; GLAI = green leaf area index; RD = root depth; SRL = specific root length; SLA = specific leaf area; LAR = leaf area ratio; LWR = leaf weight ratio; CGR = crop growth rate; RGR = relative growth rate; NAR = net assimilation rate; FLE = Furrow according to local empirical practice; FETc = Furrow according to crop water need; FDI = Furrow deficit irrigation; DLE = Drip according to local empirical practice; DETc = Drip according to crop water need; DDI = Drip deficit irrigation. Values are averages across three cultivars.

Irrigation	PH (cm)	GLAI (-)	RD (cm)	SRL ($cm.g^{-1}$)	SLA (cm^2 g^{-1})	LAR (cm^2 g^{-1})	LWR (g g^{-1})	CGR (g m^{-2} d^{-1})	NAR (mg cm^{-2} d^{-1})	RGR (mg g^{-1} d^{-1})
Experiment 1										
FLE	72.6D	3.75c	32.8D	37.2b	793d	434d	0.547C	1.64c	1.07c	464d
FETc	74.7C	5.23b	33.8C	36.2bc	835c	463c	0.554B	1.75b	1.12b	518c
FDI	64.8F	2.40e	30.6F	39.6a	627f	336f	0.536D	1.51de	0.84e	321f
DLE	76.9B	5.28b	35.1B	34.5d	857b	473b	0.552BC	1.82b	1.14b	539b
DETc	80.6A	6.64a	36.6A	32.5e	883a	499a	0.565A	1.93a	1.25a	624a
DDI	68.9E	2.60d	31.6E	37.5b	788e	430e	0.545D	1.58cd	0.95d	408e
Experiment 2										
FLE	58.6D	3.08d	30.5c	46.4c	594c	320d	0.538C	1.34d	0.76d	195d
FETc	62.3C	3.28c	32.0b	42.9d	609b	328c	0.539BC	1.48c	0.87c	230c
FDI	52.2F	1.98f	26.4e	52.3a	465e	246f	0.529D	1.11f	0.64e	149f
DLE	67.8B	4.39b	32.4b	39.0e	617b	336b	0.545AB	1.61b	1.16b	310b
DETc	71.9A	5.53a	34.2a	35.1f	644a	352a	0.546A	1.78a	2.01a	576a
DDI	55.0E	2.55e	29.0d	49.0b	552d	295e	0.534CD	1.26e	0.75d	183e

Means within columns for each variable and year followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) or $p \leq 0.01$ (upper case letter).

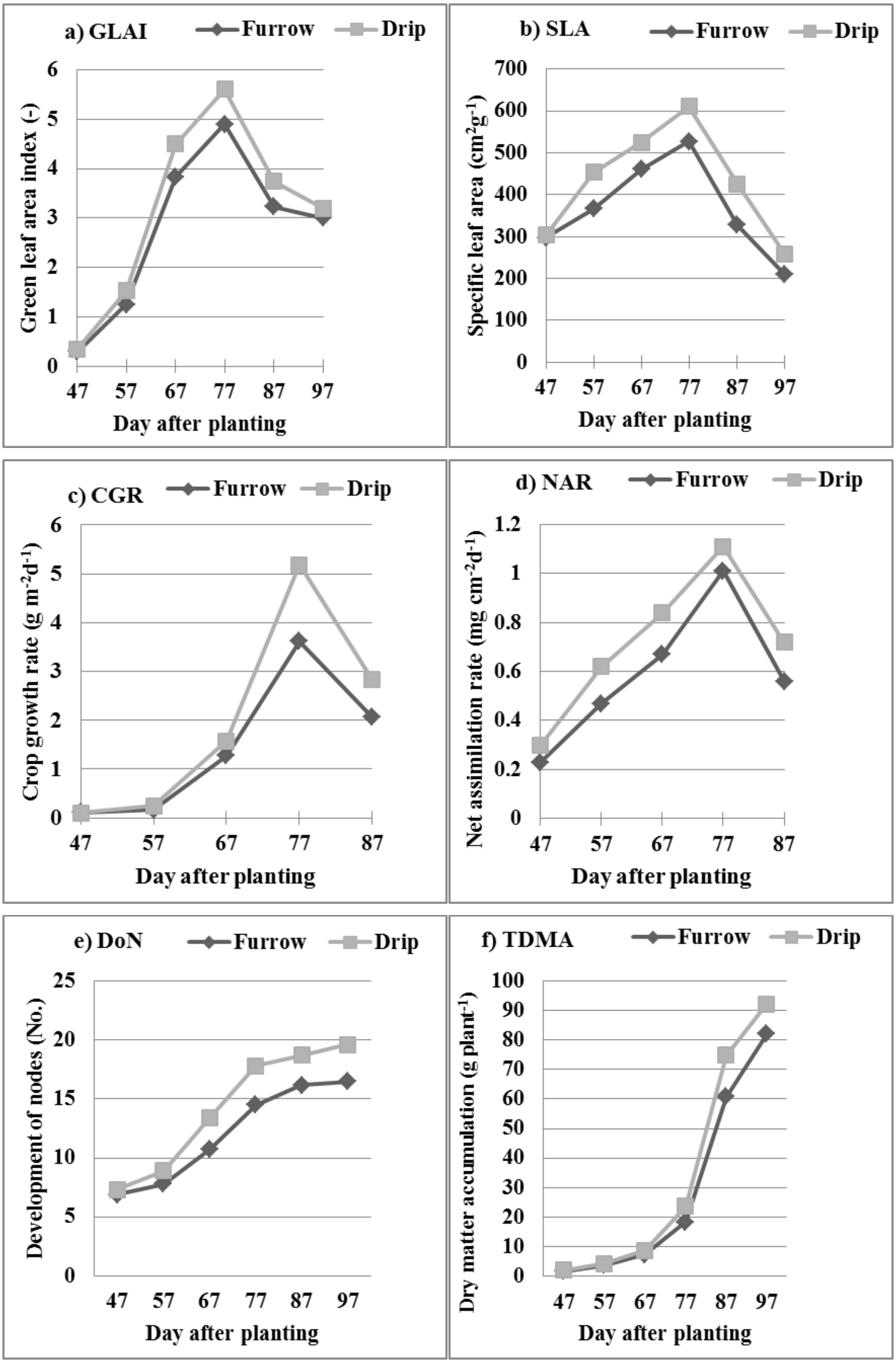

Fig. 4.1. Comparison of drip and furrow irrigation systems on growth of tomatoes.

second season values for FETc and FLE (Table 4.1) were comparable to those reported by Teasdale and Abdul-Baki (1997) who observed a GLAImax of 3.25. GLAI and development of node (DoN) were highly, positively correlated (r^2 = 0.90). The linear increase shown in Fig. 4.1a and 4.1e suggests an exponential relationship between GLAI and DoN. This may be related to the formation of both primary and secondary axillary branches as the DoN increases, with an associated exponential increase in number of leaves (Scholberg *et al.*, 2000).

Specific root length (SRL)

SRL is the ratio of total root length to total root biomass. Greater SRL values were registered for FDI and DDI in both experiments, whereas lowest values were found for DETc and FETc crops (Table 4.1). A negative correlation (r^2 = 0.90) between SRL and CGR was found in this study. Boot (1989) asserted that slow growing grass had a much higher SRL than faster growing species. Poorter and Remkes (1990) in their study on 24 wild plants concluded that the negative correlation between SRL and RGR would only strengthen the positive relationship between LA: root length ratio and RGR and added that fast growing species are more oriented to maximize shoot functioning, whereas slow-growers tend to maximize root functioning. According to these authors' findings, the lower values observed in DETc and FETc crops here probably indicate faster growth compared to FDI and DDI crops and also favoured shoot functioning.

Specific leaf area (SLA)

Specific leaf area is a variable that describes the allocation of leaf biomass per unit of leaf area; it is associated with aspects of plant growth and survival (Garnier *et al.*, 2001; Shipley and Vu, 2002). Moreover, differences in SLA can be ascribed either to morphological (thickness or vein structure) or to the chemical composition of leaf biomass (Dijkstra, 1989). Correspondingly, Poorter and Van der Werf (1998) asserted that SLA explains variations in potential RGR of plants under different environmental situations. Poorter and de Jong (1999) in their review elucidated that SLA is involved in the trade-off between rapid biomass production (high SLA, low leaf dry matter content (LDMC) species) and efficient conservation of nutrients (low SLA, high LDMC species). In this study it was shown that tomatoes grown under DETc (SLA = 883 and 644 $cm^2\ g^{-1}$) and DLE (SLA = 857 and 617 $cm^2\ g^{-1}$) exhibited significantly higher SLA in Experiments 1 and 2, respectively, compared to FETc (Table 4.1).

Plants that are grown with DETc and DLE regimes produced leaves with a low investment in their biomass perhaps attributed to morphological modification that resulted in the increment of photosynthates induced the formation of thinner leaves and increase leaf area (LA) produced by addition of a given unit of this photosynthates favored by sufficient and uniform water distribution to root zone. The low SLA values under FDI (627 and 465 cm^2 g^{-1}) in Experiments 1 and 2 indicated a stress effect on plant growth. Drip irrigation significantly increased SLA by 19, 12, 14, 23 and 19% at 57, 67, 77, 87 and 97 DAP, respectively, over furrow (Fig. 4.1b) as a result of good crop water application.

Leaf weight ratio (LWR)

The leaf weight ratio is an index of the 'leafiness of the plant' on DM basis, a measure of the "productive investment" of the plant, dealing with the relative expenditure on potentially photosynthesizing organs (Thomas *et al.*, 2003). The balance between shoot and root can be formulated from the LWR or the S:R (Poorter and Remkes, 1990), or better the LA: root length ratio (Korner and Renhardt, 1987). In an environment, with a lower productivity, competition for light will be less severe, whereas root competition will gain importance (Tilman, 1984), where a shift in allocation from above to below ground biomass is expected (high root weight ratio, low LWR). In Experiment 1, significantly higher values for LWR were observed under DETc followed by FETc and DLE; however, in Experiment 2 both DETc and DLE allocated more DM to leaves (or higher LWR) and were statistically at par with the other treatments (Table 4.1). Allocation of DM to leaves was increasing from 47-77 DAP as a result of early foliage expansion and a fast increment in the fraction of radiation intercepted but afterwards declined again probably because of a shift in allocation from vegetative to generative organs (Fig. 4.2a, b, c, d, e).

Crop growth rate (CGR) and Relative growth rate (RGR)

Crop growth rate will vary with incident solar irradiance and abiotic stresses may reduce CGR (Sinclair and Muchow, 1999). Average CGRs during initial crop development (47-57 DAP) were low (0.11-0.16 and 0.10-0.24 g DM m^{-2} d^{-1}) for furrow and drip respectively due to low light interception (Fig. 4.1c). The exponential increase in CGR during this growth phase (Fig. 4.1c) was probably due to the linear increase in GLAI as rate of DM accumulation is directly linked to GLAI (Thomas *et al.*, 2003). During this phase both DETc and FETc exhibited similar exponential growth patterns possibly because of good soil

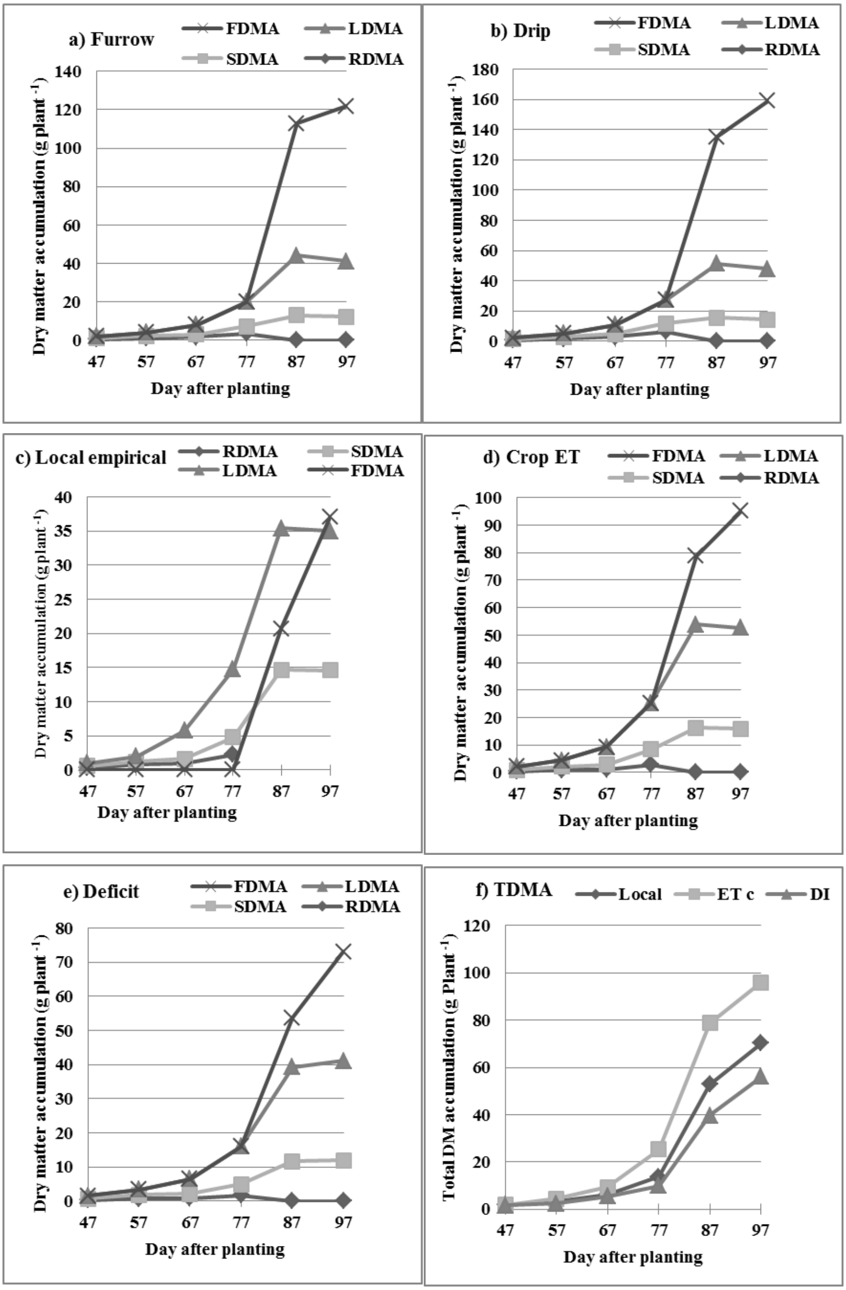

Fig. 4.2. Comparison of furrow and drip irrigation systems and strategy on dry matter accumulation of various plant fractions. FDMA = fruit dry matter accumulation; LDMA = leaf dry matter accumulation; SDMA = stem dry matter accumulation; RDMA = root dry mater accumulation. Different panels indicate dry matter accumulation of fractions (a, b, c, d, e) or of whole plant (f) for different irrigation methods and regimes.

moisture, whereas at 57, 67, 77 and 87 DAP the DETc outperformed the furrow treatment by 33, 19, 30 and 27%, respectively (Fig. 4.1c).

TDM accumulated during the period of a relatively constant rate of DMA is closely related to the duration of the period (57-77 DAP) (Fig. 4.1c), and hence CGR was relatively constant at this phase. However, growth and developmental events in tomato plants seem to overlap, that is, plants produce flowers and fruits while vegetative growth is still continuing, all at the same time (Fig. 4.2a, b, c, d, e). Nevertheless, one can identify a particular process which is predominant over other processes during a particular time. This is in line with Malash *et al.* (2005) who reported that shoot growth decreased with increased shift in allocation of DM to generative organs during flowering. Furthermore, the decline in CGR, during this phase, was 43 and 45% in furrow and drip irrigated plants, respectively (Fig. 4.1c) indicating faster growth of plants under the latter system. The reduction in CGR under FDI tomato plants (compared to those under DETc and DLE) were 19% and 17%, whereas the percentage decrease in CGR under DDI was 14 and 11%, respectively (Table 4.1). CGRs measured in Experiments 1 and 2 were significantly higher for drip than for furrow irrigation (Table 4.1). This may imply that drip irrigation enhanced plant growth through uniform water distribution to the root zone compared to furrow irrigation which activates growth slowly in the season.

The RGR describes the rate of increase in plant mass per plant unit mass already present (Van der Ploeg and Heuvelink, 2005), and differences in RGR can be explained by differences in LAR or NAR, as RGR is the product of LAR and NAR (Hunt, 1990). Tomato under different irrigation treatments varied significantly ($p<0.05$) in mean RGR during both experiments, ranging from 321 for FDI to 624 for DETc in Experiment 1 and from 149 for FDI to 576 mg g^{-1} d^{-1} for DETc in Experiment 2 (Table 4.1). Growth variations among irrigation treatments could be attributed to variations in NAR and LAR during Experiment 1. Increases in NAR and LAR related with increased RGR. However, in Experiment 2 growth variation was entirely attributed to differences in NAR, possibly because of high irradiances. The decrease in NAR under FDI was 32% for Experiment 1 and 68% for Experiment 2 relative to DETc, whereas the decrease in LAR with FDI was about 33% for Experiment 1 and 30% for Experiment 2 (Table 4.1). Likewise, the decrease in NAR under DDI was 24% for Experiment 1 and 62% for Experiment 2 relative to DETc, whereas the decrease in LAR with DDI was about 14% for Experiment 1 and about 16% for Experiment 2. According to

Pons (1977) growth differences can be totally ascribed to a difference in NAR. Contrary to this, Poorter and Remkes (1990) and Dijkstra and Lambers (1989) reported variations in RGR to be due to differences in LAR. Nevertheless our result is contradicting these authors' work, but corroborated with Corré (1983a) who reported that LAR and NAR were linked to the inherent difference in RGR (as in Experiment 1), and with Poorter and Van der Werf (1998), who stated that NAR is the dominant factor at high irradiance in explaining variation in growth.

Net assimilation rate (NAR) and Leaf area ratio (LAR)

As a result of the increase in GLAI under DETc (6.64 and 5.53) (Table 4.1), there was an increase in rate of DM accumulation by roots, stems, leaves and fruits during both years, associated with changes in the rate of DM accumulation per unit of LA (Table 4.2; Fig. 4.1a). During this stage of development (up to 57 DAP), an increase in GLAI led to an increase in rate of DM accumulation. An increase in DM accumulation led to an increase in LA because the proportion of DM allocated to the leaves remained fairly constant during the exponential growth phase (up to 57 DAP). Higher (1.25 and 2.01) and lower (0.84 and 0.64) values of NAR in mg (crop) cm^{-2} (leaf) d^{-1} were registered in Experiments 1 and 2 under DETc and FDI, respectively (Table 4.1). The significant reduction in NAR values under FDI and DDI was a result of a reduction in GLAI which leads to reduced dry matter production (Alarcon *et al.*, 1994; Li and Stanghellini, 2001; Kutuk *et al.*, 2004) through induced water stresses. Significant differences were also noted between furrow and drip irrigation from 57-87 DAP; drip irrigation increased NAR over furrow irrigation by 24%, 20%, 9% and 22% during 57, 67, 77 and 87 DAP, respectively (Fig. 4.1d).

LAR is a morphological index describing the leafiness of the plant (Thomas *et al.*, 2003); it deals with the potentially photosynthesizing and the potentially respiring component of the plant. The ratio is useful in explaining differences in RGR, relating total photosynthetic to total respiratory material within the plant, thereby giving information concerning the plant's available energy balance (Poorter and Remkes, 1990). LAR is the product of the morphological component (SLA) and LWR revealing the fraction of total plant weight allocated to leaves. In this study, highly significant differences among treatments were observed with maximum LAR values (499 and 287 cm^2 g^{-1}) under DETc followed by DLE, FETc, FLE, DDI and least in FDI during Experiment 1 and 2 periods (Table 4.1).

Table 4.2. Development of node (DoN), average node development rate (ANDR), leaf area (LA), shoot:root (S:R) and dry matter accumulation (DMA) of roots, stem, leaves, fruits and total and the fruit dry matter indices (FDMI) of field-grown tomatoes as influenced by the various combinations of irrigation systems (furrow (F) or drip (D)) and strategies (local empirical (LE) or crop water requirement (ETc) or deficit irrigation (DI)) in 2010 (Experiment 1) and 2010/2011 (Experiment 2). Values are averages across three cultivars.

Irrigation	DoN (No)	ANDR (d^{-1})	LA (cm^2)	S:R	RDMA (g)	SDMA (g)	LDMA (g)	FDMA (g)	TDMA (g)	DMHI (%)
Experiment 1										
FLE	13.7d	0.45d	4841D	5.88c	4.29d	5.66D	14.9d	27.7D	48.3D	36.3BC
FETc	14.1c	0.47c	5215C	6.17ab	4.80c	6.12C	15.7c	29.2C	51.08C	37.2B
FDI	12.5f	0.41f	4202F	5.53d	2.44f	4.70F	11.1f	23.4F	39.28F	34.5D
DLE	14.5b	0.48b	5647B	6.13abc	8.05b	6.82B	16.5b	33.1B	56.4B	38.0B
DETc	14.7a	0.49a	6465A	6.30a	10.02a	7.74A	18.0a	38.1A	63.8A	40.7A
DDI	13.3e	0.43e	4579E	5.54d	4.27d	5.16E	13.7e	26.0E	44.9E	35.5C
Experiment 2										
FLE	11.1D	0.37d	3997D	5.82b	4.13D	4.64D	12.2d	22.6d	39.4D	35.6d
FETc	11.8C	0.39c	4289C	5.97a	4.68C	5.10C	13.1c	24.3c	42.5C	36.5c
FDI	10.0F	0.33f	3447F	5.57c	2.50F	3.63F	8.8f	18.6f	31.0F	35.0d
DLE	12.8B	0.42b	4631B	5.95a	8.48B	5.93B	14.1b	28.9b	48.9B	38.0b
DETc	13.7A	0.45a	5203A	6.04a	9.59A	6.95A	15.5a	34.4a	56.9A	40.3a
DDI	10.6E	0.35e	3719E	5.74b	4.14D	4.22E	10.8e	20.7e	35.7E	35.1d

Means within columns for each variable and year followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) and $p \leq 0.01$ (upper case letter). DoN = Development of node; ANDR = Average node development rate; LA = leaf area (cm^2 $plant^{-1}$); S:R = shoot: root; RDMA = Root dry matter accumulation $plant^{-1}$; SDMA = Stem dry matter accumulation $plant^{-1}$; LDMA = Leaf dry matter accumulation $plant^{-1}$; TDMA = Total dry matter accumulation $plant^{-1}$; FDMA = Fruit dry matter $plant^{-1}$; and DMHI = Fruit dry matter harvest index.

Shoot: root (S:R ratio)

Successful plant growth depends on maintenance of a balance between root and shoot growth, but there are differences among species with respect to growth because it reduces the supply of carbohydrates. When nutrient or water is limiting in the soil solution, the growth of shoots slows down, whereas the depth of roots increases. Maximum (6.30 and 6.04) and minimum (5.53 and 5.57) values of S:R were recorded for DETc and FDI, respectively in Experiments 1 and 2. Such a decrease of S:R under deficit irrigation resulted either from an increase in root depth (RD) or from a relatively larger decrease in shoot growth than in RD. Several authors also reported similar results for different plants: *Lonicera implexa* (Navarro *et al*., 2008), *Lotus creticus* (Franco *et al*., 2001; Banon *et al*., 2004), *Myrtus communis* (Banon *et al*., 2002), *Rhamnus alaternus* (Banon *et al*., 2003), *Rosmarinus officinalis* (Sanchez-Blanco *et al*., 2004) and *Silene vulgaris* (Arreola *et al*., 2006; Franco *et al*., 2008).

Growth and development components

Drip irrigation increased plant growth in terms of root growth (RD) and plant height (PH) (Table 4.1), development of meristems (DoN), average node development rate (ANDR) and leaf area (LA) (Table 4.2) as compared to furrow irrigation, in all respective strategies and in both experiments. Drip irrigation according to crop water requirement (DETc) enhanced RD, PH, DoN, ANDR and LA by 8, 7, 4, 4 and 19% (Experiment 1), and by 6, 13, 14, 13 and 18% (Experiment 2), respectively, over the furrow system (FETc) (Tables 4.1 and 4.2). Such a response of plant height to drip system was also described by Bark *et al*. (1979) in watermelon vegetative growth vis-à-vis sprinkler and furrow irrigation. Decreases in RD, PH, DoM, ANDR and LA of tomato plants with furrow deficit irrigation (FDI) were also relevant: 3, 6, 6, 5 and 8% (Experiment 1), and 9, 5, 6, 6 and 7% (Experiment 2), respectively, in relation to drip deficit (DDI). The reduction in leaf area reduced light interception and thus dry matter produced (cf. Malash *et al*., 2008).

Root depth (RD)

Roots depend on shoots for carbohydrates and growth regulators. A reduction in leaf area (LA) by pruning, insect defoliation, grazing, or diversion of assimilates into fruit and seed production reduces root depth, whereas shoots are dependent on roots for water, nutrients and growth regulators (abscisic acid, cytokinins, and gibberellins). Soil moisture status is among the factors known to influence RD and development (Roberts, 1973); high RD values were registered under DETc (36.6 cm) followed by DLE (35.1 cm) and FETc (33.8 cm) in Experiment 1 with similar trend but lower values in Experiment 2. Lower RD values were recorded under FDI (30.6 and 26.4 cm) and DDI (31.6 and 29.0 cm) in both Experiments 1 and 2, respectively (Table 4.1), possibly due to roots failing to develop where soils were devoid of adequate levels of moisture. Moisture stressed plants may exhibit a small root system configuration and decreased root system size proportional to the magnitude of irrigation water applied as shown in Tables 4.1 and 4.2, in which DI strategy causes a decrease in the RD and RDMA because the pattern of root distribution was similar to that of the moisture distribution (Levin *et al*., 1979; Kramer 1995). Decreasing the root system due to water stress led to a decrease in shoot dry weight (Nuruddin, 2001), because the maintenance of a proper balance between these organs is required; if either is too limited or too great in extent, the other will not thrive. The roots grew deep downward (34.2 and 36.6 cm depth by DETc in Experiment 1 and Experiment 2, respectively) to a high soil moisture content resulting in a higher RD compared to the FDI and DDI treatment (Table 4.1). Water stress alters the root system structure by promoting the production of long lateral roots that emerged from the basal portion of the taproot and thus making the direction elongation of these lateral roots more downward (Wright, 2002). However, for tomato RD values with DETc and FETc and DLE; FLE and DDI; DDI and FDI were found statistically at par in Experiment 1. During Experiment 2, no significance difference was found among DETc, DLE and FETc; or between FLE and DDI (Table 4.2).

Development of nodes (DoN) and average node development rate (ANDR)

High node development was recorded in DETc followed by DLE in both years (Table 4.2); the results of the first growing cycle corroborated well with the result of 0.49 nodes d^{-1} under open conditions (Schulbeg *et al*., 2000) and 0.50 nodes d^{-1} under greenhouse situations (Jones *et al*., 1989), whereas the second cycle performed less than the reported value of these authors probably due to the occurrence of high temperature compared with the first season experiment. Drip irrigated tomatoes outperformed furrow irrigated tomatoes by 12%, 20%, 19%, 13% and 16% during 57, 67, 77, 87 and 97 DAP, respectively (Fig. 4.1e). Significant differences among treatments were observed for DoN and ANDR. Higher final numbers of nodes (14.7, 14.5 and 14.1 nodes $plant^{-1}$) were recorded for DETc, DLE and FETc, respectively, as a result of uniform water application via drip and crop demand-based furrow irrigation. But these values are lower than those reported by Scholberg *et al*. (2000), who reported a total maximum number of 19-21 nodes. This is perhaps due to differences in genetic traits, environment or management practices (possibly nitrogen supply). In Experiment 1 node development reduced by 11 and 9% under FDI and DDI in comparison to FETc and DETc, respectively, which might be because of morphological changes in the roots related to the reordering of the assimilate gradient as the flow of solutes towards the roots intensified under water stress situations. The effects of irrigation systems and strategies on ANDR were also similar to those recorded on DoN. Low ANDR under deficit irrigation strategies in both years might be attributed to larger values for root growth characteristics (root length, deep rooting and cortex thickness).

Leaf area (LA)

Table 4.2 shows that maximum leaf growth was observed under DETc (6465 and 5203 cm^2 $plant^{-1}$) followed by DLE (5647 and 4631 cm^2 $plant^{-1}$), respectively during Experiment 1 and 2 growing seasons. At earlier growth stage no difference in LA development between FETc and DETc was found (not presented), but after 57 DAP the LA increased much higher in DETc compared to FETc treatment, probably as a result of increased root development via better water application to the root zone because increasing the root development increased the leaf growth and consequently leaf area. Similar results were observed by Ismail and Davies (1998) who found that restricting root growth reduces the leaf growth.

Plant height (PH)

The effects of irrigation system and strategy on PH were similar to those found on GLAI. PH was enhanced by DETc (80.6) and DLE (76.9) followed by FETc (74.7). Similar pattern was also observed during Experiment 2. Yuan *et al.* (2003) in their work reported that with increasing water utilized, plant height was also increased.

Dry matter accumulation (DMA)

Shoot dry matter accumulation showed an exponential increase from 47-67 DAP followed by a more or less linear growth pattern (constant crop growth rate; Fig. 4.2a, b, c, d, e) between 67 and 87 DAP. Drip irrigation recorded higher values than furrow irrigation in all DMA *viz.,* RDMA, SDMA, LDMA and TDMA throughout the growing period (Fig. 4.2a, b, f). Shoot DMA exhibited exponential and linear growth patterns before 67 and from 67-87

DAP, respectively, but afterwards growth declined due to allocation of DM to sink organs. The increase in total dry matter accumulation (TDMA) was higher under drip irrigation (1.95-92.2 g DM plant^{-1}) compared to furrow (1.68 to 82.0 g DM plant^{-1}) between 47-97 DAP (Fig. 4.2a and b). Higher TDMA was recorded by crop water requirement (ETc) over local (LE) and deficit (DI) strategies. Values in the range of 4.4-96.0, 3.4-70.4 and 2.4-56.0 g (plant)$^{-1}$ were recorded for ETc, LE and DI, respectively from 57-97 DAP (Fig. 4.1f). Likewise, high TDMA values were also observed with DETc followed by DLE and FETc in both Experiments 1 and 2 (Table 4.2). But lower TDMA values resulted from DI strategies.

The increase in leaf dry matter accumulation (LDMA) from 47-67 DAP under both drip (1.04-6.12 g DM plant^{-1}) and furrow (0.89-4.97 g DM plant^{-1}) was gradual and similar (Fig. 4.2a, b), but from 67 DAP onwards the increment by drip irrigation was much higher (6.12-35.9 g DM plant^{-1}) and reduced at 97 DAP because of increased sink strength (Table 4.3 and Fig. 4.2a, b). Likewise the increase for stem dry matter accumulation (SDMA) was gradual for both drip (0.59-1.68 g DM plant^{-1}) and furrow (0.53-1.44 g DM plant^{-1}) during 47-67 DAP (Fig. 4.2a, b). But the increase for both irrigation systems was up to 87 DAP and decreased afterwards. A reduction in both LDMA and SDMA at 97 DAP is related to leaf senescence due to physiological maturity and partitioning to sink organs. RDMA increased from 0.47 to 3.58 and 0.62-6.32 g DM plant^{-1} from 47-77 DAP for furrow and drip irrigation, respectively (Fig. 4.2a,b).

Maximum RDMA values of 9.6-10.0 and 4.7-4.8 g were recorded under DETc and FETc irrigation respectively, whereas minimum ranges (4.1-4.3 and 2.4-2.5 g were observed for drip- and furrow-deficit, respectively (Table 4.2). This may be related to more pronounced root senescence under frequently induced water stress situations near the rooting zone for furrow and deficit irrigated plants. Consistent with findings by Perniola *et al.* (1994), lower DM plant^{-1} from deficit irrigated crops appeared to be related to induced water stress (Table 4.2). Rahman *et al*. (1999) also found that water stress decreased dry matter production in all tomato varieties tested.

High and significant FDMA were observed with DETc (38.1) followed by DLE (33.1) and FETc (29.2) g DM plant^{-1}, respectively in Experiment 1 (Table 4.2), whereas the values observed during Experiment 2 were lower due to increased temperature (briefed earlier) and frequent incidences of Fusarium wilt. However, Teasdale and Abdul-Baki (1997) found higher values than these values of DM plant^{-1} for drip irrigated tomatoes. The lower values

Table 4.3. Fraction (%) of dry matter allocation to roots, stems, leaves and fruits at different developmental stages (DVS) for three cultivars of field-grown tomato in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Days after planting	Roots			Stems			Leaves			Fruits		
	Chali	Miya	Malkashola	Chali	Miya	Malkashola	Chali	Miya	Malkashola	Chali	Miya	Malkashola
Experiment 1												
47	0.29d (16)	0.29d (16)	0.30d (16)	0.56e (31)	0.55e (31)	0.56e (30)	0.96E (53)	0.96f (53)	0.99E (54)	-	-	-
57	0.79c (20)	0.80c (18)	0.81c (20)	1.17d (30)	1.17d (27)	1.19d (30)	1.91D (50)	1.90e (55)	1.99D (50)	-	-	-
67	0.89b (11)	0.88b (11)	0.90b (11)	1.58c (20)	1.53c (19)	1.58c (19)	5.50C (69)	5.45D (70)	5.68C (70)	-	-	-
77	2.22a (11)	2.17a (10)	2.30a (11)	4.57b (22)	4.42b (22)	4.65b (22)	14.10B (67)	13.93C (69)	14.57B (67)	-	-	-
87	-	-	-	14.26a (21)	13.96a (21)	14.44a (21)	33.08A (49)	33.94B (50)	33.55A (49)	19.88B (39)	19.62B (38)	20.55B (35)
97	-	-	-	14.21a (16)	13.93a (16)	14.30a (16)	33.33A (39)	34.40A (39)	33.74A (38)	38.98A (45)	38.84A (45)	39.62A (46)
Experiment 2												
47	0.24d (16)	0.24d (16)	0.25d (16)	0.46e (31)	0.46e (31)	0.47e (30)	0.80e (53)	0.79e (53)	0.83e (54)	-	-	-
57	0.66c (18)	0.65c (18)	0.67c (17)	0.98d (26)	0.96d (26)	0.99d (26)	2.12d (56)	2.06d (56)	2.16d (57)	-	-	-
67	0.76b (16)	0.74b (16)	0.76b (15)	1.34c (28)	1.28c (27)	1.33c (28)	2.68c (56)	2.65c (57)	2.74c (57)	-	-	-
77	1.92a (11)	1.82a (11)	1.97a (10)	3.80b (22)	3.63b (21)	3.94b (21)	11.91b (67)	11.69b (68)	12.50b (69)	-	-	-
87	-	-	-	11.99a (21)	11.72a (21)	12.31a (21)	27.98a (49)	28.20a (50)	28.78a (50)	16.78B (39)	16.35B (38)	17.65B (38)
97	-	-	-	11.95a (16)	11.73a (16)	12.14a (16)	28.07a (39)	28.86a (40)	28.47a (38)	32.64A (45)	32.37A (44)	33.62A (46)

Means within columns for each variable followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) and $p \leq 0.01$ (upper case letter). The first numbers indicate dry matter (g) of roots, stems, leaves and fruits while numbers between brackets indicate % of dry matter allocation of these organs to total biomass. Number followed by letter = dry matter accumulation (g $plant^{-1}$); number in bracket = % of dry matter allocation.

reported here may be because of differential response of genetic traits, environmental or nitrogen supply from those reported elsewhere. During the initial growth phase, DMA by tomato plant was limited by low GLAI (Fig. 4.1a), in conformity with the literature report of Hsiao (1990) that tomato DMA was limited by low canopy interception of radiation.

Lower overall DMA for furrow irrigated crops could be ascribed to lower GLAI values (Fig. 4.1a), resulting in less complete interception of radiation.

Dry matter partitioning (DMP)

DMP is the end product of the flow of assimilates from source organs through a transport pass to the sink organs. DMP among the sinks of a plant is primarily regulated by the sinks themselves. The influence of source strength on DMP is sometimes not a direct one, but indirect through the formation of sink organs. Despite the translocation rate of assimilates may depend on the transport path, the transport path has less role for regulation of DMP at the whole plant level.

Stem and leaf growth exhibited exponential and linear growth patterns during 47-67 and 67-87 DAP, respectively (Fig. 4.2a, b, c, d, e), but from 87 DAP onwards the fraction accumulated by these organs decreased at the expense of sink organs development as a result of a shift in assimilates to these organs. DM accumulation by roots accounted for about 34 and 28% of TDMA by DETc and FETc, respectively at 57 DAP but decreased to 20 and 17% at 77 DAP. DM accumulation by leaves accounted for about 60 and 64% of TDMA for DETc and FETc, respectively at 77 DAP (Fig. 4.2a, b), but decreased to 21 and 24% during 97 DAP. RDMA was limited to certain growing period due to not feasible in obtaining reliable data as root growth getting deep in the soil.

The fractions of DM accumulation in stems at 67 DAP accounted for 28 and 18% of TDMA for DETc and FETc, respectively. The decrease in the respective plant component fractions can be caused by a reduction in plant part partitioning as Scholberg *et al*. (1997) elucidated that a pronounced decrease in leaf and root DM fractions was related to increase additional partitioning to stems and fruits and to greater concurrent senescence rates of leaves and roots. Correspondingly, Scholberg *et al*. (2000) reported that leaf senescence typically begins 30 to 50 days after leaf formation, whereas stems senescence occur only near the end of the growing season. The finding of this study was also in line with the results of these authors. Significant differences due to irrigation strategies (ETc, LE and DI) were also observed in DMP to roots, stems, leaves and fruits (Fig. 4.2c, d, e).

As shown in Table 4.3, DMP by roots accounted for 16-20% of total biomass for Chali and Malkashola (processing type), whereas for 16-18% for Miya (fresh market type) during 47-57 DAP, but accounted for 11, 10 and 11% for Chali, Miya and Malkashola between 57 and 77 DAP. In Experiment 2, DMP by roots accounted for 16-18% for Chali and Miya, and for 16-17% in Malkashola during 47-57 DAP. Between 57-77 DAP the decrease in root DMP for Chali and Miya was 18-11, and 17-10% for Malka Shola. Also DMP by stems accounted for 31-20, 31-19 and 30-19% of total biomass for Chali, Miya and Malkashola, respectively between 47-77 DAP, but decreased to 22-16% afterwards.

In Experiment 2, SDM accounted for 31-16% (Chali and Miya) and 30-16% (Malkashola) of total biomass during 47-97 DAP. DMP by leaves accounted for 53-69, 53-70 and 54-70% of total biomass for Chali, Miya and Malkashola, respectively from 47-67 DAP, but decreased to 39 (Chali and Miya) and 38% (Malkashola) from 77 DAP onwards. Likewise, in Experiment 2, LDM accounted for 53-67, 53-68 and 54-69% of plant biomass between 47 and 77 DAP, then decreased to 39, 40 and 38% of the same order. Fruit dry mass harvest indices (FDMHI) values expressed as the ratio of fruit DM to total above-ground biomass (both on dry mass basis) were 39-55, 38-55 and 35-54% (Experiment 1) and 39-45, 38-44 and 38-46% (Experiment 2) from 87-97 DAP for Chali, Miya and Malkashola, respectively. Scholberg *et al.* (2000) in their study also reported a FDMHI of 60 and 53% for drip and sub irrigated field-grown tomatoes.

Conclusions

Irrigation strategy according to crop water requirement with both drip and furrow irrigation systems increased SLA and LWR in tomato and consequently resulted in a high LAR, whereas water stress (deficit irrigation) resulted in tomato plants with low SLA and a high fraction of root mass, hence low LAR. Variation in RGR among irrigation treatments resulted from the growth traits SLA and LWR. The differences in growth under various irrigation treatments reflected the variation in productivity under such differential water management practices.

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Chapter 5

Comparison of the performance of fresh market and processing tomatoes under different irrigation management practices

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Abstract

Various irrigation systems can be used to apply water to plants where irrigation is crucial. Presently, attention has been given to drip irrigation because it saves water. Irrigation systems can also affect growth components and yield related traits of tomato and occurrence of disease, blossom end rot (BER) and parasitic weeds. Field experiments were conducted in the growing seasons of 2010 (Experiment 1) and 2010/2011 (Experiment 2) to compare the performance of fresh market and processing tomato (*Solanum lycopersicum* L.) under drip and furrow irrigation with different irrigation strategies *viz.,* strategies based on local empirical methods, on crop evapotranspiration and on deficit irrigation practices. Fruits were harvested for 33 (Experiment 1) or 31 (Experiment 2) days. Individual plants were monitored every week and the occurrence of *Phytophthora* root rot, Fusarium wilt *(Fusarium oxysporum)*, BER and *Orobanche ramosa* on roots or leaves, stems or fruits was assessed until the end of harvest. Number of trusses and fruits per plant, number of flowers and fruits per truss, fruit set percentage and fruit weight, stem growth, dry matter production (root, stem, leaf and fruit) were highest for drip irrigation according to crop water requirement, followed by drip irrigation according to local practice and furrow irrigation based on crop water requirement. Deficit irrigation delayed flower initiation and enhanced *Fusarium oxysporum*, BER and *Orobanche ramosa*. *Phytophthora* root rot, however, was most frequent under local empirical furrow irrigation. Cultivar Miya showed a better drought avoidance mechanism than cultivars Chali and Malkashola implying that this fresh market cultivar could adapt better than the two processing types to water deficit areas.

Keywords: Blossom end rot, *Fusarium oxysporum*, growth components, irrigation, *Phytophthora* root rot, *Orobanche ramosa*, tomatoes, cultivar.

Introduction

Drip irrigation is a system of crop irrigation involving the controlled delivery of water directly to individual plants through a network of small emitter openings from plastic tubing or pipes which may be laid on the soil surface, buried, or suspended from trellises. Drip irrigation has improved water use efficiency (WUE) in dry and hot climate areas by reducing runoff and evapotranspiration losses (Dessalegn Lemma, Malkassa Agricultural Research Centre, Ethiopia, personal communication, 2011). Drip irrigation minimizes plant water stress during growth and development by supplying frequent, small-volume irrigations (Hanson *et al*., 2003; Hartz, 2001; Phene, 1999).

In furrow irrigation, water is applied to small and regular channels (furrows) having a small discharge in each furrow to favour water infiltration while the water advances down the field. In the furrow irrigation system about 40% of the applied water is lost due to runoff. Furrow irrigation is suitable for row crops that would be damaged if water covered their stem or crown, which are grown on uniform flat or gentle slopes that should not exceed 0.5%. Soils that crust easily and friable soils are suitable for this irrigation because the water does not flow over the ridge.

Tomato production in the semi-arid regions of the Central Rift Valley of Ethiopia relies on irrigation (Dessalegn, 2002). Furrow irrigation is frequently used in this Valley, as in other countries (Ashcroft *et al*., 2003; Locascio, 2005; Hanson and May, 2006). Surface irrigation by furrow is practised by almost all tomato growers in Ethiopia (Yohannes and Tadesse, 1998; Birhanu and Tilahun, 2010). Most growers have problems due to irregular watering during tomato production. Poor watering practice contributes to blossom drop: the flowers fall off and no fruit develops at all. Research comparing drip irrigation to furrow irrigation in many crops including tomatoes has revealed that drip systems also have better water-use efficiency and offer maximum yields (Flowers *et al*., 2005; Hebbar *et al*., 2004; Singandhupe *et al*., 2003; Tiwari *et al*., 2003).

Irrigation systems may also have large effects on plant health (Rotem and Palti, 1969); furrow irrigation has been associated with disease and salinity, resulting in seedling mortality, in several crops, including tomato and pepper (Miyamoto *et al*., 1986). Furrow irrigation is also considered to encourage the occurrence of soil-borne diseases including *Phytophthora* root rot. A reduction of downy mildew of lettuce caused by *Bremia lactucae* was observed in crops grown with drip irrigation, compared to furrow irrigation, (Scherm and van Bruggen, 1995). However, in another study no significant difference was found between the two irrigation systems (Subbarao *et al*., 1997).

As Allen *et al*. (1992) reported, the incidence of bacterial blight of cotton (*Xanthomonas campestris* pv. *malvacearum)* was neither greater nor lower in furrow than in drip-irrigated plots in different years. In studies conducted on field tomatoes with furrow irrigation, root rot (*Phytophthora parasitica*) disease severity was greater in plots that received prolonged irrigation treatments than with less abundant irrigation (Ristaino *et al*., 1988). Similar results were obtained with chilli wilt or root and fruit rot (*Phytophthora capsici*) on pepper (Cafe-Filho *et al*., 1995). In comparative studies of drip and furrow irrigation, the incidence of *Phytophthora* root rot was greater and the commercial yield of pepper was lower with furrow than with drip irrigation (Xie *et al*., 1999). Growers should be aware that compared to furrow irrigation, drip irrigation's high revenue (i.e. reduction of diseases, increase of crop yield and of water use efficiency) can trade-off its disadvantages (i.e. high initial costs and difficult installation).

This study presents a comparison of the performance of field-grown fresh market and processing tomato cultivars at Batu (Ziway) in two different growing seasons grown under different irrigation systems and strategies. We hypothesize that irrigation system and strategy could influence plant performance, occurrence of disease, blossom end rot and parasitic weeds, and that changing from traditional furrow irrigation to drip irrigation could help growers reducing their impacts on yield. The effects of irrigation system and strategy on yield related traits of tomato and occurrence of disease, blossom end rot and weeds are little known in the area. But evidence suggests that irrigation management affects growth of plant component parts and yield related characteristics of tomato. Thus, the aim of this study was to compare drip and furrow irrigation practices for their impact on yield-related characteristics and growth components, and the development of disease, blossom end rot and weeds and their effects on fresh market and processing tomatoes. We also explored which of these irrigation management practices resulted in best performances for yield-related characteristics and growth components and reduction of yield reducing factors in tomatoes.

Materials and methods

Experiments were conducted at Batu (Ziway) area (07^{o} 96' N and 038^{o} 72' E), Central

Rift Valley, Ethiopia on the technology testing site of the premises of the International Development Enterprise (IDE) in the open field between August 2010 and March 2011. Seeds of fresh market (Miya) and processing (Chali and Malkashola) cultivars were obtained from Malkassa Agricultural Research Centre and sown on 03 August and transplanted on 04 September 2010 for Experiment 1. In the same way, for Experiment 2, seeds were sown on 04 November 2010 and transplanted one month later in the same year. The individual plot dimensions were 4.9 m × 3.0 m. Row distance was 0.7 m; Average planting density was ca. 4.73 plants m^{-2}.

These tomato cultivars were grown on fields having sandy clay loam texture arranged in a split-plot design with three replicates, with the three cultivars as main plots and the irrigation treatments (furrow and drip systems along with three strategies, viz. local empirical, crop water requirement and deficit) as sub-plots. Differential water supply began 14 days after transplanting. The two irrigation systems (drip and furrow) were used as follows. The drip irrigation system was designed as the one used by IDE in tomato production farms in the open field in Central Rift Valley (using 16 mm tubes, with drippers delivering 2 L/h, set 0.3 m apart). Also, the irrigation water was supplied to furrow-irrigated plots by watering cans. Irrigation water was taken from ground water by a diesel driven pump to 200 L capacity barrels for collecting water that could then be used to water plants, near the experimental farm. From these barrels 15 L capacity watering cans were used to apply the irrigation water according to the three irrigation strategies described below. For the drip irrigation plots water was applied to a 20 L capacity jerrycan (drip kit) hanged at 1.5 m while for furrow plots water was directly applied to the furrow between adjacent tomato plants throughout the growing period. At the present time, because of water shortages, growers are encouraged to adopt drip irrigation by IDE in Ethiopia. Drip and furrow irrigation were used as stated by the three strategies described below.

1. Based on practical experience: Despite observable progresses, practice of irrigation is yet depending upon experience or observation alone, without using scientific method or theory and described by below an optimal level irrigation scheduling. Water use for tomato crop is done at length of time according to the growers' opinion, not necessarily supported by experimental observation that describes aspects of tomato irrigation requirement (Ayele Kebede, International Development Enterprise, Ethiopia, personal communication, 2008; Jansen *et al*., 2007). The drip and furrow irrigation methods were examined according to these

irrigation application methods which keep a high soil water level at all time. Producers irregularly adopt scheduling for furrow overflow with 3-5 or even 7 days intervals with heavy watering while those using drip irrigation, supplied water daily 1-2 time(s) based on growth stages. In accordance, producers' averaged amount and irrigation scheduling situations were used to represent practical experience.

2. According to crop water requirement: The amount of water and the number of days between irrigation were determined according to criteria deduced from the calculated maximum allowable depletion (MAD) and the total available soil water (TAW). These were applied (for both drip and furrow) from two weeks after transplanting (47 DAP or vegetative growing) to fruit ripening or fruit harvesting periods.

3. Deficit irrigation strategy (50% MAD): Tomatoes were intentionally under-irrigated during life cycles that are in comparison not susceptible to water stress with regard to the quality and quantity of harvestable yield. This strategy permits evapotranspiration (ET) stresses to the plant resulting in yield reduction.

Data on yield-related traits (number of trusses per plant, number of flowers and fruits per truss, fruit set percentage, average fruit number and weight), growth components (dry matter production of root, stem, leaf and fruit, days to 50% flower initiation, stem diameter) and yield reducing factors (occurrence of *Phytophthora* root rot, Fusarium wilt, blossom end rot (BER) and *Orobanche ramosa*) were recorded for all tomato cultivars. Number of trusses, flowers and fruits were recorded weekly. Fruits were picked at the red ripe stage. Individual plants were monitored for disease symptoms for *Phytophthora* root rot and Fusarium wilt, infection by parasitic weeds, and for number of BER affected fruits per plant; these evaluations were done every 3 to 4 days.

To compare the growth components of fresh market and processing tomato cultivars two representative plants per plot were sampled and weighed and then separated into roots, stems, leaves and fruits. Fresh matter of all collected plant parts (root, stem, leaf and fruit) was measured right after harvesting, whereas dry matter percentage of plant parts was determined after drying for 48 h at 65.8 ^{o}C (vegetative organs) or 105 ^{o}C (fruits) to a constant weight. Identical procedures were followed for data gathering in both experiments. Occurrence of Fusarium wilt, BER and *Orobanche ramosa* in Experiment 1 were negligent. Separate counts were made for healthy fruits and those showing BER during Experiment 2.

The latter number was then expressed as a percentage of the total to provide frequency of BER.

To determine the relative performance of irrigation treatments for cultivars, the following statistic was employed for all yield related traits presented in the tables.

$$RP\ (\%) = (Performance\ under\ DI \div Performance\ under\ ETc)\ \times 100$$

where RP, DI and ETc are relative performance, deficit irrigation and crop evapotranspiration, respectively.

All collected data were subjected to Analysis of Variance (ANOVA) to determine the significance of the difference between treatments using the SAS statistical software version 9.2 (SAS Institute Inc., 2008). When treatment combinations were found to be significant mean separations for two-way and three-way interactions were computed by using the Method of Least Squares Means (lsmeans). Pearson's correlation test was used to analyze the relationships between growth and yield related traits.

Results and discussion

Plant yield-related characteristics and growth components

Number of trusses per plant, number of flowers per truss, number of fruits per truss and per plant, fruit set percentage and fruit weight were lower under furrow deficit irrigation (FDI) than for the other irrigation treatments (Table 5.1). These effects might result in reduced yields (authors' own observation).

Effects of irrigation system and strategy on yield-related traits (number of trusses per plant, the number of flowers per truss, fruit set percentage, number of fruits per truss and per plant, and fruit weight) varied significantly ($p<0.05$) in both experiments (Table 5.1). Deficit-drip and deficit-furrow irrigation underperformed in all yield-related traits compared with drip- and furrow-irrigation according to crop water requirement in both experiments. The relative performances of deficit to crop water requirement strategy for number of trusses and fruits per plant, and number of flowers and fruits per truss, fruit weight and days to flower initiation were in the range of low to high (35-89%) under both drip and furrow irrigation (Table 5.1).

Table 5.1. Comparative performance of full- and deficit-drip and furrow irrigation practices on yield related traits and growth components of tomato in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Yield related trait	Experiment 1						Experiment 2					
	Furrow			Drip			Furrow			Drip		
	ETc	DI	RP (%)	ETc	DI	RP (%)	ETc	DI	RP (%)	ETc	DI	RP (%)
No. of trusses $(plant)^{-1}$	7.9ab	4.9e	62	8.7a	6.0d	69	6.5c	4.0f	62	8.1a	5.7e	70
No. of flowers $(truss)^{-1}$	4.7C	3.0F	64	5.1A	3.6E	71	4.0c	2.4f	60	4.7a	3.2e	68
No. of fruits $(truss)^{-1}$	3.9c	2.2e	56	4.4a	3.1d	70	3.5c	2.0e	57	4.0a	2.7d	68
Fruit set (%)	81.6c	75.0de	92	87.4a	77.0d	97	82.4c	80.0e	93	86.6a	80.8de	97
Average no. of fruits $(plant)^{-1}$	30.8c	10.8f	35	37.4a	18.6e	50	22.8c	8.0f	35	32.4a	15.4e	48
Average fruit weight (g)	49.8c	35.3f	71	53.7a	46.3d	86	50.8a	35.2d	69	51.3a	43.3c	84
DTF (day)	49.3c	68.5a	72	46.6e	62.6b	74	53.3c	64.5a	83	43.4f	59.0b	74
Stem diameter (mm)	11.5c	10.2e	89	12.4a	10.5d	85	9.5c	7.2f	76	11.2a	9.0e	87

Means within rows for each yield related trait and year followed by different letters are statistically significantly different from each other at $p \leq 0.05$ (lower case letter) or $p \leq 0.01$ (upper case letter). The lettering is based on a wider data set and therefore might look odd. DTF = days to 50% flower initiation. ETc = According to crop water requirement; DI = Deficit irrigation. RP = Relative performance.

Furthermore, during Experiment 1 drip irrigation showed significantly higher commercial yield (94.1 Mg ha^{-1}) than furrow irrigation (70.6 Mg ha^{-1}), which amounted to 25% yield increase (authors' own observation). This can be attributed to more fruits per plant and higher fruit weight with drip than with furrow irrigation (Table 5.1). Also other authors reported higher yields for drip than for furrow irrigation (Badr *et al*., 2010). Drip local (DLE) also had lower values for yield-related traits relative to plants grown with drip according to crop water requirement (DETc) in both experiments due to inundated water application via DLE compared with DETc.

DETc on the other hand compared with furrow according to crop water requirement (FETc), produced good values for yield-related traits (trusses $(plant)^{-1}$, flowers $(truss)^{-1}$, fruit set percentage, fruits $(truss)^{-1}$, fruit weight and fruits $(plant)^{-1}$) 9%, 8%, 7%,11%, 7% and 12% increase, respectively, in their respective order, in Experiment 1. In Experiment 2, however, DETc had higher values for a few yield-related traits (trusses $(plant)^{-1}$, flowers $(truss)^{-1}$, fruits $(truss)^{-1}$ and fruits $(plant)^{-1}$) than FETc by 20%, 15%, 12%, and 30%, respectively (Table 5.1). Similarly lower performance for these traits was also observed under FLE compared with DETc in both experiments (Table 5.1).

Trusses $(plant)^{-1}$, flowers $(truss)^{-1}$, fruits $(truss)^{-1}$, fruit set and fruits $(plant)^{-1}$) were reduced by 38%, 36%, 44%, 8% and 65% with FDI compared with FETc in Experiment 1. The under-performance by these traits in Experiment 2 with FDI compared with FETc were also 38%, 40%, 43%, 7% and 65%, respectively (Table 5.1).

Compared with furrow irrigation, drip irrigation enhanced yield-related traits, days to 50% flower initiation and stem growth in both experiments (Table 5.1). Better vegetative (authors' own observation) and generative growth (Table 5.1) with drip irrigation resulted in heavier fruits and more fruits per plant which in turn enhanced yield (data not shown). Significant difference between individual treatments performance was observed. But the relative performance (RP) of drip irrigation compared with deficit-drip irrigation and that of furrow irrigation to deficit-furrow irrigation strategy for fruit set and days to 50% flower initiation (DTF) were similar (Table 5.1).

The underperformance in various yield-related traits such as average fruit weight, flowers $(truss)^{-1}$, fruits $(truss)^{-1}$, trusses $(plant)^{-1}$ and average fruits $(plant)^{-1}$ under DDI compared with DETc ranged from 14-50% in Experiment 1, whereas in Experiment 2 traits performance was smaller than these figures (Table 5.1).

Low (35.3 g) and high (53.7 g) fruit weights were observed with FDI and DETc, respectively, in Experiment 1. Corresponding to Experiment 1 results, low fruit weight of 35.2 g and high fruit weight of 51.3 g were also obtained in FDI and DETc, respectively, in Experiment 2 (Table 5.1).

Performance of yield-related traits of fresh market and processing tomatoes as affected by irrigation practice and cultivar

Table 5.2 shows that performance of cultivar with irrigation practice was significant ($p<0.05$) for yield-related traits. For all the three cultivars performance in trusses $(plant)^{-1}$, flowers and fruits $(truss)^{-1}$, fruit set, fruits $(plant)^{-1}$, fruit weight, days to 50% flower initiation and stem growth was higher with DETc than for the other treatments in both experiments.

The performance of Chali, Malkashola and Miya cultivars with deficit-drip irrigation and deficit-furrow irrigation and full-irrigation treatments is presented in Table 5.2. Performance of cultivar with irrigation management practice indicated that more trusses per plant were observed for Chali (10.0) followed by Malkashola (9.7) and Miya (9.2) in Experiment 1, whereas in Experiment 2, maximum values of 9.1, 8.7 and 8.1 were also observed by these cultivars in their respective order (Table 5.2). As observed from achievement of cultivar with irrigation management practice, the decreases in yield-related traits were greater for FDI than for others treatments in relation to cultivars grown with DETc in both experiments. Water deficit affected fruit set and significantly decreased the number of red fruits in line with the results of Losada and Rincon (1994).

Maximum flowers $(truss)^{-1}$ was observed for Chali (5.4) followed by Malkashola (5.0) and Miya (4.8) with DETc in Experiment 1, but in Experiment 2, Chali showed lower values (4.9) followed by Miya (4.7) and Malkashola (4.6). FDI imposed by reducing irrigation volume by 50% of ETc, in two growing seasons, led to a decrease in trusses $(plant)^{-1}$, fruits $(plant)^{-1}$, flowers and fruits $(truss)^{-1}$ and fruit weight (Table 5.2) and ultimately to lower commercial yield (data not shown) in agreement with the findings of Colla *et al*. (1999). Lowest figure of 2.4 observed by Chali and Malkashola with FDI might be because of the high temperature resulting in flower reduction during this season. Less fruit set for Chali (70%) was observed with FDI in Experiment 1, and such differential response of cultivars to deficit irrigation was matching to Rahman *et al*. (1999) who reported that water stress decreased yield, flower number, fruit set percentage and dry matter production in all cultivars tested and also consistent with Yama *et al*. (2006) who reported that fruit set is highly dependent on cultivar.

As Gladden *et al*. (2011) reported, water deficit earlier during tomato plant growth showed a significant reduction in leaf chlorophyll content and plant height, and rate of truss formation or number of fruits per plants. Table 5.2 shows that the fruits (plant)$^{-1}$ decreased from 46 to 11, from 43 to 13 and from 40 to 10 for Chali, Malkashola and Miya subjected to DETc and FDI respectively during Experiment 1. In the same way, in Experiment 2, the fruits (plant)$^{-1}$ decreased from 38 to 6.5, from 33 to 8 and from 32 to 8 for Chali, Miya and Malkashola, respectively. Fruit weight reduced from 57.1 to 34.1, from 52.5 to 36.5 and from 51.5 to 35.4 g for Chali, Miya and Malkashola, respectively, with DETc and FDI in Experiment 1. Similarly, the decrease in fruit weight ranged from 52.2 to 34.5, from 50.8 to 36.1 and from 51.1 to 35.1 g for Chali, Miya and Malkashola, respectively, in Experiment 2. These results are consistent with findings of Mohammad *et al*. (2012), who reported that flower and fruit number per plant and fruit weight decreased under water stress conditions.

Comparative performance of processing tomatoes with drip irrigation according to crop water requirement and other irrigation treatments

Performance of Chali cultivar for yield-related traits under DLE, FETc and FLE was smaller compared with performance under DETc in both Experiments (Table 5.2). Performance for trusses (plant)$^{-1}$ (14-29%), flowers (truss)$^{-1}$ (11-26%), fruits (truss)$^{-1}$ (17-30%), fruit set percentage (7-14%), fruits (plant)$^{-1}$ (34-48%) and fruit weight (22-30%) was smaller compared with observations under DETc in Experiment 1. In Experiment 2 the proportional declines in these traits were similar.

With regards to Malkashola, decreases for trusses (plant)$^{-1}$, flowers (truss)$^{-1}$, fruits (truss)$^{-1}$, fruit set percentage, fruits (plant)$^{-1}$ and fruit weight under DLE, FETc and FLE were smaller, in the range of 10-26%, 4-14%, 7-25%, 3-11%, 34-48% and 12-40% respectively, compared with performance under DETc in Experiment 1. Likewise, the decreases in Experiment 2 under DLE, FETc and FLE for trusses (plant)$^{-1}$ (25-53%), flowers (truss)$^{-1}$ (4-17%), fruits (truss)$^{-1}$ (7-10%), fruit set percentage (4-12%), fruits (plant)$^{-1}$ (15-30%) and fruit weight (1-7%) were smaller compared with performance under DETc (Table 5.2).

Table 5.2. Performance of cultivar with irrigation management practice on yield related traits and growth components of fresh market and processing tomato cultivars in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Cultivar	Experiment 1						Experiment 2					
	Furrow			Drip			Furrow			Drip		
	LE	ETc	DI	LE	ETc	DI	LE	ETc	DI	LE	ETc	DI
	No. of trusses plant^{-1}											
Chali	7.1c	8.0bc	5.2e	8.6b	10.0a	6.9d	5.7d	6.5c	3.6e	7.4b	9.1a	6.2cd
Miya	7.0cd	7.5bc	4.6e	8.2b	9.2a	6.3d	5.4cd	7.0b	4.2e	7.2b	8.7a	6.1c
Malkashola	7.2cd	8.1bc	5.4f	8.7b	9.7a	6.7d	5.8 b	6.1b	3.6c	7.6a	8.1a	5.5b
	No. of flowers truss^{-1}											
Chali	4.6c	4.8b	3.0f	4.0d	5.4a	3.7e	3.7d	4.0c	2.4f	4.4b	4.9a	3.3e
Miya	4.5c	4.6b	3.0f	4.2d	4.8a	3.5e	3.6d	3.9c	2.5f	4.2b	4.7a	3.3e
Malkashola	4.7c	4.8b	2.9f	4.3d	5.0a	3.6e	3.8d	4.1c	2.4f	4.4b	4.6a	3.2e
	No. of fruits truss^{-1}											
Chali	3.4c	3.8b	2.1f	3.2d	4.6a	3.1e	2.9d	3.4c	1.8f	3.5b	4.2a	2.8e
Miya	3.3d	3.7b	2.2f	3.4c	4.3a	3.1e	2.9c	3.3b	2.0e	3.3b	3.8a	2.6d
Malkashola	3.9c	4.1b	2.4f	3.3d	4.4a	3.0e	3.3d	3.7b	2.1f	3.6c	4.0a	2.7e
	Fruit set (%)											
Chali	73.7c	79.1b	70.1d	79.0b	85.2a	83.7a	78.4b	85.0a	75.0c	79.5b	87.5a	84.4a
Miya	74.2c	80.3b	73.2c	80.6b	89.1a	88.4a	81.5ab	84.6a	80.0b	78.6b	80.8b	78.7b
Malkashola	83.0bc	85.4b	81.8c	78.1d	88.0a	83.3bc	86.8bc	90.2a	87.5ab	81.8d	86.7bc	84.2cd

Table 5.2. Continued…

Cultivar	Experiment 1						Experiment 2					
	Furrow			Drip			Furrow			Drip		
	LE	ETc	DI	LE	ETc	DI	LE	ETc	DI	LE	ETc	DI
	Average number of fruits plant^{-1}											
Chali	24.1c	30.4b	11.0d	27.5b	46.0a	21.4c	16.5d	22.1c	6.5e	25.9b	38.2a	17.4d
Miya	23.1c	27.8b	10.1e	27.9b	39.6a	19.5d	15.7d	23.1c	8.4e	30.2b	33.1a	16.0d
Malkashola	28.0c	33.2b	13.0e	28.7c	42.7a	20.1d	19.1d	22.6c	7.6f	27.4b	32.4a	15.0e
	Average fruit weight (g)											
Chali	44.3c	50.1b	34.1d	49.4b	57.1a	48.6b	48.5b	51.0a	34.5d	48.7b	52.2a	43.7c
Miya	45.5c	49.9b	36.5d	48.8b	52.5a	46.5c	47.0c	50.5b	36.1e	48.2c	50.8b	43.8d
Malkashola	45.1c	49.4b	35.4d	48.0b	51.5a	43.9c	47.6b	50.8a	35.1d	47.8b	51.1a	42.5c
	Days to 50% flower initiation (day)											
Chali	60.1c	48.6d	69.2a	43.0f	44.8e	62.6b	56.6c	53.5d	65.2a	47.0e	40.5f	58.7b
Miya	60.0b	48.6c	65.2a	48.5c	46.6d	61.2b	56.7b	51.9c	61.5a	49.8d	44.0e	57.7b
Malkashola	59.8c	50.8d	71.1a	46.6f	48.4e	64.1b	56.8c	54.6d	67.0a	48.8e	45.7f	60.5b
	Stem diameter (mm)											
Chali	11.0c	11.5b	10.1e	11.6b	12.6a	10.5d	8.7e	9.6d	6.9f	10.3b	11.6a	9.8c
Miya	10.8d	11.7b	10.3e	11.3c	12.4a	10.7d	9.3c	9.5b	7.6d	10.8a	10.7a	9.5b
Malkashola	10.7c	11.4b	10.2e	11.4b	12.2a	10.4d	9.1e	9.5d	7.1f	10.3b	11.4a	9.9c

Means within rows in each parameter and year followed by different letters are statistically significantly different from each other at $p \leq 0.05$ (lower case letter). FLE = Furrow local empirical FETc = Furrow according to crop water requirement; FDI = Furrow deficit irrigation; DLE = Drip local; DETc = Drip according to crop water requirement; DDI = Drip deficit irrigation.

In general, a decrease in flowers and fruits $(truss)^{-1}$, and fruits and trusses $(plant)^{-1}$ was observed with DDI relative to DETc, followed by FLE and FETc for Chali in descending order in both experiments (Table 5.2). However, for Malkashola the decrease was more with DLE (14%, 25%) than with FETc (4%, 7%) in Experiment 1.

Comparative performance of fresh market tomatoes with drip irrigation according to crop water requirement and other irrigation treatments

For Miya, the relative performance of flowers $(truss)^{-1}$, fruits $(truss)^{-1}$, fruit set, trusses $(plant)^{-1}$, fruit weight and fruits $(plant)^{-1}$ under DETc was 12%, 21%, 10%, 11% 13% and 30% respectively, compared with attainment under DLE in Experiment 1, whereas in Experiment 2 it was, 11%, 13%, 3%, 17%, 5%, and 9% in their respective order (Table 5.2). Concurrently, decreases for the aforementioned traits under FETc relative to DETc were 4%, 14%, 10%, 18%, 5% and 30% in Experiment 1, while in Experiment 2, with the exception of fruit set, the decreases were 17%, 13%, 20%, 1% and 30% in the same order (Table 5.2). In the same way, performance under FLE in comparison with DETc for fruit set percentage and fruits $(plant)^{-1}$ were 17% and 42% in Experiment 1, whereas in Experiment 2, the decrease was only for fruits $(plant)^{-1}$ (53%).

The decrease in flowers and fruits $(truss)^{-1}$ was more with DLE (13%, 21%) than with FETc (4%, 14%) for Miya. Also in Experiment 2, however, performance of Miya for all yield-related traits was in line with that of Chali, whereas Malkashola was in line with its performance in Experiment 1. Moreover, we generally explored that greatest performance was observed for traits grown with DETc followed by DLE, FETc, FLE and DDI in descending rank but with poor performance with FDI.

As a result of Miyas' better drought avoidance mechanism than Chali and Malkashola cultivars it is possible to suggest Miya cultivar for water deficit areas or dry season cultivation. This work is in line with Cherinet's (2011) findings who reported good performance of this cultivar in arid area (Humera).

The relative performance (RP) of Miya for number of flowers per truss observed with FDI was 65% and 65% of FETc and that for DDI was 73% and 69% of DETc for Miya in Experiments 1 and 2, respectively. Like for the number of flowers per truss, a similar pattern was also observed for the number of fruits per truss for this cultivar. The RP of FDI to FETc of Malkashola for fruit set was 96%, whereas RP of DDI to DETc of Miya was 99% in

Experiment 1. Similarly, in Experiment 2 the RP of FDI to FETc of Malkashola was 97%, whereas that of DDI to DETc of Miya was 97% (Table 5.3).

As Reina-Sanchez *et al*. (2005) reported, yield of tomato is determined by average fruit weight and fruit number. We observed for Chali that FDI significantly reduced the number of fruits (36% of FETc), whereas fruit weight was only 68% of FETc. FDI reduced fruit number in Miya in similar proportions (36%), but had a major effect on fruit weight, yielding 68%, 73% and 72% of FETc for Chali, Miya and Malkashola, respectively, in Experiment 1 (Table 5.4). In Experiment 2, however, a noticeable reduction in fruit number and fruit weight was observed in Chali (29% and 68%) followed by Malkashola (34% and 69%), respectively. This result is in conformity with Mohammad *et al*. (2012) who reported that flower and fruit number per plant and fruit weight decreased under water deficit conditions.

The RP of FDI to FETc of Chali, Miya and Malkashola for flower initiation was delayed by 42%, 34% and 40% respectively, whereas the RP of DDI to DETc of these same cultivars was delayed by 40%, 31% and 32% in the same order in Experiment 1. The RP of DDI to DETc for flower initiation in Experiment 2 also had a similar pattern as in Experiment 1. But the RP of FDI to FETc for this trait was delayed by 22%, 19% and 23% respectively, indicating a delay in flower initiation due to induced water deficit. Although the RPs with deficit (DI) and crop water requirement (ETc) treatments were similar for each cultivar in both seasons, early flowering was observed in Experiment 1 as a result of moderate increase in temperature (data not shown), thereby advancing flower initiation. The RP of DI to ETc of Miya for stem diameter increased in both experiments showing that Miya may be adapted to water deficit compared with the two cultivars.

Comparison of growth components of fresh market and processing tomatoes with drip irrigation according to crop water requirement and other irrigation treatments

Days to 50% flowering (DTF): Relative to FETc, days to 50% flowering (DTF) was delayed by 28% with FDI, and stem thickness was reduced by 11% (Table 5.1). Performance of these variables with DDI and FDI relative to full-drip and full-furrow irrigation was shown in Table 5.1, and similar patterns for yield related characteristics were also observed.

Table 5.2 showed that significant differences among treatments for all cultivars were observed and deficit irrigation resulted in later flower initiation than local empirical and full-

Table 5.3. Comparison of performance of fresh market and processing tomato cultivars under full- and deficit-drip and furrow irrigation practices in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Cultivar	Experiment 1						Experiment 2					
	Furrow			Drip			Furrow			Drip		
	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)
	No. of trusses plant^{-1}											
Chali	8.0bc	5.2e	65	10.0a	6.9d	69	6.5c	3.6e	55	9.1a	6.2cd	68
Miya	7.5bc	4.6e	61	9.2a	6.3d	68	7.0b	4.2e	60	8.7a	6.1c	70
Malkashola	8.1bc	5.4f	67	9.7a	6.7d	69	6.1b	3.6c	59	8.1a	5.5b	68
	No. of flowers truss^{-1}											
Chali	4.8b	3.0f	62	5.4a	3.7e	69	4.0c	2.4f	61	4.9a	3.3e	67
Miya	4.6b	3.0f	65	4.8a	3.5e	73	3.9c	2. 5f	65	4.7a	3.3e	69
Malkashola	4.8b	2.9f	60	5.0a	3.6e	71	4.1c	2.4f	59	4.6a	3.2e	68
	No. of fruits truss^{-1}											
Chali	3.8b	2.1f	55	4.6a	3.1e	67	3.4c	1.8f	54	4.2a	2.8e	66
Miya	3.7b	2.2f	60	4.3a	3.1e	72	3.3b	2.0e	59	3.8a	2.6d	68
Malkashola	4.1b	2.4f	59	4.4a	3.0e	68	3.7b	2.1f	58	4.0a	2.7e	67
	Fruit set (%)											
Chali	79.1b	70.1d	89	85.2a	83.7a	98	85.0a	75.0c	88	87.5a	84.4a	96
Miya	80.3b	73.2c	91	89.1a	88.4a	99	84.6a	80.0b	95	80.8b	78.7a	97
Malkashola	85.4b	81.8c	96	88.0a	83.3bc	95	90.2a	87.5ab	97	86.7bc	84.2cd	97

Table 5.3. Continued…

Cultivar	Experiment 1						Experiment 2					
	Furrow			Drip			Furrow			Drip		
	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)
	Average number of fruits plant^{-1}											
Chali	30.4b	11.0d	36	46.0a	21.4c	47	22.1c	6.5e	29	38.2a	17.4d	46
Miya	27.8b	10.1e	36	39.6a	19.5d	49	23.1c	8.4e	36	33.1a	16.0d	48
Malkashola	33.2b	13.0e	39	42.7a	20.1d	47	22.6c	7.6f	34	32.4a	15.0e	46
	Average fruit weight (g)											
Chali	50.1b	34.1d	68	57.1a	48.6b	85	51.0a	34.5d	68	52.2a	43.7c	84
Miya	49.9b	36.5d	73	52.5a	46.5c	89	50.5a	36.1e	72	50.8b	43.8d	86
Malkashola	49.4b	35.4d	72	51.5a	43.9c	85	50.8a	35.1d	69	51.1a	42.5c	83
	Days to 50% flower initiation (day)											
Chali	48.6d	69.2a	142	44.8e	62.6d	140	53.5d	65.2a	122	40.5f	58.7b	145
Miya	48.6c	65.2a	134	46.6d	61.2b	131	51.9c	61.5a	119	44.0e	57.7b	131
Malkashola	50.8d	71.1a	140	48.4e	64.1b	132	54.6d	67.0a	123	45.7f	60.5b	132
	Stem diameter (mm)											
Chali	11.5b	10.1e	88	12.6a	10.5d	83	9.6d	6.9f	72	11.6a	9.8c	84
Miya	11.7b	10.3e	88	12.4a	10.7d	86	9.5b	7.6d	80	10.7a	9.5b	89
Malkashola	11.4b	10.2e	89	12.2a	10.4d	85	9.5d	7.1f	75	11.4a	9.9c	87

Means within rows in each parameter and year followed by different letters are statistically significantly different from each other at $p \leq 0.05$ (lower case letter). FLE = Furrow local empirical FETc = Furrow according to crop water requirement; FDI = Furrow deficit irrigation; DLE = Drip local; DETc = Drip according to crop water requirement; DDI = Drip deficit irrigation; [1]RP = Relative performance furrow irrigation treatments. Early flower initiation was observed for Chali at 43 and 41 days after planting, in Experiments 1 and 2, respectively under DETc. But delays in flower initiation were observed for Malkashola (71 DAP) followed by Chali (69 DAP) under FDI compared with DETc in Experiment 1. This finding is corroborated with previous work: Angus and Moncur (1977) reported that days to flower initiation also seems sensitive to water stress. Relative delays of flower initiation for Chali under FDI and DDI compared with DETc were 55% and 40%, respectively in Experiment 1, whereas this delay was longer during Experiment 2 (62% and 45%, respectively).

Similarly, in Malkashola days to flower initiation was delayed by 47% and 32% with FDI and DDI, whereas with FLE and FETc delayed by 24% and 5%, respectively, relative to DETc during Experiment 1, and this was consistent with FDI, DDI and FLE in Experiment 2 (Table 5.2). In Miya, however, flower initiation was delayed by 40%, 31% and 29% under FDI, DDI and FLE, respectively, compared with DETc in Experiment 1, and this was also consistent with Experiment 2.

Growth of stem diameter

Although significant differences were noted in individual treatment performance, the differences observed between RP (%) of drip- and furrow- for stem growth were small (Table 5.1). In Experiment 2, stem growth of tomatoes grown under different irrigation treatments (Table 5.1) was also significantly different ($p<0.05$). As Costa *et al*. (2007) reported, we also found that plants irrigated with deficit-drip and deficit-furrow had thinner stems than plants with full irrigation (Table 5.1). Interaction effects of cultivar and irrigation management were found to be significant ($p<0.05$) for stem diameter, with values ranging from 10.2 until 12.4 mm) with FDI and DETc, respectively, in Experiment 1 (Table 5.2).

In this study (Table 5.2), significant differences were observed among irrigation treatments for all cultivars, and reduction in stem diameter was larger in deficit irrigation than for local empirical and full furrow irrigation practices. A reduction of 20%, 17%, 13% and 9% was recorded for Chali under FDI, DDI, FLE and FETc, respectively compared with DETc in Experiment 1. The reduction in stem thickness with FDI, FLE and FETc was larger in Experiment 2.

In Malkashola, the reduction of stem diameter with FDI and DDI was 16.4% and 14.8% with a slight decline with FLE, FETc and DLE in Experiment 1. In Experiment 2, however, the reduction was larger than in Experiment 1. In Miya, the response to irrigation treatments was also similar for both experiments, except for the larger reduction with FDI than with other treatments in Experiment 2.

Maximum stem thickness was observed for Chali (12.6 mm) followed by Miya (12.4 mm) and Malkashola (12.2 mm) with DETc in Experiment 1. A reduction in 50% crop water requirement (FDI and DDI) in Miya was found to perform better (10.3 and 10.7 mm) than in Chali and Malkashola under the same condition of water deficit possibly because its ability to avoid drought under high evaporative demand, thereby maintaining high leaf water status (Table 5.3). Other studies indicate also that by decreasing 40% in crop water requirement, a better performance of this tomato cultivar under deficit irrigation has been observed because of its drought avoidance mechanism (Bwarama and Henderson, 1985).

Dry matter production of plant parts

The interaction between cultivar and irrigation management for vegetative dry matter production was highly significant ($p \leq 0.01$). Variation in irrigation management significantly influenced dry matter production in all cultivars. Table 5.4 shows that full drip-irrigation significantly enhanced dry matter production of all plant organs compared with furrow, in all three tomato cultivars.

Root dry matter production

Maximum root dry matter (RDM) production was observed with full drip irrigation (DETc) for all cultivars in Experiments 1 and 2 (Tables 5.4 and 5.5). Greater reduction in RDM occurred with FDI (48%) followed by plants grown with DDI (39%), FLE (35%), and FETc (30%) for Chali relative to DETc in Experiment 1, whereas in Experiment 2, the reduction was 55.4%, 44%, 38% and 37.4% in the same order.

The underperformance in root dry matter (RDM) production with FDI, DDI, FLE, FETc and DLE compared with DETc for Miya was 37%, 34%, 33%, 28% and 22%, respectively in Experiment 1, but the reduction was 42%, 34%, 34%, 31% and 23%, respectively in Experiment 2, (Table 5.4). Performance of Malkashola with the above treatments was in line with that of Chali and Miya.

Table 5.4. Comparison of growth components of fresh market and processing tomato cultivars under full- and deficit-irrigation practices in 2010 (Experiment 1) and 2010/2011 (Experiment 2). Since not all treatments are represented in this table, mean separation does not show all letter options.

Cultivar	Experiment 1						Experiment 2					
	Furrow			Drip			Furrow			Drip		
	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)
	Root dry matter (g plant^{-1})											
Chali	1.03c	0.77f	75	1.48a	0.90e	61	0.87c	0.62e	71.3	1.39a	0.78d	56
Miya	1.00c	0.88e	88	1.39a	0.92d	66	0.83c	0.70f	84.3	1.21a	0.76e	66
Malkashola	1.05c	0.84f	80	1.43a	0.91e	64	0.88c	0.66e	75.0	1.28a	0.80d	64
	Stem dry matter (g plant^{-1})											
Chali	6.1C	3.8F	62.3	8.2A	5.16E	62.9	5.09C	3.20F	62.9	7.40A	4.79D	64.7
Miya	5.9C	3.9F	66.0	7.3A	4.78E	65.5	4.86C	3.21E	66.1	6.58A	4.42D	67.2
Malkashola	6.3C	4.1F	65.0	7.7A	4.94E	64.2	5.36C	3.46F	64.6	6.88A	4.50E	65.4
	Leaf dry matter (g plant^{-1})											
Chali	15.7C	10.3F	65.6	18.6A	12.48E	67.1	13.04B	8.42E	64.6	16.04A	7.4F	46.1
Miya	15.4C	10.2F	66.3	17.6A	11.88E	67.5	12.71B	6.6F	51.9	14.96A	8.52E	69.1
Malkashola	15.9C	10.5F	66.0	17.8A	11.81E	66.4	13.45B	6.9F	51.3	15.51A	8.77E	67.2
	Fruit dry matter (g plant^{-1})											
Chali	28.9c	22.3f	77.2	39.3a	25.3e	64.4	24.36c	16.14e	66.3	35.70a	22.6d	63.3
Miya	28.6c	24.5f	85.7	37.1a	26.7e	72.0	23.2c	15.76e	67.9	32.87a	22.1d	67.2
Malkashola	30.3c	23.4f	77.2	38.0a	26.0e	68.4	25.8c	17.35f	67.2	34.57a	23.0e	66.5

Means within rows for each parameter and year followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) and $p \leq 0.01$ (upper case letter). FLE = Furrow local empirical FETc = Furrow according to crop water requirement; FDI = Furrow deficit irrigation; DLE = Drip local; DETc = Drip according to crop water requirement; DDI = Drip deficit irrigation; [1] RP = Relative performance

Stem dry matter production

The reduction in stem dry matter (SDM) production under FDI and DDI compared with DETc was large for all cultivars in both experiments, but the reduction varied among cultivars in Experiment 2. The reductions for Chali, Miya and Malkashola were 53.7%, 46.6% and 46.8% with FDI and 37.1%, 34.5% and 35.8%, with DDI respectively, relative to DETc in Experiment 1, whereas in Experiment 2, these were 56.8%, 51.4% and 49.7% with FDI and 35.3%, 32.8% and 34.6% with DDi, in their respective order (Table 5.4).

Underperformance for SDM of Miya and Malkashola with FLE and FETc relative to DETc was similar. Reduction in SDM with FLE for Miya and Malkashola was 24.7% (both experiments), and the decline with FETc for these cultivars was also 19.2% (Experiment 1) and 18.2% (Experiment 2) in relation to DETc (data not shown).

However, the reduction for Chali was greater than for the other cultivars in Experiment 1: 31.7% with FLE and 25.6% with FETc. In Experiment 2, SDM reduction for Chali, Miya and Malkashola was 37.8%, 31.8% and 30.4% with FLE and 31%, 25.8% and 21.7% with FETc, respectively, compared with DETc.

Leaf dry matter production

The observed reduction in leaf dry matter (LDM) production with FDI and DDI in relation to DETc for all cultivars during Experiment 1 was found to be similar. Reduction in LDM for Chali, Miya and Malkashola was 44.6%, 42.0% and 41.0% with FDI and 32.9%, 32.5% and 33.6% with DDI, respectively, relative to DETc in Experiment 1. In Experiment 2, except with DDI for Chali, a similar pattern of LDM reduction with FDI and DDI was observed for both cultivars (Table 5.4).

Higher performance of drip irrigation over furrow irrigation was also elucidated by several authors (Yohannes and Tadesse, 1998; Kataria and Michael, 1990). Shoot plant dry matter (including leaf and stem) also tended to decrease under deficit irrigation but the decrease was inconsistent among cultivars (Table 5.4). In line with findings of Perniola *et al.* (1994) crop water status was strongly influenced by the water amount, the dry matter production was reduced with the increase of water deficit.

Reduction in LDM by Chali, Miya and Malkashola with FLE compared to DETc was 20%, 17% and 15.2% in Experiment 1, and 32%, 31% and 33% in Experiment 2, respectively.

Fruit dry matter production

The reduction in fruit dry matter (FDM) production for Chali, Miya and Malkashola with FDI compared with DETc was 43%, 34% and 38%, and that of DDI was 36%, 28% and 32%, respectively during Experiment 1 (Table 5.4). In Experiment 2, however, the reduction was slightly higher than these values for FDI and DDI (Table 5.4). Hsiao and Bradford (1983) reported that dry matter partitioning was usually not affected by deficit irrigation and the fruit dry matter indices (FDMI) were maintained.

Reduction in FDM with FLE compared with DETc for Chali, Miya and Malkashola was rather small: 30%, 26% and 26% (Experiment 1), and 33%, 29% and 32% (Experiment 2), respectively. Moreover, FDM obtained with FETc relative to DETc for Chali, Miya and Malkashola was reduced by 27%, 23% and 20% (Experiment 1), and by 32%, 29% and 25% (Experiment 2), respectively.

It was generally observed that DETc resulted in higher performance of RDM, SDM, LDM and FDM production, followed by DLE and FETc in descending order, respectively, in all cultivars across both experiments. Performance of DDI and FLE was similar in RDM production for Miya during both experiments, in SDM and FDM for Chali and Malkashola and in LDM production for Miya and Malkashola during Experiment 2. Low DM production by roots, stems, leaves and fruits under furrow irrigation system is generally due to large water losses occurring through seepage or percolation (Phene, 1999) and water is used inefficiently. In contrast to findings from Lapushner *et al*. (1986), we explored that deficit irrigation (FDI or DDI) reduced growth, fruit weight and commercial yield (Gemechis and Struik, 2017), but improved total soluble solids, total acidity and fruit dry matter content in all cultivars studied (data not shown). Differences in response among cultivars were observed.

Effects of local empirical, full- and deficit-drip and furrow irrigation on occurrence of Blossom end rot, Phytophthora root rot, Fusarium oxysporum and Orobanche ramosa

Blossom end rot (BER) The incidence of BER was significantly higher in deficit furrow irrigated plants than under full- or deficit-drip irrigation. The average non-commercial yield due to small size, fruit with blossom end rot and other physiological disorders (Gemechis and Struik, 2017) for Experiment 2 was high under FDI (90%) and FETc (70%) in relation to DETc (Table 5.5).

The number of fruits showing BER under FDI also contributed to yield reduction (data not shown). The low BER fruit found for the three cultivars under DETc and DLE (Table 5.5) implicates occurrence of BER related to irrigation management practices. FDI exhibited increased BER in all three cultivars experimented (Table 5.5), although each cultivar showed a differential response of BER to deficit irrigation. Variety Malkashola exhibited 88% BER occurrence with FDI relative to FETc followed by Chali (73%) and Miya (89%) (Table 5.5).

With regards to drip system, however, BER occurred relatively less frequent under deficit strategy as a result of uniform water distribution via the drip system. Under DDI the occurrence of BER relative to DETc for Malkashola, Chali and Miya was 3.0, 5.8 and 5.2 times, respectively. The possible reason might be that during water supply by furrow deficit growing leaves and stems become greater sinks for calcium ions than developing fruits or the fruit's transpiration decreases due to water movement via the epidermal cells and evaporation into outside air become difficult. The resulting decrease of calcium that flows into those young fruit tissues via xylem transport is believed to contribute to the onset of BER (Mayfield and Kelley, 2012). Despite high and significant differences observed for all cultivars among irrigation treatments in this experiment, no significant difference was observed with regard to available soil calcium, magnesium, potassium, phosphorus and nitrogen (data not shown).

Other researchers reported that water stress leads to an increase in abscisic acid (ABA) by lowering potassium and phosphorus content but increases calcium and iron contents in the leaves (Dekock *et al*., 1979). It has also been argued that under water deficit, the transpiration stream is shifted from the sink organs to the leaves so the sinks are deprived of calcium supplies transported in the sap (Tromp and Wertheim, 1980).

Phytophthora root rot The occurrence of *Phytophthora* root rot of tomato can become severe under water-saturated soil conditions associated with irrigation management (Duniway, 1983). Prolonged irrigation with FLE increased disease development, while less frequent irrigations (according to crop water requirement and deficit strategies) decreased disease incidence. The occurrence of *Phytophthora* root rot observed under FLE relative to FETc was about 90%, 70% and 80% as much for Chali, Miya and Malkashola, respectively (Table 5.5). Matching with this result, Ristaino *et al*. (1988) evidenced that variations in frequency and duration of furrow irrigation had large effects on the rate at which

Table 5.5. Incidence (%) of Blossom end rot, *Phytophthora* root rot, *Fusarium oxysporum* and *Orobanche ramosa* under local empirical, full- and deficit-irrigation practices on fresh market and processing tomato cultivars in 2010/2011 (Experiment 2).

Cultivar	Irrigation system and strategy											
	Furrow			Drip			Furrow			Drip		
	ETc	LE	RP[1] (%)	ETc	LE	RP[1] (%)	ETc	DI	RP[1] (%)	ETc	DI	RP[1] (%)
	Phytophthora root rot *						Fusarium wilt disease (*Fusarium oxysporum*)*					
Chali	4.8C	9.0A	188	1.2E	7.1B	592	1.4CD	8.6A	614	1.9C	3.84B	202
Miya	4.7C	8.1A	172	1.0D	6.2B	620	1.0D	6.7A	670	1.7CD	3.83B	225
Malkashola	3.8C	10.7A	282	1.4E	8.1B	579	1.4DE	9.4A	671	2.0CD	4.80B	240
	Blossom end rot#						*Broom rape (Orobanche ramosa)* *					
	ETc	DI	RP	ETc	DI	RP1 (%)	ETc	DI	RP	ETc	DI	RP[1] (%)
Chali	1.9D	14.7A	773	1.6D	9.20B	575	12.0D	40.7A	339	7.0F	31.3B	447
Miya	1.9C	9.3A	489	1.3D	6.70B	515	10.7D	36.3A	339	6.4F	26.0B	406
Malkashola	1.5CD	13.3A	886	2.1C	6.30B	300	16.3D	53.4A	328	9.4E	33.6B	357

* No. of infected plants per plot (%); # No. of affected fruits per plant (%). Means within rows for each variable and year followed by different letters are statistically different from each other at $p \leq 0.01$ (upper case letter). DI = Deficit irrigation; LE = Local empirical; ETc = Crop water requirement; [1]RP = Relative performance.

Phytophthora root rot developed and caused yield loss in processing tomatoes. *Phytophthora* root rot symptoms on the roots occurred earlier in furrow irrigation, 67 DAP on average, than in drip irrigation. However, the appearance under DLE in relation to DETc were 5.9, 6.2 and 5.8 times as much for these cultivars in the same order.

Fusarium oxysporum Leaf drying due to Fusarium wilt (*Fusarium oxysporum*) was first recorded at 72 and 80 DAP, respectively, in the furrow- and drip- irrigated tomatoes. These results may indicate that drip irrigation could help reducing the disease occurrence. The incidences of *Fusarium oxysporum* under FDI relative to FETc were 6.1, 6.7 and 6.7 times as much for Chali, Miya and Malkashola, respectively (Table 5.5). In the same way, infestation under DDI compared to DETc were 2.0, 2.2 and 2.4 times as much for these cultivars in that order.

Orobanche ramose The occurrences of *Orobanche ramosa* with FDI relative to FETc were about 3.0, 3.4 and 3.3 times as much for Chali, Miya and Malkashola respectively (Table 5.5). Similarly, weed appearance under DDI in relation to DETc was about 4.5, 4.1 and 3.6 times as much for Chali, Miya and Malkashola, respectively.

Conclusions

Improved performance of yield-related traits and growth components was observed for tomatoes grown under drip irrigation compared with furrow irrigation. Reduced performance of all yield related traits and growth components was observed with deficit-drip and deficit-furrow irrigation in relation to full-drip and full-furrow irrigation. Yield related traits and growth components were lower with decreasing water supply.

Occurrence of blossom end rot, Fusarium wilt disease and *Orobanche ramosa* weed increased under deficit irrigation, particularly with deficit-furrow irrigation during the dry season (Experiment 2), whereas *Phytophthora* root rot appeared on plants grown with furrow local empirical practices during the wet season (Experiment 1). These results imply that drip irrigation according to crop water requirement could increase yield related traits and growth components and reduce occurrence of yield reducing factors compared to furrow irrigation in both fresh market and processing tomatoes.

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Chapter 6

Tomato yield and water use efficiency as affected by irrigation scheduling in the Central Rift Valley of Oromia, Ethiopia

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Abstract

Influence of irrigation scheduling with drip and furrow irrigation along with three strategies on tomato yield and water use efficiency were determined in two experiments carried out in 2010 and 2010/2011. Fresh market and processing tomato (*Solanum lycopersicum* L.) varieties were treated with variable water amount and irrigation scheduling. The influences of irrigation scheduling with irrigation systems and volume of water were evaluated considering the commercial yield, agronomical water use efficiency (AWUE) and biological water use efficiency (BWUE) of tomatoes. The results of experiments gave useful indications on the possibilities to improve tomato yield and water use efficiency by reducing irrigation water during tomato cropping. For the Central Rift Valley areas of tomato production, promising results for commercial yield, AWUE and BWUE of fresh market and processing tomato were achieved both with deficit drip irrigation and full drip irrigation according to crop water requirement in two experiments. The results indicate that the commercial yield was higher for drip irrigation according to crop water requirement (94.1 Mg ha^{-1} and 82.3 Mg ha^{-1}), but decreased significantly for deficit irrigation based on 50% crop water requirement with drip (46.0 Mg ha^{-1} and 36.3 Mg ha^{-1}) and furrow (33.9 Mg ha^{-1} and 26.8 Mg ha^{-1}) in both experiments. Lower yields were recorded under furrow irrigation than for drip irrigation. Mean commercial yield for drip irrigation according to crop water requirement implemented with proper scheduling increased by 51% and 56% compared with the respective deficit drip irrigation, in Experiments 1 and 2, respectively. Similarly, with furrow irrigation according to crop water requirement (70.6 Mg ha^{-1} and 58.3 Mg ha^{-1}) yield increased by 52% and 54% compared with the respective deficit furrow, in Experiments 1 and 2, respectively. In contrast, WUE decreased with an increasing water volume. AWUE decreased by about 18.2% and 9.6%, whereas BWUE decreased by about 43% and 36% in Experiments 1 and 2, respectively, with an increase in irrigation water volume from 1013 to 2214 m^3 ha^{-1}.

Keywords: commercial yield, Ethiopia, irrigation scheduling, irrigation system, tomatoes, water use efficiency.

Introduction

Irrigation scheduling can be defined as the practice of specifying future irrigation timing and amounts in the implementation of a water management strategy (Martin *et al*., 1990). As Phene *et al*. (1990) explained, it is a tool for maximizing plant yield, quality and disease resistance; it can be considered the technique which enables an irrigator to decide when to irrigate the crop and how much water to apply.

The aims of irrigation management are to maximize net return and yield, to minimize irrigation costs and groundwater pollution, and to optimally distribute water supply (Huygen *et al.,* 1995). As excessive and too little irrigation can have negative effects on soil and crop quantitative and qualitative yield, deciding when and how much to irrigate is crucial (Hess, 1996; Deumier *et al.,* 1996). Excessive irrigation results in delays in maturity and harvesting, encourages vine growth, and reduces soluble solids, causes lack of aeration in soils, surface runoff, deep percolation, and build-up of water table with subsequent decrease in root zone depth, water logging, and possibly salinity, whereas under irrigation reduces crop dry matter production, yield and quality (Wesseling and Van den Broeck, 1988; Ramalan and Nwokeocha, 2000). The increasing water shortages in general and the arid areas water scarcities (Jones, 2004; OIDA, 2011) in particular and irrigation costs have led to a search for proper irrigation scheduling along with suitable irrigation systems that maximize water use efficiency (WUE). Water use increases with the expansion of agricultural activities. Thus, increased irrigation efficiency is needed because of increased demand for water in agriculture, hydropower, industry and domestic use.

Irrigation scheduling can be established by using soil water measurements, soil water balance estimates and plant stress indicators. Crop water requirement is influenced by variety, soil type, soil moisture regime, physiological and environmental factors (Huygen *et al.,* 1995). Scheduling is also influenced by irrigation system, plant responses to water deficit, growth stage, soil infiltration features, salinity check and soil water deficit (Phene *et al*., 1990); significant performance gains and water savings can be made via improved scheduling (Van Halsema *et al*., 2011).

In the Central Rift Valley, when rainfall starts receding in mid-June and finally ceases in mid-September, tomato production and quality can be sustained via irrigation. However, growers in this valley and those with similar locations, use varied irrigation practices with varied frequencies and amounts of water for the same crop under similar ecologies. In irrigated tomato production, some growers use drip irrigation in a frequency of twice every day. Others empirically adopted four times irrigation in a week for drip, whereas two times irrigation in a week for furrow irrigation is practised. In this area, so far no tomato specific scheduling has been practised. Consequently, smallholders have been using irrigation scheduling of vegetable crops for tomatoes, and ignorantly obtain low yields because they either under- or over-irrigate, either of which leads to loss of yield and reduction of quality (Assefa, 2008). Pereira (1996) argued also irrigation scheduling as a decision-making process, and in undeveloped countries, only a few growers can understand and thus adopt it.

Such practice forces against the growers efforts to escape from their present poverty chain resulting in poor yield and low water use efficiencies particularly in areas with predominantly soils having high infiltration rate and low water retention features. We hypothesized that irrigation scheduling and volume could influence commercial yield, agronomical and biological water use efficiency, and that changing from empirical furrow irrigation to drip irrigation according to crop water requirement could enable growers to reduce water wastage and improve crop yield and water use efficiency. Thus, the aim of this research was to assess which irrigation scheduling and volume of water would provide optimum commercial yield and water use efficiency of irrigated tomato by smallholder in Ziway area, Central Rift Valley. Drip irrigation according to crop water requirement with 2026 m^3 ha^{-1} by proper scheduling resulted in more yield and better WUE.

Materials and methods

Irrigation experiments

Field experiments were carried out in Batu (Ziway), Oromia region, at 07^o 96’ N and 038^o 72’ E, 1649 m above sea level. Experiment plots were cultivated, harrowed and leveled using a tractor and human labour. Seeds were sown on 03 August and 04 November, and were transplanted four weeks later for Experiments 1 and 2, respectively.

Seedlings were transplanted at a spacing of 0.30 m between plants and 0.70 m between rows or drip laterals on a sandy clay loam soil (sand: 50%; silt: 30%; clay: 20%), having the following characteristics: average depth 0.70 m; pH 7.4; organic matter 2.3%; irrigation water salinity content 0.32 dS m^{-1}; total nitrogen 0.19%; available P 26.3 ppm; K^+ 4.3 meq (100 g soil)$^{-1}$; Ca^{++} 25.7 meq (100 g soil)$^{-1}$; Mg^{++} 16.6 meq (100 g soil)$^{-1}$; Na^+ 4.3 meq (100 g soil)$^{-1}$

volumetric water content 36% at field capacity (0.33 bar) and 16% at permanent wilting point (15 bar); bulk density 1.5 g/cm^3 at 0-0.15 m, 1.4 g/cm^3 at 0.16-0.30 m, 1.6 g/cm^3 at 0.31-0.45 m, and 1.1 g/cm^3 at 0.46-0.60 m depth. The weather patterns during both experiments are presented in Table 6.1.

A split-plot design was carried out with three replications, allocating varieties to the main plot and the irrigation systems (furrow and drip) and strategies (local empirical, crop evapotranspiration and deficit) to the sub-plot. Weed control was done by tillage and hand weeding. Insect pests were controlled by spraying thionix carbaryl and diseases were controlled with ridomil. Fertilizer was applied by the ring application method using 82 kg N ha^{-1} and 92 kg P_2O_5 ha^{-1} after establishing the transplants in both experiments.

Harvesting of tomatoes was done from 05 November to 07 December 2010 (Experiment 1) and from 06 February to 04 March 2011 (Experiment 2). Fruit dry matter yield was determined after drying for 48 h at 105 °C to a constant weight. Agronomical water use efficiency (AWUE, kg m^{-3}) was calculated using the relationship (Van Cleemput, 2000):

$AWUE = Fresh\ fruit\ yield \left(\frac{\mathrm{Mg}}{ha}\right) \div water\ consumed\ by\ the\ crop \left(\frac{\mathrm{M}^3}{ha}\right)$ where,

AWUE = the ratio of fresh fruit yield to irrigation water consumed by the crop.

$BWUE = \text{Dry fruit yield} \left(\frac{\mathrm{kg}}{ha}\right) \div \text{ cycle irrigation volume } \left(\frac{\mathrm{M}^3}{ha}\right)$ where,

BWUE= Biological water use efficiency (kg/m^3) was calculated as the ratio between dry fruit yield kg ha^{-1} to seasonal or cycle irrigation volume (m^3/ha).

Estimation of crop water requirement and irrigation scheduling

To quantify the influence of irrigation scheduling, a simple and uniform schedule basing on soil moisture content was applied for a duration of 78 and 77 days per season for Experiments 1 and 2, respectively. Drip and furrow irrigation systems were used as follows. The drip irrigation system was designed as the ones used by International Development Enterprise (IDE) in vegetable production farms in the open field in Batu (Ziway) area using 16 mm tubes, with drippers delivering 2 L/h, set 0.3 m apart. Also, the irrigation water was delivered to furrow-irrigated plots by watering cans. Irrigation water was abstracted from ground water by a diesel driven pump to a water tank (200 L capacity barrels and lined boreholes) at the side of the experimental farm. From this tank 15 L capacity watering cans were used to apply the irrigation water according to the three irrigation strategies described. For the drip irrigation plots water was applied to a 20 L capacity drip kit hanged at 1.5 m

Table 6.1. Main monthly weather data during the Experiments (2010 and 2010/2011) and their comparison with their correspondent long-term averages (1980-2009)

Months	2010					
	Rainfall (mm)		Temperature (^oC)		Relative humidity (%)	
	Deviation[1]	Long-term average	Deviation[1]	Long-term average	Deviation[1]	Long-term average
August	-6.9	121.8	+0.05	20.3	-2.2	68
September	+6.5	70.3	+0.10	20.7	-1.4	65
October	-2.8	42.5	+0.10	20.4	-1.0	52
November	+0.9	5.1	-0.36	19.7	+3.4	49
December	+0.4	3.8	-0.31	19.3	+4.0	45
Total deviation or average	-1.9[a]	48.70	-0.42[a]	20.08	+2.85[a]	55.8
2010/2011						
November	+0.9	5.1	-0.36	19.7	+1.4	49
December	+0.4	3.8	-0.31	19.3	+1.0	45
January	-12.1	15.1	-0.11	20.0	-1.8	56
February	-32.3	32.3	+0.40	21.0	-3.2	48
March	+7.0	44.0	+0.38	22.3	+1.2	59
Total deviation or average	-36.1[b]	20.06	+0.00	20.46	-1.40[b]	51.4

[1] deviation from long-term average values; [a] 2010: August-December growing period; [b] 2011: November-March growing period.

Source: (NMSA, 2011).

while for furrow plots water was directly applied to the furrow between adjacent tomato plants throughout the growing seasons.

Irrigation scheduling was done using the gravimetric soil moisture sampling method for ETcrop and adopting the 4-5 days irrigation timing often practised by the smallholder growers in the area for furrow local empirical (FLE). For drip local empirical (DLE), IDE experience was adopted. Crop water requirement was estimated according to the maximum allowable depletion (MAD) of total available soil water (TAW) criteria: $Vd = \frac{MAD(FC-WP)RzA}{100}$ where Vd is the volume of irrigation water (m^3), Rz the effective root depth (cm), A the surface area of the plot (ha). The values of MAD, FC and WP are in fractions. The surface area of each plot was 14.7 m^2 with effective root depth considered at 0.70 m in all treatments. Irrigation water was provided right after the calculated level of MAD was known, and was calculated as $MAD = p \times TAW$ where p (= 0.4) is the average fraction of TAW that can be depleted from the root zone before reduction in evapotranspiration (ET) occurred. Identical procedures were also followed for data gathering during Experiment 2.

Statistical analysis

All data were subjected to Analysis of Variance (ANOVA) to determine the significance of the difference between treatments using the SAS statistical software version 9.2 (SAS Institute Inc., 2008). Mean separations for two-way and three-way interactions were computed by using the Method of Least Square Means (lsmeans) for variables that showed significant difference among treatment combinations. Pearson's correlation test was used to analyze the relationships between fruit yield and water used. Means separation was done on significant ANOVA tests using Least Significant Difference (LSD) ($p<0.05$).

Weather data

The weather variables, registered in 2010 from August-December and November 2010-March 2011 when the growth of fresh market and processing tomato occurred are presented in Table 6.1. During 2010, the values of these variables differed from their long-term values, with temperature and rainfall being 0.42 °C and 1.9 mm lower and relative humidity (RH) being 2.85% higher, on average, respectively compared with the long-term values; the largest deviations from the norm were registered in August for rainfall. Long-term average rainfall was exceeded by 6.5 mm in September and in November and December it was little different from those recorded in previous 30 years.

In Experiment 2, the temperature was not different from the long-term mean values from November 2010 to March 2011. Rainfall was 36.1 mm and RH 1.40% less than the norm. Mean temperature in February and March 2011 exceeded by 0.40 and 0.38 ^{o}C the respective values of the previous 30 years; furthermore, February was specifically dry with evident negative deviations recorded for both rainfall (-32.3 mm) and RH (-3.2%).

Results and discussion

Proper scheduling allows growers to optimize the timeliness and the water volumes applied, thus controlling return flows, deep percolation, transport of fertilizers and biocides out of the root zone, and avoiding water-logging in the parts of the field receiving excess water (Pereira, 2007).

Tomato requires frequent and sufficient irrigation for its optimum growth and yield. Based on climatic conditions and soil type it requires about 20 to 70 mm every week (Kazemi *et al*., 2009). Growers, however, apply water without regard to what the plant actually needs (Gemechis *et al*., 2012). Irrigation scheduling can result in higher and more consistent yields and quality. Tan *et al*. (2003) reported a yield increase of up to 81% on a range of soil types with the use of properly scheduled irrigation on processing tomatoes. Badr *et al*. (2010) reported tomato fruit yield of 58.6 Mg ha^{-1} with drip irrigation and 47.4 Mg ha^{-1} with furrow irrigation.

The prevailing temperatures were in the range of 19.0-19.9 ºC (Table 6.1) in relation to the temperatures range (22ºC-25 ºC) required for rate of leaf and truss appearance, and rate of progress to flower initiation and a temperature of 26 ºC for fruit formation (Adams *et al*., 2001). Despite the reports on frequent pests in February-March compared to the low occurrence during Experiment 1, the temperatures in these months were relatively suitable for fruit development and maturation (Table 6.1) in conformity with the elucidation of Sato *et al*. (2000).

Influence of irrigation system, volume and scheduling on commercial yield of fresh market (Miya) and processing (Chali and Malkashola) tomato varieties

The relationship between yield and irrigation is affected by factors such as climate, soil properties and irrigation practices (Farre and Faci, 2009). Significant yield differences were recorded among three varieties with FDI in both seasons. The observed commercial yields (CY) for Chali, Miya and Malkashola were 28.7, 39.7 and 33.3 Mg/ha in Experiment 1 whereas 22.4, 31.7 and 26.3 Mg/ha Experiment 2, respectively (Tables 6.2 and 6.3). Significant yield difference was noted between Chali and the two varieties during both seasons in DDI treatment, perhaps due to seasonal climate variation (Table 6.1). About 42.4, 49.5 and 46.0 Mg/ha (Experiment 1) and 33.0, 39.3 and 36.6 Mg/ha (Experiment 2) were obtained for Chali, Miya and Malkashola, respectively (Tables 6.2 and 6.3). However, Birhanu and Tilahun (2010) reported no significant yield difference between fresh market (Malkassa Marglobe) and processing (Malkashola) tomatoes in the same valley.

Correspondingly, Losada and Rincon (1994) reported that water deficit severely affected fruit set and significantly decreased the number of red fruits and thereby the yield. However, several researchers (Lowengart-Aycicegi *et al*., 1999; Bhattarai and Midmore, 2005) indicated that DI applied from first red fruit colour improved total soluble solid (TSS) at harvest, without significantly lowering the yield.

Under DDI less reduction in CY was observed for Miya than for Chali and Malkashola. Reduction in CY under DDI relative to FLE, FETc, DLE and DETc was less by 9%, 26%, 36% and 45% for Miya, 27%, 39%, 49% and 57% for Chali, and 23%, 39%, 47% and 51% for Malkashola, respectively. Similar patterns for these varieties were also observed under DDI during Experiment 2 (Tables 6.2 and 6.3). FDI showed lower performance than DDI for all varieties during both experiments.

Other studies found also non-linear relationship between commercial yield (CY) and seasonal irrigation (Tolk and Howell, 2003; Mantovani *et al*., 1995).

Higher CY was observed with drip irrigation scheduled every 3, 2, 4 and 6 days intervals at developmental stage, developmental stage to mid-season, mid-season to late season and late season respectively for Chali, Miya and Malkashola during both experiments demonstrating differential varietal response to irrigation volume and timing. This is followed by drip irrigation scheduled every day and every 3-4 days intervals at developmental stage to mid-season and mid-season to late season respectively (Tables 6.2 and 6.3). Maximum CY of 94.1 Mg ha^{-1} was observed for Chali under drip irrigation system with adequate volume (2026 m^3 ha^{-1}) followed by drip local (87% of yield by drip irrigation) with an irrigation volume of

Table 6.2. Development phase, applied water ($m^3 ha^{-1}$), irrigation scheduling (days) and commercial yields of field grown tomato varieties in 2010 (Experiment 1).

Treatments	Days after planting	Development phase	Applied water ($m^3 ha^{-1}$)		Irrigation scheduling (days)	Commercial yield ($Mg ha^{-1}$) of varieties		
			During development phase	Total		Chali	Miya	Malkashola
FLE	47-52	DS	213	1875	Every 5 days	58.1f	54.3g	59.7f
	57-97	DS-MS	851		Every 5 days			
	98-109	MS	319		Twice per week			
	109 onwards	LS	492		Once per week			
FETc	47-66	DS	516	2026	Every 3 days	69.5e	66.9e	75.4d
	67-91	DS-MS	715		Every 2 days			
	92-116	MS-LS	636		Every 4 days			
	116 onwards	LS	159		Every 6 days			
FDI	47-66	DS	258	1013	Every 3 days	28.7k	39.7i	33.3j
	67-91	DS-MS	357.5		Every 2 days			
	92-116	MS-LS	318		Every 4 days			
	116 onwards	LS	79.5		Every 6 days			
DLE	47-66	DS	773	2214	Every day	82.6c	77.8d	86.1c
	67-96	DS-MS	961		Every day			
	96 onwards	MS-LS	480		Every 3-4 days			
DETc	47-66	DS	516	2026	Every 3 days	98.4a	90.4b	93.5b
	67-91	DS-MS	715		Every 2 days			
	92-116	MS-LS	636		Every 4 days			
	116 onwards	LS	159		Every 6 days			
DDI	47-66	DS	258	1013	Every 3 days	42.4i	49.5h	46.0h
	67-91	DS-MS	357.5		Every 2 days			
	92-116	MS-LS	318		Every 4 days			
	116 onwards	LS	79.5		Every 6 days			
Mean					**Every 3.5 days**	**63.3**	**63.1**	**65.7**

DS = Developmental stage (31-70 DAP); DS-MS = Developmental stage to mid-season stage; MS = Mid season stage (71-110 DAP); MS-LS = Mid season to late season stage; LS = Late season stage (111 DAP onwards). Differential treatment duration = 78 days; No. of irrigation days in a season = 22 days; rainfall extrapolated to irrigation water amount was 0.6762 m^3. FLE = Local empirical furrow; FETc = Furrow according to crop water requirement; FDI = Deficit furrow irrigation; DLE = Local drip; DETc = Drip according to crop water requirement; DDI= Deficit drip irrigation. *Means within rows and columns in each variety followed by different letters are statistically different from each other at $p \leq 0.05$.*

Table 6.3. Development phase, applied water ($m^3 ha^{-1}$), irrigation scheduling (days) and commercial yields of field grown tomato varieties in 2010/2011 (Experiment 2).

Treatments	Days after planting	Development phase	Applied water ($m^3 ha^{-1}$) During development phase	Total	Irrigation scheduling (days)	Commercial yield ($Mg ha^{-1}$) of varieties Chali	Miya	Malkashola
FLE	47-52	DS	213	1875	Every 5 days	46.4i	41.3j	48.7i
	57-97	DS-MS	851		Every 5 days			
	98-109	MS	319		Twice per week			
	110 onwards	LS	492		Once per week			
FETc	47-66	DS	516	2026	Every 3 days	58.4g	52.5h	64.1f
	67-91	DS-MS	715		Every 2 days			
	92-116	MS-LS	636		Every 4 days			
	117 onwards	LS	159		Every 6 days			
FDI	47-66	DS	258	1013	Every 3 days	22.4n	31.7l	26.3m
	67-91	DS-MS	357.5		Every 2 days			
	92-116	MS-LS	318		Every 4 days			
	117 onwards	LS	79.5		Every 6 days			
DLE	47-66	DS	773	2214	Every day	72.6d	66.2e	76.3c
	67-96	DS-MS	961		Every day			
	97 onwards	MS-LS	480		Every 3-4 days			
DETc	47-66	DS	516	2026	Every 3 days	87.6a	79.0bc	80.4b
	67-91	DS-MS	715		Every 2 days			
	92-116	MS-LS	636		Every 4 days			
	117 onwards	LS	159		Every 6 days			
DDI	47-66	DS	258	1013	Every 3 days	33.0l	39.3jk	36.6k
	67-91	DS-MS	357.5		Every 2 days			
	92-116	MS-LS	318		Every 4 days			
	117 onwards	LS	79.5		Every 6 days			
Mean					**Every 2.5 days**	**53.4**	**51.7**	**55.4**

DS = Developmental stage (31-70 DAP); DS-MS = Developmental stage to mid-season stage; MS = Mid season stage (71-110 DAP); MS-LS = Mid season to late season stage; LS = Late season stage (111 DAP onwards). Differential treatment duration = 77 days; No. of irrigation days in a season = 30 days. FLE = Local empirical furrow; FETc = Furrow according to crop water requirement; FDI = Deficit furrow irrigation; DLE = Local drip; DETc = Drip according to crop water requirement; DDI = Deficit drip irrigation. *Means within rows and columns in each variety followed by different letters are statistically different from each other at $p \leq 0.05$.*

9.3% more than drip irrigation with frequent scheduling; and furrow irrigation (75% of yield by drip irrigation) (Table 6.4). Local empirical furrow, FLE (1875 m^3 ha^{-1}) also yielded 57.4 Mg ha^{-1} of Chali which is below the overall mean yield (Table 6.4)

Lower CYs were obtained with deficit drip- and deficit furrow irrigation scheduled every 3, 2, 4 and 6 days intervals at developmental stage, developmental stage to mid-season, mid-season to late season and late season respectively for all varieties under study. The observed CY of Chali, Miya and Malkashola under deficit drip was more by 48%, 25% and 38% (Experiment 1) and more by 47%, 24% and 39% (Experiment 2), respectively, compared with deficit furrow with the same volume and irrigation scheduling (Tables 6.2 and 6.3).

Gemechis and Struik (2017) reported that deficit drip irrigation recorded larger fruits per plant compared with deficit furrow irrigation for all varieties in both experiments. The obtained yield for Chali, Miya and Malkashola with deficit drip irrigation was more by 49%, 48% and 35% (Experiment 1) and 63%, 48% and 49% (Experiment 2), respectively, in relation to the observed values under deficit furrow irrigation. Similarly, gain in mean fruits weight for Chali, Miya and Malkashola under deficit drip irrigation was higher by 30%, 22% and 19% (Experiment 1) and 21%, 18% and 17% (Experiment 2), respectively, compared with FDI (Tables 6.2 and 6.3). From the above discussion and Gemechis and Struik (2017), it is possible to deduce that CY reduction with deficit furrow irrigation may be because of fewer fruits and lower fruit weights in these varieties. Other literature reported evidence that CY was reduced by reduction in fruit number whilst fruit weight remained almost unchanged (Bwarama and Henderson, 1985).

Lowest CY was observed for Chali with deficit furrow irrigation in both experiments (Tables 6.2 and 6.3) due to fewer fruits per plant (Gemechis and Struik, 2017) revealing that Chali was less adaptable to deficit furrow irrigation than Miya and Malkashola. From Tables 6.2 and 6.3 it is observed that drip irrigation with 2026 m^3 ha^{-1} yielded more by 42%, 35% and 24% (Experiment 1) and by 50%, 50% and 25% (Experiment 2) for Chali, Miya and Malkashola, respectively, compared with furrow irrigation with identical irrigation volume and scheduling attributing to inadequate water supply via the poorly efficient furrow irrigation system as reported by Yohannes and Tadesse (1998), Birhanu and Tilahun (2010), and Kataria and Michael (1990). As Hartz (2001) reported, drip irrigation has typically increased processing tomato fruit yield by 10-25% or more compared to furrow irrigation.

Table 6.4. Commercial yield (CY), noncommercial yield (NCY), agronomical water use efficiency (AWUE) and biological water use efficiency (BWUE) of field grown tomatoes as affected by irrigation system, volume and scheduling in 2010 (Experiment 1).

Treatments	Days after planting	Development phase	Applied water (m^3 ha^{-1})		Irrigation scheduling (days)	Yield (Mg ha^{-1}) and water use efficiency (kg m^{-3})			
			During development phase	Total		CY	NCY	AWUE	BWUE
FLE	47-52	DS	213	1875	Every 5 days	57.4d	18.7b	30.6d	1.39E
	57-97	DS-MS	851		Every 5 days				
	98-109	MS	319		Twice per week				
	110 onwards	LS	492		Once per week				
FETc	47-66	DS	516	2026	Every 3 days	70.6c	13. 6c	34.9c	1.39E
	67-91	DS-MS	715		Every 2 days				
	92-116	MS-LS	636		Every 4 days				
	117 onwards	LS	159		Every 6 days				
FDI	47-66	DS	258	1013	Every 3 days	33.9f	24.2a	33.5c	2.18B
	67-91	DS-MS	357.5		Every 2 days				
	92-116	MS-LS	318		Every 4 days				
	117 onwards	LS	79.5		Every 6 days				
DLE	47-66	DS	773	2214	Every day	82.2b	9.6d	37.1b	1.40D
	67-96	DS-MS	961		Every day				
	97 onwards	MS-LS	480		Every 3-4 days				
DETc	47-66	DS	516	2026	Every 3 days	94.1a	5.0e	46.4a	1.84C
	67-91	DS-MS	715		Every 2 days				
	92-116	MS-LS	636		Every 4 days				
	117 onwards	LS	159		Every 6 days				
DDI	47-66	DS	258	1013	Every 3 days	46.0e	20.7b	45.4a	2.46A
	67-91	DS-MS	357.5		Every 2 days				
	92-116	MS-LS	318		Every 4 days				
	117 onwards	LS	79.5		Every 6 days				
Mean					Every 2.57 days	**64.0**	**15.3**	**37.97**	**1.78**

DS = Developmental stage (31-70 DAP); DS-MS = Developmental stage to mid-season stage; MS = Mid season stage (71-110 DAP); MS-LS = Mid season to late season stage; LS = Late season stage (111 DAP onwards). Differential treatment duration = 78 days; No. of irrigation days in a season= 22 days; rainfall extrapolated to irrigation water amount was 0.6762 m^3. FLE= Local empirical furrow; FETc = Furrow according to crop water requirement; FDI = Deficit furrow irrigation; DLE = Local drip; DETc = Drip according to crop water requirement; DDI= Deficit drip irrigation. *Means within columns followed by different letters are statistically different from each other at $p\leq 0.05$(lower case letter) and $p\leq 0.01$ (upper case letter).*

Chali had significantly higher CY than Miya (4% in Experiment 1 and 11% in Experiment 2), respectively with furrow irrigation of 2026 m^3 ha^{-1} with scheduling of every 3, 2, 4 and 6 days intervals at developmental stage, developmental stage to mid-season, mid-season to late season and late season respectively (Tables 6.2 and 6.3). However, Chali yielded less by 28% and 29% compared with Miya under deficit furrow irrigation during Experiments 1 and 2, respectively. Significant difference was observed between only Malkashola and other two varieties with furrow irrigation of 2026 m^3 ha^{-1}, whereas between only Miya and processing varieties with local drip of 2214 m^3 ha^{-1} was noted in Experiment 1 (Table 6.3).

Under deficit drip irrigation Miya had higher CY than Chali and Malkashola by 17% and 8% in Experiment 1 and by 19% and 7% in Experiment 2 revealing that Miya was more tolerant to water deficit than Chali and Malkashola. The present finding is in agreement with an earlier report (Cherinet, 2011) at Humera, North Ethiopia.

Also lowest yield was observed for Chali with deficit furrow under the same irrigation volume and scheduling showing its susceptibility to water deficit. All varieties grown with deficit drip- and deficit furrow and local empirical furrow irrigation showed yields below the overall mean CY (Tables 6.2 and 6.3).

Commercial yields of tomato varieties as affected by irrigation scheduling

Water use efficiency (WUE) is crucial in identifying the adaptation and productivity of crops in water-deficit regions, either under the current climate or future global climate change. For these experiments, tomato crop yields for the two growing seasons for each irrigation treatment are presented in Tables 6.4 and 6.5. Variation in amount of irrigation water applied ($p<0.01$) influenced the commercial yield (CY) (Experiment 1). The average CYs were 64 Mg ha^{-1} and 53.5 Mg ha^{-1} with a coefficient of variation of 8.3% and 9.0% in Experiments 1 and 2, respectively. The same tables showed that yield obtained using drip irrigation of 2026 m^3 ha^{-1} was greater by 25% and 29% than that of furrow irrigation with identical irrigation scheduling ($p<0.05$) in Experiments 1 and 2, respectively.

Despite the same irrigation volume (2026 m^3 ha^{-1}) applied with drip- and furrow irrigation, Table 6.4 demonstrates that CY increase with drip irrigation with volume of 2026 m^3 ha^{-1} was 25% more than with furrow irrigation, which may associate with more fruits per plant and higher fruits weight (Gemechis and Struik, 2017) during Experiment 1. Table 6.5

shows significant and higher CY with drip irrigation scheduled every 3, 2, 4 and 6 days intervals at developmental stage, developmental stage to mid-season, mid-season to late season and late season respectively; followed by drip local scheduled every day and every 3-4 days intervals at developmental stage to mid-season and mid-season to late season respectively.

Increasing irrigation interval with local empirical furrow (FLE) to every 5 days (DS-MS), every 3-4 days (MS), and every week (LS) saved plant water consumption by 7.4% while it decreased the CY by 39% and 19% (Experiment 1) or 45% and 22% (Experiment 2) compared with drip- and furrow irrigation based on crop water requirement respectively (Tables 6.4 and 6.5). This tendency can possibly be attributed to the fact that inadequate frequency of watering conditions with FLE in both Experiments led to such low CY.

Tomato, which was subjected to 50% crop water requirement with furrow (1013 m^3 ha^{-1}), resulted in CY of 33.9 Mg ha^{-1}, yield reduction of 64% and 52% (Experiment 1) and 67% and 54% (Experiment 2) of CY compared with CY obtained under full crop water requirement with drip- and furrow irrigation, respectively (Tables 6.4 and 6.5). This yield decrease with deficit furrow would have been greater if the crop had been subjected to deficit drip irrigation (DDI). The yield decrease due to DDI was 51% and 35% (Experiment 1) and 56% and 38% (Experiment 2) of CY compared with CY obtained with full crop water requirement with drip- and furrow irrigation, respectively. Qasem and Judah (1985) also stated that the water applied and its uptake by plants are decreased with increasing soil moisture tension. As the amount of irrigation water reduced by half the amount of crop water needs, productivity was decreased. These findings were consistent with the results reported in other studies which attributed to lower leaf production and dry matter to water deficit (Pandy *et al*., 1983; EI-Bagoury and Shaheen, 1977). Other studies have also found that biomass production per plant of haricot bean was significantly reduced due to soil moisture deficit (Tolk and Howell, 2003).

Bazza and Tayaa, (1999) reported that the lowest yield was obtained with experiments on deficit irrigated vegetables and cereals during the partial stress (50% deficit) throughout the growing season. Higher proportions of noncommercial yield were also recorded in tomatoes irrigated with deficit furrow followed by deficit drip and local empirical furrow in descending order in both experiments as a result of low water amount or no uniform water application.

Table 6.5. Commercial yield (CY), noncommercial yield (NCY), agronomic water use efficiency (AWUE) and biological water use efficiency (BWUE) of field grown tomatoes as affected by irrigation system, volume and scheduling in 2010/2011 (Experiment 2).

Treatments	Days after planting	Development phase	Applied water (m^3 ha^{-1})		Irrigation scheduling (days)	Yield (Mg ha^{-1}) and water use efficiency (kg m^{-3})			
			During development phase	Total		CY	NCY	AWUE	BWUE
FLE	47-52	DS	213	1875	Every 5 days	45.5D	19.3C	24.3F	1.14F
	57-97	DS-MS	851		Every 5 days				
	98-109	MS	319		Twice per week				
	110 onwards	LS	492		Once per week				
FETc	47-66	DS	516	2026	Every 3 days	58.3C	14.6D	28.8D	1.16E
	67-91	DS-MS	715		Every 2 days				
	92-116	MS-LS	636		Every 4 days				
	117 onwards	LS	159		Every 6 days				
FDI	47-66	DS	258	1013	Every 3 days	26.8F	28.2A	26.5E	1.74B
	67-91	DS-MS	357.5		Every 2 days				
	92-116	MS-LS	318		Every 4 days				
	117 onwards	LS	79.5		Every 6 days				
DLE	47-66	DS	773	2214	Every day	71.7B	10.7E	32.4C	1.23D
	67-96	DS-MS	961		Every day				
	97 onwards	MS-LS	480		Every 3-4 days				
DETc	47-66	DS	516	2026	Every 3 days	82.3A	6.0F	40.6A	1.60C
	67-91	DS-MS	715		Every 2 days				
	92-116	MS-LS	636		Every 4 days				
	117 onwards	LS	159		Every 6 days				
DDI	47-66	DS	258	1013	Every 3 days	36.3E	23. 6B	35.8B	1.93A
	67-91	DS-MS	357.5		Every 2 days				
	92-116	MS-LS	318		Every 4 days				
	117 onwards	LS	79.5		Every 6 days				
Mean					Every 2.57 days	**53.5**	**17.1**	**31.39**	**1.47**

DS = Developmental stage (31-70 DAP); DS-MS = Developmental stage to mid-season stage; MS = Mid season stage (71-110 DAP); MS-LS = Mid season to late season stage; LS = Late season stage (111 DAP onwards). Differential treatment duration = 77 days; No. of irrigation days in a season = 30 days. FLE = Local empirical furrow; FETc = Furrow according to crop water requirement; FDI = Deficit furrow irrigation; DLE = Local drip; DETc = Drip according to crop water requirement; DDI = Deficit drip irrigation. *Means within columns followed by different letters are statistically different from each other at* $p \leq 0.01$ *(upper case letter).*

According to Gemechis and Struik (2017) it was revealed that total biomass production was significantly ($p<0.01$) influenced by variation in amount of water application. The biomass production in the experiments was proportional to the availability of water which in turn influenced CY (Tables 6.4 and 6.5).

Influence of irrigation scheduling on agronomical and biological water use efficiency of fresh market (Miya) and processing (Chali and Malkashola) tomato varieties

Irrigation scheduling can reduce runoff from irrigation, decrease percolation below the root zone in excess of any required leaching for salinity management, reduce soil water evaporation after an irrigation, or control soil water depletion in a manner that reduces evaporation transpiration during known non-sensitive crop growth stages. In some cases, irrigation scheduling may actually increase irrigation water use, while concurrently increasing crop yield by avoiding soil water deficits that reduce crop yield or by supplying both water and nutrients needed by the crop at a more “optimum” time for the particular crop (Howell, 1996). Hanson *et al*. (1997) reported in their work that using drip and furrow irrigation systems on lettuce the drip irrigation system saved water by about 43 to 74% of water applied by the furrow system.

The variations in agronomical water use efficiency (AWUE) and biological water use efficiency (BWUE) in tomatoes were significant because of the cumulative effect of irrigation systems and strategies, volume and scheduling. Tables 6.4 and 6.5 presented the AWUE and BWUE values in kg m^{-3} water applied to tomato under different levels and irrigation scheduling. AWUE and BWUE were smaller with increasing irrigation intervals by local empirical furrow (FLE).

However, reducing the crop water supply by 50% using drip irrigation scheduling every 3, 2, 4 and 6 days intervals at developmental stage, developmental stage to mid-season, mid-season to late season and late season respectively during development phase resulted in greater AWUE and BWUE in both experiments. Deficit drip irrigation received 50% the volume of crop water requirement resulted in greater AWUE of 45.4 and 35.8 kg/m^3 and BWUE of 2.46 and 1.93 kg/m^3 in both Experiments 1 and 2, respectively. The smaller the water volume used with shorter irrigation intervals, the greater was the WUE under deficit irrigation by the tomato plants (Tables 6.4 and 6.5).

Although tomatoes were grown under identical deficit irrigation level and irrigation scheduling, using deficit furrow reduced significantly AWUE by 26% and BWUE by 11% and 10% as compared to stressing the crop using deficit drip in both Experiments 1 and 2, respectively. These reductions may be because of water deficit during flower initiation and fruit development stages that reduce flowers number and fruits weight (Gemechis and Struik, 2017). Kirda and Kanber (1998) also reported reduction in WUE due to water deficit at crop sensitive periods like root growth, flowers opening and fruits development phases. They also disclosed that when a stress follows, the crop rapidly depletes the soil water stored in the root zone and wilts before the completion of additional root development at greater soil depths.

AWUE increased from a minimum of 30.6 kg m^{-3} with local empirical furrow to a maximum of 46.4 kg m^{-3} with drip irrigation in Experiment 1, whereas in Experiment 2 it increased from 24.3 to 40.6 kg m^{-3}.

Table 6.6 shows that interaction effects of variety and irrigation scheduling practice on tomato AWUE and BWUE in Experiments 1 and 2 were significant. Greater AWUE and BWUE were observed under drip irrigation (2026 m^3 ha^{-1}) scheduled every 3, 2, 4 and 6 days intervals at developmental stage, developmental stage to mid-season, mid-season to late season and late season respectively compared with local drip (2214 m^3 ha^{-1}) with shorter irrigation intervals for all varieties across experiments. Similarly, identical irrigation scheduling with furrow irrigation (2026 m^3 ha^{-1}) resulted in more AWUE compared with local empirical furrow irrigation (1875 m^3 ha^{-1}) with longer irrigation interval for all varieties. Except for Chali, irrigation scheduling with furrow irrigation (2026 m^3 ha^{-1}) gave more BWUE compared with local empirical furrow irrigation.

Increased AWUE of 11.3 kg m^{-3} , 9.5 kg m^{-3} and 7.2 kg m^{-3} with drip irrigation (2026 m^3 ha^{-1}) compared with local drip (2214 m^3 ha^{-1}) was observed for Chali, Miya and Malkashola, respectively in Experiment 1.

In the same way the increases in AWUE were 14.3, 11.6 and 8.9 kg m^{-3}, compared with furrow irrigation (2026 m^3 ha^{-1}) for these varieties. Increase of AWUE with furrow irrigation (2026 m^3 ha^{-1}) was 3.3 kg m^{-3}, 4.1 kg m^{-3} and 5.4 kg m^{-3} compared with local empirical furrow (1875 m^3 ha^{-1}) for Chali, Miya and Malkashola, respectively in Experiment 1. Gains in AWUE for Chali, Miya and Malkashola under drip irrigation compared with local drip and furrow irrigation in Experiment 2 were very much the same to those in Experiment 1.

Higher AWUE was observed under drip irrigation (2026 m^3 ha^{-1}) scheduled every 3, 2,

Table 6.6. Agronomical and biological water use efficiency as affected by interaction effects of variety and irrigation scheduling practice (Experiment 1)

Treatments	Days after planting	Development phase	Applied water (m^3 ha^{-1})		Irrigation	AWUE (kg m^{-3})			BWUE (kg m^{-3})		
			During development phase	Total	scheduling (days)	Chali	Miya	Malkashola	Chali	Miya	Malkashola
FLE	47-66	DS	213	1875	Every 5 days	31.0a	28.9b	31.8a	1.40a	1.38a	1.41a
	57-97	DS-MS	851		Every 5 days						
	98-109	MS	319		Twice per week						
	110 onwards	LS	492		Once per week						
FETc	47-66	DS	516	2026	Every 3 days	34.3b	33.0b	37.2a	1.35b	1.33b	1.48a
	67-91	DS-MS	715		Every 2 days						
	92-116	MS-LS	636		Every 4 days						
	117 onwards	LS	159		Every 6 days						
FDI	47-66	DS	258	1013	Every 3 days	28.4c	39.2a	32.9b	2.08c	2.29a	2.18b
	67-91	DS-MS	357.5		Every 2 days						
	92-116	MS-LS	318		Every 4 days						
	117 onwards	LS	79.5		Every 6 days						
DLE	47-66	DS	773	2214	Every day	37.3a	35.1b	38.9a	1.38b	1.33b	1.49a
	67-96	DS-MS	961		Every day						
	97 onwards	MS-LS	480		Every 3-4 days						
DETc	47-66	DS	516	2026	Every 3 days	48.6a	44.6b	46.1b	2.00a	1.73b	1.77b
	67-91	DS-MS	715		Every 2 days						
	92-116	MS-LS	636		Every 4 days						
	117 onwards	LS	159		Every 6 days						
DDI	47-66	DS	258	1013	Every 3 days	41.8c	48.8a	45.4b	2.36b	2.49a	2.52a
	67-91	DS-MS	357.5		Every 2 days						
	92-116	MS-LS	318		Every 4 days						
	117 onwards	LS	79.5		Every 6 days						

FLE = Furrow local empirical; FETc = Furrow according to crop water requirement; FDI = Furrow deficit; DLE = Drip local; DETc = Drip according to crop water requirement; DDI = Drip deficit. AWUE = agronomical water use efficiency; and BWUE = biological water use efficiency. *Means within rows followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter).*

4 and 6 days intervals during various developmental stages and deficit drip irrigation in both experiments and statistically at par value, whereas smaller values observed with deficit furrow irrigation and local empirical furrow for all varieties. It can be observed from Tables 6.6 and 6.7 that deficit irrigation of 50% crop water requirement using proper scheduling with drip system maximized AWUE for both fresh market as well as processing tomatoes. Generally 50% crop water requirement with drip irrigation (1013 m^3 ha^{-1}) having identical scheduling with drip irrigation full crop water requirement (2026 m^3 ha^{-1}) has recorded highest AWUE for Miya variety over the other treatments indicating Miya's adaptation and productivity in water-deficit areas.

Drip irrigation scheduling every 3, 2, 4 and 6 days intervals at developmental stage, developmental stage to mid-season, mid-season to late season and late season respectively with 2026 m^3 ha^{-1} gave extra BWUE of 0.62, 0.4 and 0.28 kg m^{-3} (Experiment 1) and 0.46, 0.37 and 0.29 kg m^{-3} (Experiment 2) compared with local drip for Chali, Miya and Malkashola, respectively. Furthermore, increase in BWUE with drip system was 0.65, 0.40 and 0.29 kg m^{-3} (Experiment 1) and 0.55, 0.38 and 0.40 kg m^{-3} (Experiment 2) compared with furrow irrigation (2026 m^3 ha^{-1}) for Chali, Miya and Malkashola, respectively. However, irrigation scheduling with furrow irrigation of 2026 m^3 ha^{-1} gave smaller BWUE compared with local empirical furrow (1875 m^3 ha^{-1}) for Chali and Miya, while more by 0.07 kg m^{-3} for Malkashola in Experiment 1.

Conclusions

Water-use efficiency (WUE) of Chali, Miya and Malkashola varieties were varied with the irrigation system, water volume and irrigation scheduling. Higher agronomic water use efficiency (AWUE) and commercial yields (CYs) were obtained for Chali and Malkashola with shorter irrigation intervals using drip irrigation full crop water requirement in both experiments. Irrigation scheduling with drip system according to crop water requirement is proper timing and may increase WUE and increase commercial yield compared to local empirical drip irrigation. Increasing irrigation intervals using local empirical furrow irrigation decreased WUE and CYs. Lowest AWUE was observed with local empirical furrow (Miya and Malkashola) and with deficit furrow irrigation (Chali). Furthermore, irrigation scheduling for tomatoes using deficit furrow irrigation by 50% resulted in lower CYs followed by irrigation scheduling of deficit drip by 50% during the

Table 6.7. Agronomical and biological water use efficiency as affected by interaction effects of variety and irrigation scheduling practice (Experiment 2)

Treatments	Days after planting	Development phase	Applied water (m^3 ha^{-1})		Irrigation	AWUE (kg m^{-3})			BWUE (kg m^{-3})		
			During development phase	Total	scheduling (days)	Chali	Miya	Malkashola	Chali	Miya	Malkashola
FLE	47-66	DS	213	1875	Every 5 days	24.7a	22.0b	26.0a	1.14a	1.12a	1.16a
	57-97	DS-MS	851		Every 5 days						
	98-109	MS	319		Twice per week						
	110 onwards	LS	492		Once per week						
FETc	47-66	DS	516	2026	Every 3 days	28.8b	25.9c	31.6a	1.12b	1.15b	1.21a
	67-91	DS-MS	715		Every 2 days						
	92-116	MS-LS	636		Every 4 days						
	117 onwards	LS	159		Every 6 days						
FDI	47-66	DS	258	1013	Every 3 days	22.1c	31.3a	26.0b	1.62c	1.85a	1.74b
	67-91	DS-MS	357.5		Every 2 days						
	92-116	MS-LS	318		Every 4 days						
	117 onwards	LS	79.5		Every 6 days						
DLE	47-66	DS	773	2214	Every day	32. 8b	29.9c	34.5a	1.21b	1.16b	1.32a
	67-96	DS-MS	961		Every day						
	97 onwards	MS-LS	480		Every 3-4 days						
DETc	47-66	DS	516	2026	Every 3 days	43.3a	39.0b	39.7b	1.67a	1.53c	1.61b
	67-91	DS-MS	715		Every 2 days						
	92-116	MS-LS	636		Every 4 days						
	117 onwards	LS	159		Every 6 days						
DDI	47-66	DS	258	1013	Every 3 days	32.6c	38.8a	36.1b	1.89b	1.96a	1.94a
	67-91	DS-MS	357.5		Every 2 days						
	92-116	MS-LS	318		Every 4 days						
	117 onwards	LS	79.5		Every 6 days						

FLE = Furrow local empirical; FETc = Furrow according to crop water requirement; FDI = Furrow deficit; DLE = Drip local; DETc = Drip according to crop water requirement; DDI = Drip deficit. AWUE = agronomical water use efficiency; and BWUE = biological water use efficiency. *Means within rows followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter).*

growing season. Therefore, if deficit irrigation is unavoidable due to shortage, it is better to schedule the crop one-half deficit using drip system instead of furrow. Overall, an irrigation scheduling of deficit drip irrigation during tomato growing season provided optimum AWUE and BWUE in both experiments. Findings from this study may be applicable to years with normal weather tendencies in the Central Rift Valley area.

Chapter 7

Photosynthetic gas exchange and chlorophyll fluorescence of field-grown tomatoes under drip and furrow irrigation in a semi-arid area in Oromia, Ethiopia

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Abstract

Changes in photosynthetic gas exchange and chlorophyll fluorescence in leaves of three tomato (*Solanum lycopersicum* L.*)* cultivars under drip and furrow irrigation with three contrasting strategies of water supply were studied in a semi-arid area of Oromia, Ethiopia. Two experiments were carried out at the technology testing site of the premises of the International Development Enterprise from 03 August to 04 December, 2010 and from 04 November, 2010 to 04 March 2011. The leaf gas exchange techniques used to calculate leaf internal CO_2 concentration (C_i) are susceptible to important artifacts when applied to water deficient leaves, making such C_i estimates unreliable. As an alternative to C_i, the CO_2 concentration in the chloroplast (*CC*) can be calculated from simultaneous measurements of photosynthetic rate from gas exchange measurements, and the thylakoid electron flux from chlorophyll fluorescence. This permits diffusional effects (stomatal plus mesophyll limitations to CO_2 diffusion) to be differentiated from chloroplast-level effects. We used this method to investigate physiological limitations to photosynthesis in leaves of deficit irrigated tomato plants under open field situations. Combined leaf gas exchange/and chlorophyll fluorescence measurements differentiated the treatments effectively. Irrigation treatments showed varied and significant effects on physiological responses of two processing (Chali and Malkashola) tomatoes and one fresh market (Miya) tomato**.** Reduction in photosynthetic rate (*A*), stomatal conductance (g_s) and the maximum quantum efficiency of photosystem II (*PS II*) (F_v/F_m) were varied across seasons in green leaves of all varieties, whereas transpiration rate (*E*) and leaf temperature (T_l) increased by deficit irrigation in all varieties. Noticeable decrease under deficit irrigation in *A* and *Fv/Fm* was noted in Chali while reduction in g_s was observed in Malkashola and Miya, respectively. Stomatal limitation of *A* increased significantly with deficit irrigation suggesting a stronger influence of the stomatal factor. Reduction in leaf gas exchange variables varied across seasons and irrigation treatments for the varieties under study. In all varieties studied, Miya was found to be most tolerant to deficit irrigation.

Keywords: Chlorophyll fluorescence, gas exchange, irrigation, photosynthesis, physiological responses, semi-arid, tomato, varieties.

Introduction

Deficit irrigation is a useful technique to save irrigation water and increase water use efficiency at acceptable levels of yield. This technique might be useful for growing tomatoes in the field in semi-arid regions of Ethiopia. However, deficit irrigation may reduce leaf photosynthetic carbon assimilation via both stomatal and non-stomatal effects: stomatal effects reduce photosynthesis at a given leaf internal CO_2 concentration (C_i), and non-stomatal effects inhibit or down regulate photosynthesis at the level of the chloroplast (Said and Earl, 2005). The capacity to maintain the functionality of the photosynthetic machinery under water stress, therefore, is of major importance as deficit irrigated crops react to water deficit by rapidly closing stomata to avoid further water loss via transpiration (Cornic, 1994). The reduction in photosynthesis under water deficit has been frequently reported. Photosynthesis rate (A), stomatal conductance (g_s) and transpiration rate (E) were decreased by water deficit, decreasing CO_2 diffusion due to stomatal closure and directly inhibiting biochemical reactions of photosynthesis (Tezara *et al*., 1999). Bernacchi *et al*. (2002) noted that a large C_i**:** CO_2 concentration in the chloroplast (*CC*) ratio can also arise when the conductance to diffusion of CO_2 in the mesophyll from the substomatal cavity to the carboxylation site in the chloroplast (g_m) is very low. They also suggested that g_m is (partly) determined by aquaporins and carbon anhydrase and can be reduced by water stress (Flexas *et al*., 2004). Such a decrease in conductance to CO_2 diffusion in the mesophyll would constitute a non-stomatal limitation to photosynthesis. The maximum photochemical efficiency of photosystem II and apparent photosynthetic electron transport rate, the amount and activity of ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) were not changed by water deficit (Parry *et al*., 1993; Ohashi *et al*., 2006), whereas in leaves of sunflower, water deficit decreased CO_2 uptake more than O_2 evolution and reduced the amounts of ATP and RuBP (Tezara *et al*., 1999). Other workers (Kramer, 1983; Parry *et al*., 1993) also reported such a decrease in RuBisCO activity in leaves and thus photosynthesis by inhibiting leaf growth, closing stomata and reducing the efficiency of carbon fixation (Gu *et al*., 2012). Decreases in leaf water content initially induce stomatal closure, imposing a decrease in the supply of CO_2 to the mesophyll cells and, consequently, result in a decrease in the rate of leaf photosynthesis (Lawlor and Cornic, 2002). The decrease in A in water stressed plants has usually been ascribed to stomata closure, but water shortage severe enough to cause stomatal closure concurrently causes inhibition of CO_2 fixation by damaging the photosynthetic apparatus (Farquhar and Sharkey, 1982; Keck and Boyer, 1974; cf. Rahman *et al*., 1999). The stomatal limitations imposed on photosynthesis will be accompanied by a decrease in the rate of consumption of ATP and NADPH for CO_2 assimilation, which could result in decreases in the rate of linear electron transport and, consequently maximum efficiency of Photosystem II (*PSII*).

The net photosynthetic CO_2 assimilation rate decreases with increasing leaf temperature (T_l) (Haldmann and Feller, 2004). High T_l externally limits diffusion of gases from outside the leaf to the sites of carboxylation (Moon *et al*., 1987) and internally increases photorespiration rates (cf. Mebrhtu *et al*., 1991), dark respiration (Graham, 1980), decreases rates of electron transport and photophosphorylation (Stidham *et al*., 1982), and CO_2 fixation by the photosynthetic carbon reduction cycle (Monson *et al*., 1982).

Chlorophyll fluorescence (F_v/F_m) gives information about the state of PSII or the extent to which PSII is using the energy absorbed by chlorophyll and the extent to which it is being damaged (first manifestation of stress in a leaf). F_m is fluorescence intensity with all PS II reaction centres closed (i.e., q_p = 0); all non-photochemical quenching processes are at minimum (i.e., q_N = 0). This is the classical maximum fluorescence level in the dark or low light adapted state; F_v is maximum variable fluorescence in the state when all non-photochemical processes are at a minimum, i.e. (F_m-F_o); and F_o is fluorescence intensity with all PS II reaction centres open while the photosynthetic membrane is in the non-energized state, i.e., dark or low light adapted q_p = 1 and q_N = 0 (Van Kooten and Snel, 1990). The decrease in dark-adapted F_v/F_m and an increase in F_o show occurrence of photoinhibitory damage in response to high temperature (Gamon and Pearcy, 1989), low temperature (Groom and Baker, 1992), excess photon flux density (Ogren and Sjostrom, 1990) and water stress (Epron *et al*., 1992). Dark adapted values of F_v/F_m reflect the potential quantum efficiency of PSII and are used as a sensitive indicator of plant photosynthetic performance, with optimal figures of around 0.83 measure for most plant species (Bjorkman and Demmig, 1987; Johnson *et al*., 1993). Figures lower than this will be observed when the plant has been exposed to stress, showing the phenomenon of photoinhibition.

We hypothesized that A, g_s, E, T_l, and F_v/F_m are influenced by irrigation system and strategy, because the reduced leaf or organ growth rate is dependent on assimilate supply and water application system and strategy. To identify the response of field grown tomatoes under drip and furrow irrigation with three watering strategies, we examined the physiological responses to irrigation treatments in terms of changes in plant gas exchange and chlorophyll fluorescence in tomato leaves. This work was, therefore, aimed to determine the effects of irrigation management practices on physiological changes of fresh market and processing tomatoes under open field in a semi-arid area of Ethiopia.

Materials and methods

Plant material and field condition

Two field experiments were carried out in Adami Tullu Jido Kombolcha district (Oromia Region) at 07 ^{o}96’ N and 038 ^{o}72’ E, 1649 m a.s.l. on the technology testing site of International Development Enterprise field from 03 August to 04 December, 2010 and 04 November, 2010 to 04 March 2011. For this study, tomato varieties Chali, Miya and Malkashola (released from a National Tomato Research Programme, MARC of the country) were selected and were grown on a sandy clay loam soil (sand: 50%; silt: 30%; clay: 20%), with the following characteristics: average depth 70 cm; pH 7.4; organic matter 2.26%; salinity 0.32 dS m^{-1}; total nitrogen 0.19%; available P 26.2 ppm; K^+ 4.26 meq (100 g $soil)^{-1}$; Ca^{++} 25.7 meq (100g $soil)^{-1}$; Mg^{++} 16.6 meq (100g $soil)^{-1}$; Na^+ 4.3 meq (100 g $soil)^{-1}$, volumetric water content 36% at field capacity (0.33 bar) and 16% at permanent wilting point (15 bar); bulk density 1.52 g/cm^3 at 0-15 cm, 1.41 g/cm^3 at 16-30 cm, 1.63 g/cm^3 at 31-45 cm, and 1.13 g/cm^3 at 46-60 cm depth (ZSTLC, 2011). The tomato plants were planted at a distance of 0.30 m in the row with 0.70 m spacing between rows and fertilization was applied using 82 kg/ha of N and 92 kg/ha of P_2O_5 after transplant establishment and during crop growth, applied by the ring application method. The micro-flow drip irrigation system was used with dripping wings along the row and distributors giving 2 L/h and spacing 0.30 m among them. Water removal from different soil layers and during growth periods was calculated based on the volumetric water content values at permanent wilting point (θWP) and field capacity (θFC). Gravimetric soil water content at soil depths of 0-15, 16-30, 31-45 and 46-60 cm was determined during soil sampling and multiplied by soil bulk density to calculate volumetric water content. For both furrow as well as drip irrigation treatment three levels (local empirical practice, crop water requirement and deficit irrigation with 50% crop water requirement) were used. A split-plot design with three replications was used by assigning varieties to the main plots and irrigation treatments to the subplots. Irrigation treatments include: Furrow according to local empirical practice (FLE), Furrow according to crop water requirement (FETc), Furrow deficit irrigation (FDI), Drip according to local empirical practice (DL), Drip according to crop water requirement (DETc) and Drip deficit irrigation (DDI).

Gas exchange measurements

Photosynthetic rate (*A*), leaf transpiration rate (*E*), stomatal conductance (g_s) and leaf temperature (T_l) measurements were performed by a portable, closed-circuit infrared gas analyzer (IRGA), LCpro+ (ADC BIOSCIENTIFIC Ltd. Hoddesdon, EN110DB). The chamber temperature, T_{set}, light level, Q_{set}, CO_2 concentration, C_{set}, and humidity, e_{set} were set to 20 °C, 1500 µmol m^{-2} s^{-1}, 370 ppm and 23 mbar, respectively. T_l in the chamber was calculated adopting an energy balance equation (CE, 1997). The measurements were done from 18 September to 18 October 2010 and 28 December 2010 to 27 January 2011 for Experiments 1 and 2, respectively. Two young and fully expanded leaves in each plot were measured 5 times a day approximately every 2 h between 07:00 and 17:00 h.

Photosynthetic rate (Rate of CO_2 exchange in the leaf chamber, µmol m^{-2} s^{-1})
$A = Us$ x Δc where Us is mass flow of air per m^2 of leaf area, mol m^{-2} s^{-1}
Δc is difference in CO_2 concentration through chamber, dilution corrected, µmol mol^{-1}.

Stomatal conductance of water vapour (g_s, mol m^{-2} s^{-1})
$gs = \frac{1}{rs}$ where rs is stomatal resistance to water vapour, m^2 s^{-1} mol^{-1}.

Transpiration rate (E, mol m^{-2} s^{-1})
$E = Us$ x Δw where Δw is differential water vapour concentration, mol mol^{-1}, dilution corrected
Us is mass flow of air into leaf chamber per square metre of leaf area, mol m^{-2} s^{-1}

Leaf surface temperature, T_{leaf} (^{o}C) calculated as:

$$\mathrm{T}leaf = Tch + \left[(Q\ x\ H\ factor) - \lambda \mathrm{E} \Big/ (0.93\ Ma\ C\ p/rb) + 4\sigma(Tch + 273.16)^3) \right]$$

Where Tch is leaf chamber temperature, ^{o}C
Q is photon flux density incident on leaf chamber window, µmol m^{-2} s^{-1}
$H\ factor$ is energy conversion factor (was TRANS on LCA-3) J µmol^{-1}.
λ is latent heat of vaporisation of water, J mol^{-1}, value used is 45064.3-(t_{ch} x 42.9) Joule mol^{-1}.
E is transpiration rate, mol m^{-2} s^{-1}.

Ma molecular weight of air, value used is 28.97.

Cp is specific heat at constant pressure, J g^{-1} K. value used is 1.012 J g^{-1} K

rb is boundary layer resistance to vapour transfer, m^2 s^{-1} mol^{-1}

(0.93 is conversion factor for above to give boundary layer resistance to heat)

σ is Boltzmann's constant, W m^{-2} K^{-4}. Value used is 5.7 x 10^{-8} W m^{-2} K^{-4}.

Photosynthetically active radiation ($PAR_{absorbed}$ on leaf surface)

$Qleaf = Q \ x \ Trw$ where Q photon flux density incident on leaf chamber window, µmol m^{-2} s^{-1}, Trw leaf chamber window transmission factor to PAR (given).

Chlorophyll fluorescence measurements

The chlorophyll fluorescence was taken on the same leaves used for gas exchange using a portable fluorometer OPTI-SCIENCES model OS-30 (Opti-sciences Inc., Tyngsboro, MA, USA) simple portable device for measuring plant stress (F_v/F_m) 5 times a day approximately every 2 h between 07:00 and 17:00 h. The maximum quantum efficiency of PSII (F_v/F_m) was measured by subjecting the green leaves to a period of dark adaptation for 20 minutes, and then subjecting them to a pulse of high intensity saturated irradiance (2000 µmol photons m^{-2} s^{-1}). The fluorescence measurements were made five times on fully expanded youngest leaves as:

$$\frac{Fv}{Fm} = (Fm - Fo)/Fm$$

where Fv : is the total amount of variable fluorescence (dark adapted leaves, F_m-F_o)

F_o: is minimum fluorescence yield (dark adapted leaves, PSII fully open)

F_m: is maximum fluorescence yield (dark adapted leaves, PSII fully closed)

F_v/F_m: is the maximum quantum efficiency of photosystem II (PSII).

$$RP = (Performance\ under\ DI\ \div Performance\ under\ ETc) \times 100$$

where RP, DI and ETc are relative performance, deficit irrigation and crop evapotranspiration, respectively.

Statistical analysis

All data were subjected to Analysis of Variance (ANOVA) to decide the significance difference between treatments using the SAS statistical software version 9.2 (SAS Institute Inc., 2008). Mean separations for two-way and three-way interactions were computed by using the Method of Least Squares Means (lsmeans) for variables that showed significant difference among treatment combinations. Pearson's correlation test was used to analyze the relationships between and within leaf gas exchange and chlorophyll fluorescence.

Results and discussion

Understanding the effects of irrigation system and strategy on physiological variables such as photosynthesis, stomatal conductance, transpiration and leaf temperature could be of great importance in understanding crop yield response to irrigation. This would then permit a more rational choice of irrigation strategy as well as more efficient water use.

Photosynthetic rate (A), stomatal conductance (g_s) and maximum quantum efficiency of photosystem II (F_v/F_m)

Maximum values of A, g_s and F_v/F_m were observed for tomatoes grown using DETc, DL and FETc compared with those grown in deficit irrigation during both growing periods (Fig. 7.1 and Table 7.1). The decrease in A under deficit irrigation could be due mainly to lowered g_s, while non-stomatal limitation on A might have also occurred in leaves under stressful conditions. For instance, the lowered leaf chlorophyll fluorescence, F_v/F_m, in the deficit irrigated leaves might have contributed to the decrease of A. Generally a change in stomatal conductance affects the CO_2 assimilation rate and this effect is more severe when a plant encounters water deficit.

Farquhar and Sharkey (1982) implied that stomatal movement offers the leaf the opportunity to change both the partial pressure of CO_2 at the sites of carboxylation and the rate of transpiration, the increased rate of transpiration results in decreased leaf water content which also reduces CO_2 assimilation rate. Fig. 7.1 and Table 7.1 show that A and g_s were reduced in DDI and FDI compared to DETc, DL and FETc treatments. These decreases in A and g_s were possibly due to a reduction in tissue water content. Similar findings have been reported in wild soybean species (Kao *et al*., 2003) and *Cucumis sativus* L. (Stepien and Kibus, 2006). Samuel and Paliwal (1993) showed that there was a 50% reduction in the A and g_s under water stress. Decrease in A, g_s and F_v/F_m values was observed under FLE compared with FETc and DETc as a result of excessive irrigation at a time (Tables 7.1, 7.3, 7.4).

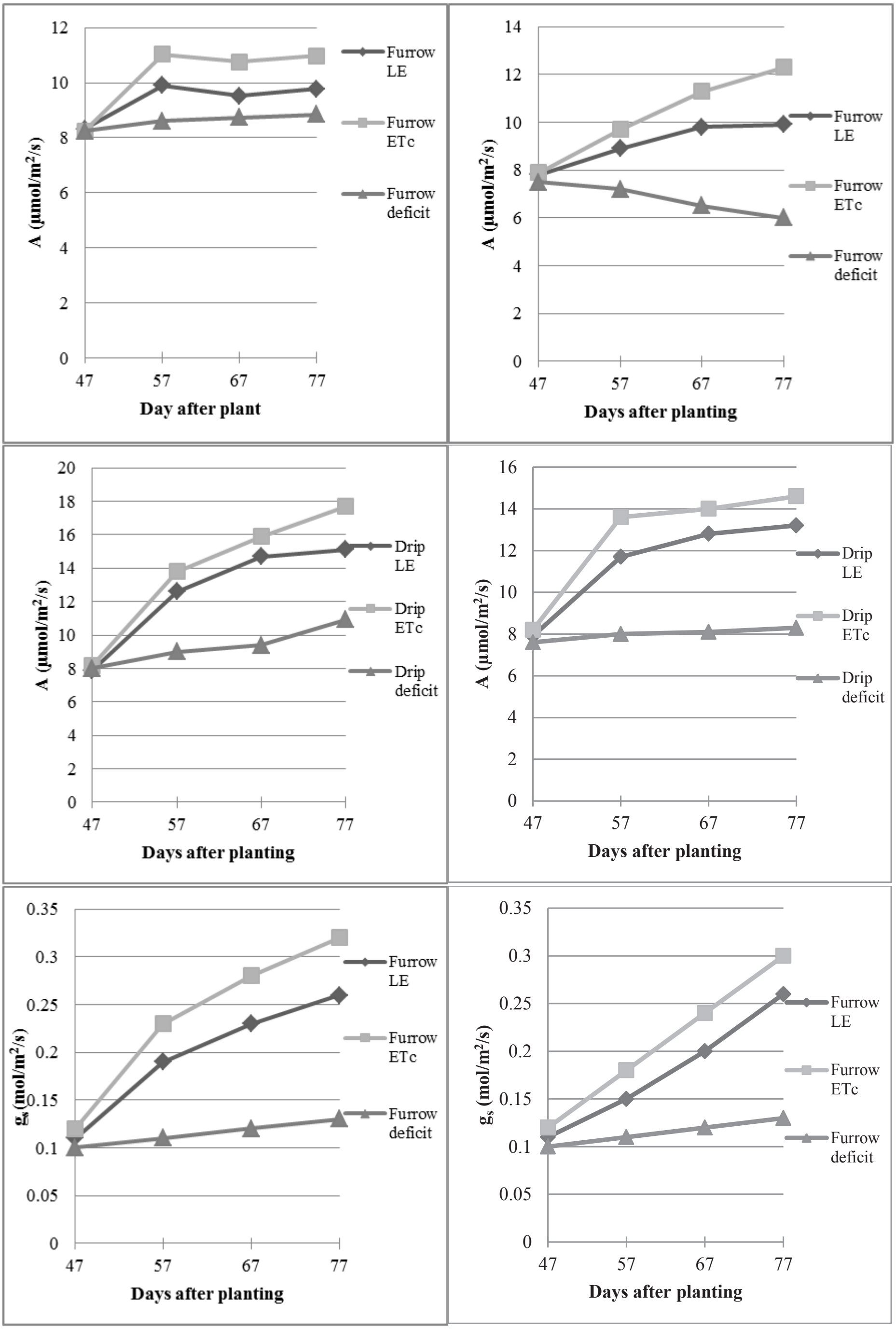
Chlorophyll fluorescence is an efficient tool for detecting changes in functioning of the photosynthetic apparatus, which can be damaged by soil inundating (Waldhoff *et al*., 2002; Mielke *et al*., 2003) by causing a decrease in chlorophyll a and b content thereby resulting in leaf chlorosis (Smethurst and Shabala, 2003). The experimental data indicated

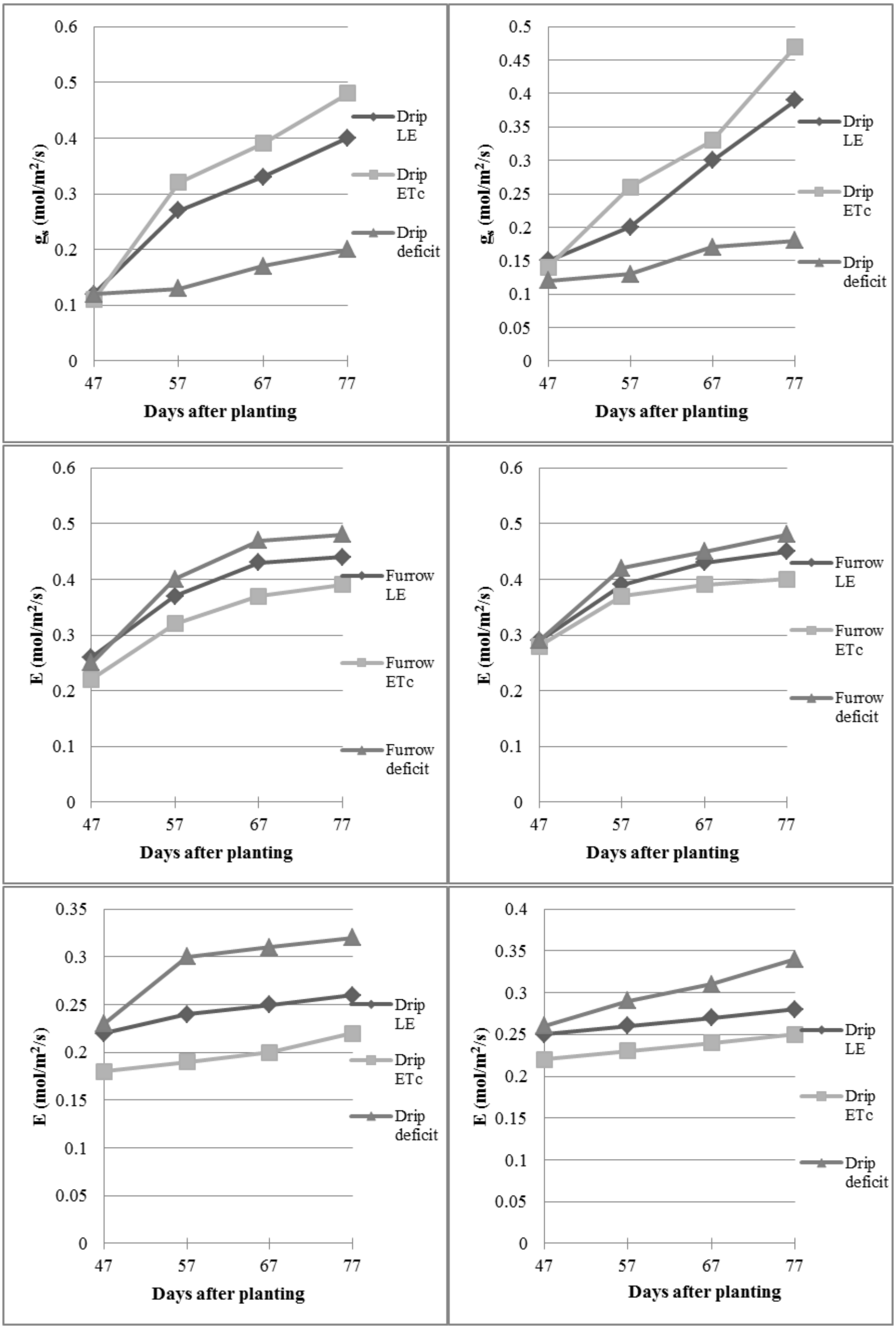
Table 7.1. Photosynthetic rate (A), stomatal conductance (g_s), transpiration rate (E), leaf temperature (T_l), chlorophyll fluorescence (F_v/F_m) and photosynthetically active radiation absorbed ($PAR_{absorbed}$) of field grown tomato leaves as influenced by irrigation system and strategy in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Treatment	**Photosynthesis parameters**					
	A (µmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	E (mol m^{-2} s^{-1})	T_l (°C)	F_v/F_m (-)	$PAR_{absorbed}$ (µmol m^{-2} s^{-1})
Experiment 1						
FLE	10.4d	0.20d	0.38b	26.0b	0.83d	456d
FETc	11.6c	0.24c	0.33c	25.3c	0.88c	476c
FDI	8.2f	0.12f	0.40a	26.5a	0.70f	423f
DL	12.6b	0.28b	0.24e	23.8e	0.89b	494b
DETc	13. 9a	0.33a	0.19f	23.0f	0.90a	516a
DDI	9.3e	0.16e	0.29d	24.5d	0.78e	444e
Experiment 2						
FLE	9.1d	0.18d	0.39b	26.4b	0.80C	434d
FETc	10.3c	0.21c	0.36c	26.1c	0.86B	460c
FDI	6.8f	0.11f	0.43a	26.8a	0.68E	395f
DL	11.4b	0.26b	0.26e	24.2e	0.89A	486b
DETc	12.6a	0.30a	0.23f	23.5f	0.89A	528a
DDI	8.0e	0.15e	0.30d	25.2d	0.74D	415e

Means within columns for each variable and year followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) and $p \leq 0.01$ (upper case letter). FLE = Furrow according to local empirical practice; FETc = Furrow according to crop water requirement; FDI = Furrow deficit irrigation; DL = Drip according to local practice; DETc = Drip according to crop water requirement; DDI = Drip deficit irrigation.

that the FLE irrigated tomato field promoted stomatal closure compared with DETc or FETc and also disturbed functioning of the photosynthetic apparatus of tomato by depressing maximum quantum yield (F_v/F_m) of PSII (Fig. 7.2 and Tables 7.1, 7.3, 7.4). In FLE, because of water inundating A was reduced via reduced effect of g_s. This decreasing effect of g_s on A was further evidenced by a highly significant and positive correlation between these variables (r = 0.95**; Table 7.2). Water inundating damage to photosynthetic apparatus resulted in a lower F_v/F_m and A, which reveal that water application by FLE strategy in the soil limits growth and injures the photosynthetic apparatus in tomato. By FLE strategy much water at a time inundated around roots for few hours during application. The response of the photosynthetic apparatus observed with FLE seems to show that changes in A depend on the stomata closure which is due to the damage of PSII (F_v/F_m) via the inundating effects around roots. This might cause decrease of root hydraulic conductivity resulting in decreased leaf turgor and stomatal conductance (Mielke *et al*., 2003) and hence the storage of CO_2 in leaves.




0.6
0.5
0.4
0.3
0.2
0.1
0
g_s (mol/m^2/s)
47
57
67
77
Days after planting
Drip LE
Drip ETc
Drip deficit
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
g_s (mol/m^2/s)
47
57
67
77
Days after planting
Drip LE
Drip ETc
Drip deficit
E (mol/m^2/s)
Days after planting
Furrow LE
Furrow ETc
Furrow deficit
E (mol/m^2/s)
Days after planting
Furrow LE
Furrow ETc
Furrow deficit
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
E (mol/m^2/s)
Days after planting
Drip LE
Drip ETc
Drip deficit
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
E (mol/m^2/s)
Days after planting
Drip LE
Drip ETc
Drip deficit

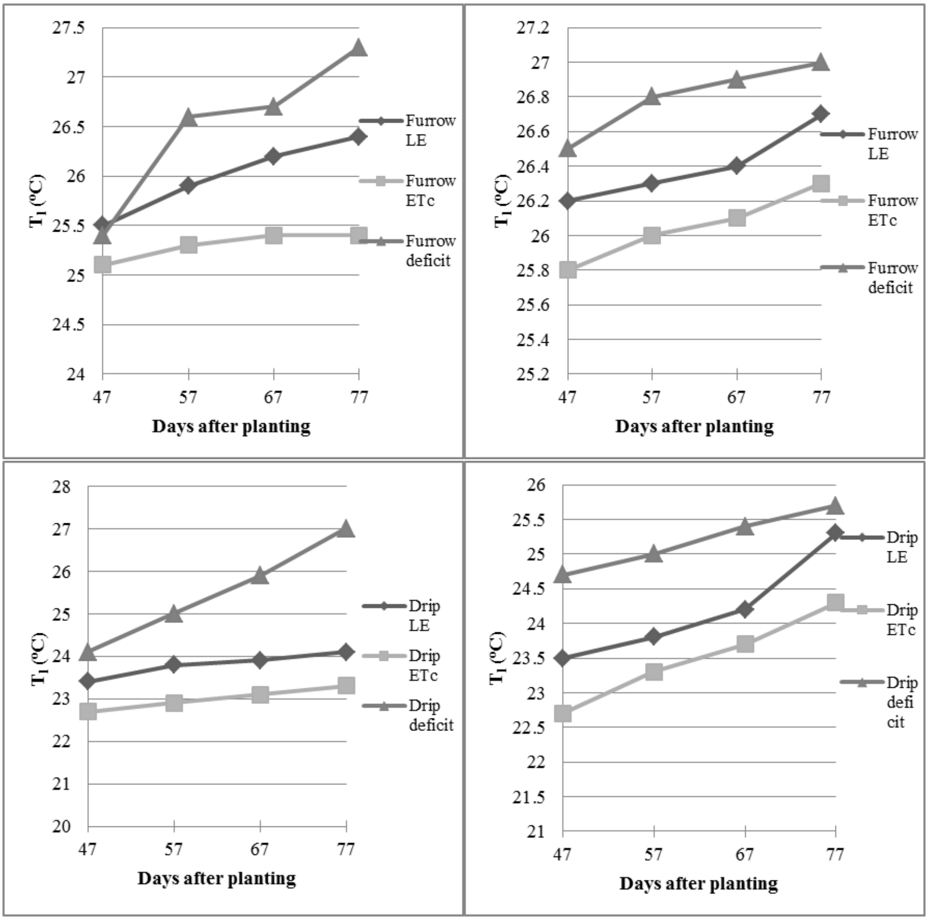


Fig. 7.1. Photosynthetic gas exchange (A), stomatal conductance (gs), evaporation (E) and leaf temperature (T_l) of field-grown tomato as affected by irrigation system and strategy, in Experiment 1 (left) and Experiment 2 (right). For codes of treatments, see Tables footnotes.

Thus, the data presented in (Figs. 7.1, 7.2 and Tables 7.1, 7.3, 7.4) leads to the idea that the effect of FLE (inundating) on leaf gas exchange in field-grown tomato may be a reduction in stomata opening that leads to the decrease of *A*.

On the other hand, in deficit irrigation, the decrease of g_s (52% and 50%) was the main reason for the decrease in *A* (33% and 29%) with DDI and FDI relative to DETc and FETc, respectively in Experiment 1 due to possible stomatal closure and metabolic impairment under deficit irrigation that limited photosynthesis (Table 7.1). Similar situation was also noted during Experiment 2. Moreover, the lower value of *A* in Experiment 2 than in

Table 7.2. Relationships among leaf gas exchange and chlorophyll fluorescence variables (n = 18)

Variables	R	Significance	Variables	R	Significance
A vs E	-0.96	**	A vs PAR	0.92	**
A vs g_s	0.95	**	E vs T_l	0.86	*
A vs T_l	-0.83	**	A vs F_v/F_m	0.93	**
E vs g_s	-0.98	**	g_s vs F_v/F_m	0.87	*
g_s vs T_l	-0.84	**	A vs N_l	0.83	*

A = photosynthetic rate, E = transpiration rate, g_s = stomatal conductance, PAR = absorbed photosynthetically active radiation, T_l = leaf temperature and F_v/F_m = chlorophyll fluorescence, N_l= leaf nitrogen, *: P<0.05; **: P<0.01.

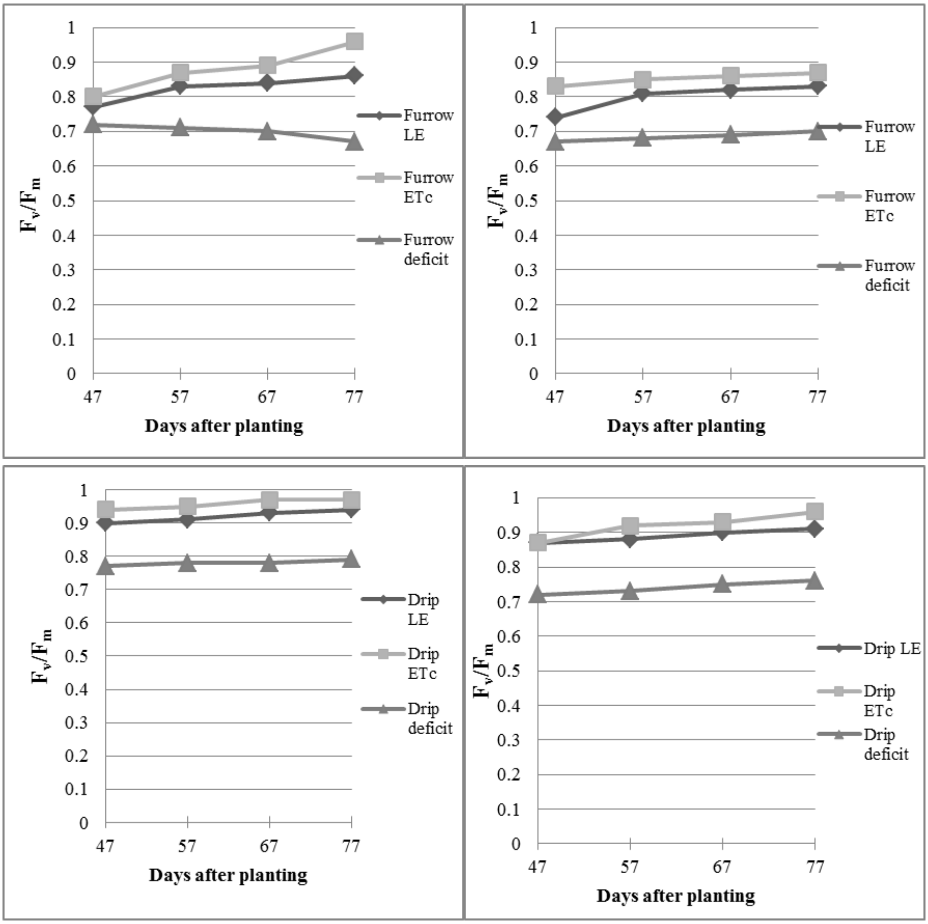


Fig. 7.2. Maximum quantum efficiency of the photosystem II (F_v/F_m) in the leaves of field-grown tomato, as affected by irrigation system and strategy; in Experiment 1 (left) and Experiment 2 (right) growing season. For treatments codes, see Tables foot notes.

Experiment 1 (Fig. 7.1 and Table 7.1) was due to higher temperatures during the Experiment 2 season (data not presented). The influence of g_s on A in this study was further supported by the positive and high degree of relationship between A and g_s (r = 0.95**) (Table 7.2). Higher A was recorded for DETc followed by DL and FETc (Fig. 7.1) whereas a minimum value was registered for DDI and FDI.

Chlorophyll fluorescence indirectly measures photosynthetic efficiency; used to detect differences in the response of plants to environment stresses and, consequently, to screen for tolerance to such stresses; and useful for assessing the integrity of the photosynthetic apparatus during the photosynthetic process within a leaf (Neil and Rosenqvist, 2004; Percival and Sheriffs, 2002; Krause and Weis, 1991; Clark *et al.,* 2000). In this study, using furrow irrigation, maximum value of F_v/F_m was recorded under FETc in both seasons (Fig. 7.2). Lower F_v/F_m was observed in FLE because of non-uniform water application. This result is in agreement with Bradford (1983) work who reported that tomato leaf epidermal conductance to water vapour decreased by 47% after flooding. In drip irrigation, however, DL showed the higher values after DETc during both seasons. Lowest F_v/F_m yield was recorded under FDI which was far below the DETc yield (≥ 89% F_v/F_m) in both growing periods suggesting that poor performance under deficit irrigation using furrow system. Several researchers (Greaves and Wilson 1987; Araus and Hogan, 1994; Hakam et *al.,* 2000; Baker and Rosenqvist, 2004; Valladares *et al.,* 2005) indicated that F_v/F_m was strongly correlated with whole-plant mortality in response to environmental stresses (water deficit, temperature, nutrient deficiency, polluting agents, attack by pathogens) and were reliable indicators of stresses. Differences in F_v/F_m for pooled data under deficit irrigation were seen from 57 to 77 DAP, whereas F_v/F_m showed no indication of stress under DETc, DL and FETc treatments (Fig. 7.2).

Absorbed quantities of photosynthetically active radiation ($PAR_{absorbed}$)

At the whole canopy level, the effects of water deficits on leaf area expansion and absorption of PAR can be measured and have been well documented (Turner *et al*., 1986; Puech-Suanzes *et al*., 1989; Ball *et al*., 1994). Light absorption is an important factor for determining crop yield, being one of the driving forces behind plant photosynthesis, and meanwhile is highly dependent on single plant architecture as well as on overall canopy structure (Niinemets, 2007). Water deficit affects the efficiency with which absorbed radiation is utilized to carry out carbon fixation at the leaf level, and the mechanisms by which this occurs have been the subject of several researches in a variety of crops over the past decades. Stomatal closure and the consequent reduction in leaf internal CO_2 concentration (C_i) are the main causes for reduced leaf photosynthetic rates under water stress (Chaves, 1991; Cornic, 2000; Flexas *et al*., 2004).

In this work similar finding was registered on $PAR_{absorbed}$ of tomato grown under different irrigation treatments as evidenced by greater $PAR_{absorbed}$ in full-irrigated plants than that of plants grown in deficit irrigated in both seasons (Tables 7.1, 7.3, 7.4). Deficit irrigation reduced $PAR_{absorbed}$ thereby decreasing *A*. This is further supported by the significant and high degree of relationship between *A* and $PAR_{absorbed}$, r = 0.92** (Table 7.2).

Leaf temperature (T_l) and leaf transpiration rate (E)

Plant physiological processes are temperature dependent and plants operate best at optimal temperatures; leaf temperature (T_l) ultimately determines these processes including organ growth (Mohotti and Lawlor, 2002). If a leaf heats up beyond its optimal range, photosynthetic enzymes start to become less efficient and can even begin to denature, preventing the leaf from performing its function. Moreover, leaf respiration increases rapidly with an increase in leaf temperature, thus reducing net photosynthesis. Thus plants attempt to maintain an equilibrium T_l to maximize their usefulness to the plant. In these experiments, elevated leaf temperatures do have a significant impact on carbon gain during the growing season (Fig. 7.1 and Tables 7.1, 7.3, 7.4, 7.5). Increase in T_l to 26.5 °C did decrease *A* to 8.2 μmol m^{-2} s^{-1} with FDI in Experiment 1, showing high temperature inhibition of *A* (Table 7.1). With this same T_l, inhibition of *A* was accompanied by reduced g_s (0.20 mol m^{-2} s^{-1}) (Table 7.1). On the other hand, T_l values of ≤ 25.3 °C were maintained under DETc, DL and FETc because of regulated water supply resulting in lowering in T_l fluctuation under full irrigation requirement thereby raising the *A* of leaves (Fig. 7.1). Hence tomatoes irrigated according to crop water requirements and with local drip had less water loss as compared to their counterparts, those grown under deficit irrigation. In the similar way, T_l of tomato leaves that were grown in FDI and DDI was significantly higher than that of tomato grown under DETc, DL and FETc (Tables 7.3, 7.4, 7.5).

An increase in T_l recorded in FDI and DDI caused subsequent lowering of g_s, induced by high CO_2 concentration in the mesophyll cells (partly caused by high photorespiration) and high water loss, possibly resulting in lower *A* under deficit irrigation than under full irrigation requirement (Tables 7.1, 7.3, 7.4). This shows that deficit irrigation does not result in a sustained high level of *A*. This is also supported by the work of Farquhar and Sharkey (1982) who explained that high temperatures reduce electron transport capacity and increase the rates of CO_2 evolution from photorespiration and other sources resulting in assimilation rate to decrease.

Leaf transpiration rate (*E*) related to T_l (Tables 7.1, 7.3, 7.4) and this was supported by highly significant and positive correlation (r = 0.86*) with each other (Tables 7.2) in line with Konis (1950; cf. Bote, 2007) who reported that the leaf temperature has marked influence on the rate of leaf transpiration. According to this report, the temperature increment of the leaves of a plant is capable of raising *E* by as much as 30-230%.

Also, a consistent trend was found for *E* under drip and furrow irrigation during Experiment 1. Maximum *E* was registered in FDI followed by FLE but with a minimum value under FETc; for drip irrigation a higher *E* was recorded under DDI followed by DL and a lower value for DETc. In Experiment 2, a similar trend was observed under both irrigation systems with higher *E* for deficit followed by local empirical practice and full irrigation requirements in descending order (Fig. 7.1).

Leaf gas exchange and chlorophyll fluorescence of tomatoes as influenced by variety and irrigation management practices

Photosynthetic performance of tomato plants under deficit irrigation (DI) is low, and recovery is gradual maybe because of injury to PSII depending on the irrigation water application system and strategy. In response to the DI strategy, a decrease in CO_2 assimilation was observed (Tables 7.3 and 7.4). This effect resulted from an inhibition of electron transport activity limiting the metabolic activity (Guo and Al-Khatib, 2003). Measuring photosynthesis traits such as chlorophyll content and chlorophyll fluorescence variables might assist in determining the influence of the environmental stress on growth and yield, since these traits were closely correlated with the rate of carbon exchange (Guo and Li, 2000; Araus *et al*., 1998; Fracheboud *et al*., 2004). Changes in the fluorescence yield reflect changes in photochemical efficiency and heat dissipation; low F_v/F_m values in plants under stress indicate damage to the PSII reaction centres (Kadir and Weihe, 2007). Under high temperatures or water stress, PSII has been recognized as the sensitive component of the entire photosynthetic system (Berry and Björkman, 1980; Mamedov *et al*., 1993). F_v/F_m is used to determine the

Table 7.3. Interaction effects of variety and irrigation system and strategy on photosynthetic rate (*A*), stomatal conductance (g_s), transpiration rate (*E*), leaf temperature (T_l) chlorophyll fluorescence (F_v/F_m) and absorbed photosynthetically active radiation ($PAR_{absorbed}$) of field-grown tomato leaves in Experiment 1.

Variety	Irrigation treatments	*A* (µmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	*E* (mol m^{-2} s^{-1})	T_l (^{o}C)	F_v/F_m (-)	$PAR_{absorbed}$ (µmol m^{-2} s^{-1})
Chali	FLE	10.4**k**	0.20**k**	0.38**e**	25.9**e**	0.83**g**	456**k**
	FETc	11.5**h**	0.24**h**	0.33**h**	25.3**h**	0.88**d**	477**h**
	FDI	7.9**r**	0.10**r**	0.42**b**	26.6**ab**	0.69**o**	413**r**
	DL	12.6**e**	0.28**e**	0.24**n**	23.8**n**	0.89**c**	495**e**
	DETc	14.6**a**	0.34**a**	0.19**q**	23.0**q**	0.91**a**	529**a**
	DDI	9.3**mn**	0.16**n**	0.29**k**	24.6**k**	0.79**j**	445**n**
Miya	FLE	10.0**l**	0.19**l**	0.36**f**	25.8**ef**	0.82**h**	450**l**
	FETc	11.3**i**	0.23**i**	0.32**i**	25.1**i**	0.87**e**	471**i**
	FDI	8.4**p**	0.13**p**	0.41**c**	26.3**c**	0.71**m**	430**p**
	DL	12.3**f**	0.27**f**	0.22**o**	23.5**o**	0.89**c**	487**f**
	DETc	13.3**c**	0.31**c**	0.17**r**	22.8**r**	0.90**b**	508**c**
	DDI	9.4**m**	0.17**m**	0.27**l**	24.2**l**	0.80**i**	449**lm**
Malkashola	FLE	10.7**j**	0.21**j**	0.39**d**	26.1**d**	0.85**f**	463**j**
	FETc	12.0**g**	0.26**g**	0.35**g**	25.6**g**	0.88**d**	481**g**
	FDI	8.2**q**	0.12**q**	0.46**a**	26.7**a**	0.70**n**	426**q**
	DL	12.9**d**	0.30**d**	0.25**m**	24.1**lm**	0.90**b**	501**d**
	DETc	13.8**b**	0.33**b**	0.20**p**	23.3**p**	0.90**b**	511**b**
	DDI	9.2**no**	0.14**o**	0.30**j**	24.8**j**	0.75**l**	438**o**

Means within columns for each parameter followed by different letters are statistically different from each other at $p \leq 0.05$. FLE= Furrow local empirical practice; FETc = Furrow according to crop water requirement; FDI = Furrow deficit irrigation; DL = Drip local; DETc = Drip according to crop water requirement; DDI = Drip deficit irrigation.

effects of environmental stresses on photosynthesis in plants exposed to adverse conditions.

In this work, chlorophyll fluorescence along with gas exchange variables was used to assess changes in photosynthesis. The relationship between *A* and *E*, as well as with T_l was negative and strongly significant, but *A* was positively and strongly correlated with g_s, leaf nitrogen and F_v/F_m (Table 7.2).

Stomatal conductance (g_s) can also be influenced by various environmental factors, *viz.* water status, irradiance and CO_2 concentration. For instance, high irradiance and CO_2 concentrations result in closure, while low irradiance and CO_2 concentrations stimulate opening (Kim *et al.*, 2004). In this study, negative, high and significant relationship was observed between g_s and *E* and T_l as well, however, it was positively and strongly correlated with F_v/F_m (Table 7.2). Higher values of leaf g_s were registered in fully irrigated than in deficit irrigated tomatoes. This offers the opportunity of increased rate of CO_2 assimilation for fully irrigated tomatoes compared with those grown under DI. The decrease of PSII photochemistry efficiency under stress may reflect not only the inhibition of PSII function, but also an increase in the dissipation of thermal energy (Demmig-Adams and Adams, 1992).

In these experiments a significant decrease in PSII efficiency (F_v/F_m) due to water deficit was observed in all varieties. DI treatments with three varieties also showed differential response, with significant decreases in physiological measurements occurring during the course of the experimentation in Chali, Miya and Malkashola (Tables 7.3, 7.4). DI decreased A, g_s, F_v/F_m, but increased T_l and E (Tables 7.3, 7.4). A in each variety decreased with a decrease in irrigation water volume. Reasons for the reduction in A were structural damage to the thylakoids, which affects the photosynthetic transport of electrons (Hatem *et al*., 2005). A reduced by 46%, 37% and 41% in FDI relative to DETc for Chali, Miya and Malkashola, respectively, during the first growing season (Table 7.3). Likewise, A decreased by 49%, 44% and 45% in FDI compared to the DETc for Chali, Miya and Malkashola, respectively, in the second growing season (Table 7.4). These results are similar to those reported by Samuel and Paliwal (1993) who observed that A and g_s decreased by 50% as a result of water stress. Rahman *et al*. (1999), however, reported that A, E, leaf water potential and WUE were reduced, while T_l and stomatal resistance (r_s; the inverse of g_s) were increased by water stress in all varieties contrary to variety-specific responses for E in this experiment. With deficit irrigation, the T_l and E of the three varieties increased consistently in both growing seasons. As leaf g_s increases leaf E of course increases. But this E depends on the atmospheric water content (or the difference in water content between the inside of a leaf and the water content of the boundary layer; or leaf-to-air-vapour pressure difference, VPD) (Eamus and Shanahan, 2002).

The value of A of the three varieties decreased under deficit irrigation, but A of Miya was higher than that of Chali and Malkashola in both experiments for deficit irrigation, implying that Miya had better acclimation to water deficit than the other two varieties (Tables 7.3, 7.4). This had a close relation with the changes of g_s. The g_s values of Chali and Malkashola were also lower than those of Miya in both Experiments 1 and 2 for deficit irrigation (Tables 7.3, 7.4). Tomato varieties Chali, Miya and Malkashola, irrigated with FDI, revealed a decrease in g_s by 70, 58 and 64% and with DDI 53%, 45% and 58% in relation to

Table 7.4. Interaction effects of variety and irrigation system and strategy on photosynthetic rate (A), stomatal conductance (g_s), transpiration rate (E), leaf temperature (T_l) and chlorophyll fluorescence (F_v/F_m) and absorbed photosynthetically active radiation ($PAR_{absorbed}$) of field-grown tomato leaves in Experiment 2.

Variety	Irrigation treatments	A (µmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	E (mol m^{-2} s^{-1})	T_l (°C)	F_v/F_m (-)	$PAR_{absorbed}$ (µmol m^{-2} s^{-1})
Chali	FLE	8.9**l**	0.17**l**	0.40**e**	26.5**cd**	0.79**i**	424**l**
	FETc	10.0**i**	0.20**i**	0.36**h**	26.0**f**	0.85**f**	452**i**
	FDI	6.7**q**	0.11**q**	0.42**c**	26.7b**c**	0.68**n**	391**q**
	DL	11.2**ef**	0.25**f**	0.26**o**	23.9**m**	0.87d	481**f**
	DETc	13.1**a**	0.31**a**	0.22**q**	23.4**o**	0.90**a**	560**a**
	DDI	7.8**n**	0.15**n**	0.30**k**	25.3**i**	0.75**k**	418**n**
Miya	FLE	9.2**j**	0.19**j**	0.37**g**	26.2**e**	0.81**g**	445**j**
	FETc	10.5**g**	0.22**g**	0.35**i**	25.8**g**	0.87**d**	472**g**
	FDI	7.0**p**	0.12**p**	0.43**b**	26.8a**b**	0.70**m**	404**p**
	DL	11.6**d**	0.28**d**	0.24**p**	23.7**n**	0.88c	492**d**
	DETc	12.6**b**	0.30**b**	0.20**r**	23.0**p**	0.90a	523**b**
	DDI	8.5**m**	0.16**m**	0.28**m**	24.6**k**	0.77**j**	423**lm**
Malkashola	FLE	9.1**jk**	0.18**k**	0.41**d**	26.6**c**	0.80**h**	433**k**
	FETc	10.3**h**	0.21**h**	0.38**f**	26.4**d**	0.86**e**	456**h**
	FDI	6.6**qr**	0.10**r**	0.45**a**	26.9**a**	0.65**o**	383**r**
	DL	11.3**e**	0.26**e**	0.29**l**	24.9**j**	0.88c	485**e**
	DETc	12.1**c**	0.29**c**	0.27**n**	24.2**l**	0.89b	501**c**
	DDI	7.7**no**	0.13**o**	0.33**j**	25.6**h**	0.72**l**	411**o**

Means within columns for each parameter followed by different letters are statistically different from each other at $p \leq 0.05$. FLE= Furrow local empirical practice; FETc = Furrow according to crop water requirement; FDI = Furrow deficit irrigation; DL = Drip local; DETc = Drip according to crop water requirement; DDI = Drip deficit irrigation.

DETc, respectively, in Experiment 1. Likewise, in Experiment 2, varieties Chali, Miya and Malkashola, irrigated with FDI, also showed a reduction in g_s with 65%, 60% and 66% in DDI and 52%, 47% and 55% relative to DETc, respectively.

Stomatal closure contributes to a reduction of carbon assimilation due to the water deficit. Such CO_2 uptake limitation contributes to an absence of a sink for the assimilated energy (Valladares and Pearcy, 1997), and may cause chloroplasts to be subjected to an excess of energy resulting in the down-regulation of photosynthesis or in photoinhibition (Demmig-Adams and Adams, 1996). Under water deficit down-regulation of different photosynthetic processes depends more on CO_2 availability in the mesophyll (i.e. on stomatal closure) than on leaf water potential or leaf water content (Sharkey, 1990). This could be understood as a direct adjustment of photosynthetic metabolism to CO_2 availability, which is well known to act as a regulator of Rubisco (Perchorowicz and Jensen, 1983; Meyer and Genty, 1999).

The observed physiological differences between the responses of the varieties were statistically significant and the ratio of variable fluorescence to maximal fluorescence after dark adaptation (F_v/F_m) was high for variety Chali (0.91 and 0.90) under DETc in Experiments 1 and 2, respectively. Tables 7.3 and 7.4 also show that in all varieties studied, DI induced a decrease in F_v/F_m because of an increase in F_o accompanied by a decrease in F_m. According to Baker and Horton (1987) an increase in F_o is characteristic of PSII inactivation, whereas a decline in F_v may indicate the increase in a non-photochemical quenching process at or close to the reaction centre. The F_v/F_m ratio, which characterizes the maximum quantum yield of the photochemical reactions in dark adapted leaves, was changed for all varieties, and treatments DETc, FETc and DL showed a slight tendency to decrease compared to DDI and FDI in both growing periods (Tables 7.3, 7.4). The differences between DETc and deficit irrigated (FDI, DDI) tomatoes were large in the effective quantum yield. Variety Chali, irrigated with FDI and DDI, indicated a decrease in Fv/Fm by 29 and 19% respectively, for DETc in Experiment 1 (Table 7.3), while under the same situations in Experiment 2, the inhibition of Chali was a little higher, 29% and 22%. On the other hand, in variety Miya the inhibition was about 25 and 16% while in Malkashola 27% and 22% (Table 7.3). In Experiment 2, the decrease was 26% and 18% for Miya, whereas it was 29% and 18% for Malkashola (Table 7.4). Similar to this result, (Meyer and Genty, 1998) reported that chlorophyll fluorescence suggested that the primary effect of water stress is stomatal closure with a consequent decrease in internal CO_2 concentration, limiting carboxylation.

In all three varieties, the decrease in F_v/F_m (Tables 7.3, 7.4) under water deficit occurred as a result of the increase of F_o and decrease of F_m. This implies the occurrence of chronic photoinhibition due to inactivation of PSII centres, possibly attributable to D1 protein damage (Campos, 1998). F_v/F_m reflects the maximal efficiency of excitation energy capture by open PSII reaction centres and the photodamage of the photosynthetic apparatus (Jia, 2001). This index could be used to express the type and degree of photoinhibition undergone by the leaves. The decrease in this variable indicates down regulation of photosynthesis or photoinhibition (Oquist *et al*., 1992).

In these experiments, A, F_v/F_m and g_s decreased slightly in Miya variety under DDI

(Tables 7.3, 7.4). Hence, Miya variety was slightly damaged by DDI. Also, Miya had higher F_v/F_m and g_s and lower E in both experiments. In addition, it had higher A. Therefore, we thought that the damage to Miya was not as serious as the damage to Chali and Malkashola. The leaves of these two varieties perhaps exhibit increased E resulting in a decreased water potential of the leaf which in turn limits CO_2 assimilation (Tables 7.3, 7.4). Deficit irrigated Miya variety may also have leaves capable of tolerating moistures at lower levels compared with those processing varieties. The reduction in water loss by stomatal closure by Miya is one of the adjustment or adaptive responses to maintain a high water potential in plants as the water stress develops and thus, these results indicated that Miya can maintain better electron transfer.

Tomato relative performance of gas exchange and chlorophyll fluorescence under full- and deficit-drip and furrow irrigation

Several studies demonstrated that water deficit results in damages of the PSII oxygen-evolving complex (Lu and Zhang, 1998; Skotnica *et al*., 2000) and of the PSII reaction centres associated with the degradation of D1 protein (Cornic, 1994). Lauer and Boyer (1992) showed that the decreased A under water stress can be attributed to the perturbations of the biochemical processes. In this study, influence of drip- and furrow-irrigation with DI strategy on the photosynthetic gas exchange and F_v/F_m was determined (Table 7.5). About 29% and 33% in FDI and DDI of inhibition in A relative to FETc and DETc, respectively, during Experiment 1. In the similar way the reduction in g_s was 50% and 52% by FDI and DDI, respectively, during the same experimentation. In Experiment 2, A was reduced by DI and the reduction in A by DI was 34% and 37% by FDI and DDI, respectively. Stomatal conductance (g_s) was also reduced, similar to the reduction in A.

The decrease in g_s was 48% and 50% by FDI and DDI, respectively, during the same season. The E increased correspondingly with the rise in T_l. DI increased in T_l by about 7% and 5% for drip and furrow, respectively, relative to full irrigation requirement during first growing season, while it decreased by 3% and 7% for same irrigation systems in the second growing periods (Table 7.5) with a consequent rise in E by about 21% and 52% in Experiment 1, and 19% and 30% in Experiment 2 in FDI and DDI, respectively. Compared to DETc, rate of transpiration increased and the leaf temperature increased in FDI and DDI. This was probably the cause of the lowered A and would also potentially have effects on other physiological processes related to fruit set, fruit growth and so on. Another study found a

Table 7.5. Gas exchange variables and chlorophyll fluorescence of field-grown tomato leaves as influenced by full- and deficit-drip and furrow irrigation in a semi-arid area in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Treatment	Gas exchange variables and chlorophyll fluorescence measurements					
	A (μmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	E (mol m^{-2} s^{-1})	T_l (^oC)	F_v/F_m	$PAR_{absorbed}$ (μmol m^{-2} s^{-1})
Experiment 1						
FETc	11.6c	0.24c	0.33c	25.3c	0.88c	476c
FDI	8.2f	0.12f	0.40a	26.5a	0.70f	423f
RP (%)	71	50	121	105	80	89
DETc	13. 9a	0.33a	0.19f	23.0f	0.90a	516a
DDI	9.3e	0.16e	0.29d	24.5d	0.78e	444e
RP (%)	67	49	153	107	87	86
Experiment 2						
FETc	10.3c	0.21c	0.36c	26.1c	0.86C	460c
FDI	6.8f	0.11f	0.43a	26.8a	0.68F	395f
RP (%)	66	52	119	103	79	86
DETc	12.6a	0.3a	0.23f	23.5f	0.89A	528a
DDI	8.0e	0.15e	0.30e	25.2d	0.74E	415e
RP (%)	64	50	130	107	83	79

Means within rows for each variable and year followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) and $p \leq 0.01$ (upper case letter). FETc = Furrow according to crop water requirement; FDI = Furrow deficit irrigation; DETc = Drip according to crop water requirement; DDI = Drip deficit irrigation. RP = Relative performance:

$$RP\ (\%) = (Performance\ under\ DI \div Performance\ under\ ETc)\ \times 100$$

pronounced decrease in *A* under a water stress treatment (Rahman *et al.,* 1999). This finding is in line with the findings of these authors DI increased stomatal limitation in all varieties. Increases in stomatal limitation accompanied the decreases in all photosynthetic variables and, consequently, stomatal closure was found to be an important factor contributing to the depressed CO_2 assimilation. PSII activity in variety Miya was more efficiently protected than in the other varieties, as indicated by the fluorescence measurements. Complete closure of stomata in patches can occur at high vapour pressure deficit (e.g. Beyschlag *et al*., 1992). Patchy stomatal closure results in a reduction in assimilation rate and stomatal conductance with no reduction in internal CO_2 concentration (Bunce, 1988).

Table 7.5 shows that F_v/F_m was lower by 21% and 19% in FDI and DDI irrigated plants compared with the DETc in Experiment 1, respectively. In Experiment 2, deficit irrigation with drip and furrow also caused a decrease by 20% and 21% in F_v/F_m, respectively. The decline in F_v/F_m suggests that a reduction in photosynthesis could be the result of damage to the photosynthetic apparatus. Some damage to PSII seems to be independent of decreases in stomatal conductance and may be caused by the changes within mesophyll cells and correlated with photoinhibition (Ahmed *et al*., 2002).

Inhibition of A (briefed earlier) in DI could be attributed to stomatal closure, although direct effects on several biochemical and photochemical processes have also been reported (Long *et al*., 1994; Cornic, 2000). This is in line with Hassan's (2006) findings that A, g_s and F_v/F_m were dramatically decreased under water deficit. In the current study, when the reduction in g_s increased, the decrease in A also increased suggesting that A was mostly reduced due to the reduction in g_s. These results suggest that the stomatal closure limited leaf photosynthetic capacity in the deficit irrigated tomato plants. Other authors also indicated that g_s declined before leaf water content was affected, and A was largely dependent on stomatal aperture in *Phaseolus vulgaris* (Cornic and Briantais, 1991). Farquhar *et al.* (1989) further reported that stomatal factors are more important than non-stomatal factors under water stress.

Soil drought and leaf water deficit lead to a progressive suppression of photosynthetic carbon assimilation (Chaves, 1991; Yordanov *et al*., 2000). Reduced photosynthetic rate is a result from stomatal and non-stomatal (biochemical) limitations (Yordanov *et al*., 2003). The study results showed that DI reduced gas exchange as explained earlier. According to Lawlor and Cornic (2002), decreased photosynthesis under low relative water content is caused by an impaired metabolism (storage of ATP, limiting RuBP synthesis without or with less inhibition of photosynthetic enzymes including RuBisCO). Similar results were reported in sunflower or bean plants, where inhibition of RuBP regeneration induced by water stress has been attributed to decrease in ATP supply resulting from a loss of ATP synthase (Tezara *et al*., 1999).

Conclusions

There exists a significant relationship between water amount applied via irrigation system and strategy (soil moisture available in the soil) and the leaf gas exchange rate. This is probably, in part, because under deficit irrigation, stomata close, and CO_2 exchange is reduced, while when the plant receives sufficient soil moisture stomata are generally open and CO_2 exchange occurs more frequently.

A, g_s and F_v/F_m of tomato decreased under water deficit, while T_l and E were increased by DI under both irrigation systems in all varieties. But A, g_s and F_v/F_m of the water deficit tolerant variety (Miya) were higher than those of non-water deficit tolerant variety (Chali and Malkashola). These variables were sensitive to the change of water status, and they can be obtained easily. Therefore, these variables could be used as physiological indexes when identifying water deficit tolerance of tomato.

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Chapter 8

Using deficit irrigation to save water and improve quality of tomato in the Central Rift Valley of Oromia, Ethiopia

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Abstract

Smallholder growers in arid and semi-arid areas of Ethiopia face problems of shortage of water for tomato (*Solanum lycopersicum* L.) production. Experiments were conducted in the Central Rift Valley, Ethiopia, at the International Development Enterprise technology testing site in 2010 (Experiment 1) and 2010/2011 (Experiment 2) growing seasons. Varieties of fresh market and processing tomato were irrigated with variable amounts of water, comparing drip and furrow irrigation systems and three irrigation strategies. We assessed seasonal irrigation water used and fruit yield and quality. Deficit drip irrigation (DDI) was the best strategy to optimize water use, yield and tomato quality. DDI / deficit furrow irrigation (FDI), local empirical furrow (FLE), and full drip irrigation (DETc) / full furrow irrigation (FETc) saved irrigation water by 54%, 15% and 9%, respectively, relative to local empirical drip irrigation (DLE). DDI increased fresh fruit yield per unit water used by 48%, 30%, 22%, and 36% compared with FLE, FETc, DLE and FDI, respectively, in Experiment 1, with similar results in Experiment 2. Gains in dry matter fruit yield produced per amount of water transpired with DDI compared with FLE, FETc, DLE and DETc were 77%, 77%, 76% and 34%, and with FDI 57%, 56%, 55% and 18%, respectively, in Experiment 1, consistent with results in Experiment 2. With DDI/FDI, the observed commercial yield was 51/52% (Experiment 1) and 56/54% (Experiment 2) compared with DETc and FETc, respectively. Fruit dry matter content, acid content and total soluble solids were significantly higher for DDI than for the other treatments. We did not observe irrigation treatment effects on pH of the fruits. Using the deficit irrigation strategy improved water use efficiency and fruit quality variables of tomato in both experiments with yield losses of about 45-50%.

Keywords: Commercial yield, deficit irrigation, quality variables, soluble solids, tomato, water use efficiency.

Introduction

Tomato *(Solanum lycopersicum* L.) is adapted to a wide range of climates (Reina *et al*., 2005) and an important vegetable crop worldwide, occupying the largest hectareage of any vegetable crop in the world (Ho, 1996). Tomato demands a large amount of water (Peet 2005). Many irrigators in different parts of the world use deficit irrigation (DI) as a result of soaring prices of irrigation pumping, low commodity prices, inadequate irrigation system capacities and limited irrigation water supplies (Craciun and Craciun, 1999). Deficit irrigation is the application of water below full crop-water requirements (evapotranspiration) and is an important tool for reducing irrigation water use (Fereres and Soriano, 2007). Geerts and Raes (2009) described deficit irrigation as an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop. Reddy and Reddy (1993) explained that DI is a method of scheduling irrigation in which adequate amounts of water are supplied during the moisture sensitive stages of flowering and fruit formation, yet allowing moderate stress at vegetative and maturity periods; they suggested that at deficit water supply, irrigation could be scheduled at 60% depletion of available soil moisture all through the crop growing period. In areas of water scarcity and long summer droughts, DI can mitigate drastic yield reductions (Kirda *et al*., 2004), while making a substantial contribution to water saving. However, the use of DI implies appropriate knowledge of crop evapotranspiration (ETcrop), crop responses to water deficits at critical crop growth periods, and the economic impacts of a strategy that will result in suboptimal yield. Hence growers are reluctant to apply DI (Pereira *et al*., 2002).

Semi-arid areas with less than 600 mm rainfall per year accounts for more than three-fourths of the total land mass and 57% of the population of Ethiopia (Awulachew *et al*., 2010). Rainfall in the Central Rift Valley has decreased by about 2.4 mm per year on average between 1980 and 2009 (NMSA, 2011). The trend towards warmer and drier weather over the last three decades in the Central Rift Valley has had serious negative effects on tomato growth, yield and quality (Dessalegn, 2002; Birhanu and Tilahun, 2010). On top of this, with global warming, climatic extremes are expected to become more frequent. As a result, there is a need to initiate drip irrigation for tomatoes to counteract the effects of reduced rainfall and to increase yields (Ayele Kebede, personal communication, 2008). An effort was made in the field-scale demonstration of drip irrigation systems by International Development Enterprise. However, e.g. according to Tan (1995), drip irrigation increases yield, but reduces fruit solids content in tomato fruits.

In Ethiopia, there is hardly any research on the influence of DI on yield and fruit quality. Because of lack of information and know-how of impact of irrigation management on crop yields and quality, smallholder growers apply water neither taking into account the crop's actual needs nor the optimum level that ensures water saving and improves quality, yet allowing only a moderate yield decrease.

Martin and Pegelow (1994) in their DI assessment on tomato, cauliflower, lettuce, carrot and onion suggested that experimental investigations needed to be carried out for determining the limiting values of maximum permissible soil water depletion under water scarcity conditions, which would give greater water use efficiency (WUE). WUE is crop yield per unit of water use. In biological terms, it is the amount of assimilates formed through photosynthesis per unit of water transpired.

Examining effects of DI on WUE and fruit quality variables could help in understanding crop water productivity and fruit quality response to irrigation, thereby allowing a better choice of irrigation strategy and efficient water use. Moreover, deficit irrigation is important in understanding the response of plants to low moisture status and evaluating the plant's capacity to acclimate to water deficit. Withholding water for a short term is the commonly used deficit irrigation method, but, to determine realistic responses to moisture stress, a cyclic water deficit is needed (cf. Garcia *et al*., 2007).

The effects of irrigation management practices on tomato quality in the Central Rift Valley have not been sufficiently studied. We hypothesized that in the semi-arid climate of the Central Rift Valley, using DI increases WUE and fruit quality variables of tomato, both under drip and furrow irrigation. The objective of this study was to quantify the effects of the DI strategy as a means of saving water and improving fruit quality under drip and furrow irrigation for both fresh market and processing tomatoes.

Materials and methods

Irrigation experiments

The field experiments were carried out in the Central Rift Valley, Oromia region, Ethiopia at 07 ^{o} 96' N and 038 ^{o} 72' E, 1649 m a.s.l., in the growing seasons of 2010 and 2010/2011, using three tomato (*Solanum lycopersicum* L.) varieties: fresh market type Miya and processing types Chali and Malkashola; planting material was obtained from Malkassa

Agricultural Research Center. The experiments were on a sandy clay loam soil (sand: 50%; silt: 30%; clay: 20%). The volumetric water content was 36% at field capacity (0.33 bar) and 16% at permanent wilting point (15 bar) (ZSTLC, 2011; Table 8.1).

Drip and furrow irrigation were applied in these experiments as follows. Drip irrigation was applied as practised by the International Development Enterprise in vegetable production farms in the open field. Ground water was abstracted using a diesel driven motor pump to fill water tanks (barrels and lined boreholes) near the experimental farm. From these tanks water was manually supplied to a 20 L capacity drip kit hanged at 1.5 m above surface level. For furrow plots, water was directly applied to the furrow between adjacent tomato plants throughout the growing season. For furrow plots a 15 L capacity watering can was used for water application to plants.

Drip and furrow irrigation based on crop water requirement (ETcrop) were applied using the gravimetric soil moisture sample method for full crop water requirement. For local empirical drip irrigation, the International Development Enterprise experience was adopted, whereas for local empirical furrow irrigation the 4-5 days irrigation scheduling often practiced by smallholder growers in the Central Rift Valley in vegetable production was used.

Estimation of crop water requirement was based on the maximum allowable depletion (MAD) of total available soil water (TAW) criterion:

$$Vd = \frac{MAD(FC-WP)RzA}{100}$$

where Vd is the volume of irrigation water (m^3), R_z the effective rooting depth (m), FC is field capacity, WP is wilting point, and A the surface area of the plot (m^2). The surface area of each plot was 14.7 m^2. The values of MAD, FC and WP are in fractions.

A split-plot design with three replications was used assigning the varieties to the main plots and irrigation treatments to the sub-plots, respectively, using a lottery method.

Seedlings were transplanted on 04 September 2010 for Experiment 1 (2010) and on 04 December 2010 for Experiment 2 (2010/2011). The seedlings were planted at a distance of 0.30 m within the row with a row spacing of 0.70 m, resulting in a plant density of 4.74 per m^2.

Fertilizer di-ammonium phosphate was applied after establishment of the transplants at

Table 8.1. Physico-chemical properties of the soil profile of the experimental plots.

a. Physical properties								
Depth (cm)	Particle size distribution (%)			FC (bar)	PWP (bar)	Texture		Bulk density (g/cm^3)
	Sand	Silt	Clay	0.33	15	Sandy clay loam		
0-15	50	30	20	-	-	-	-	1.52
16-30	-	-	-	-	-	-	-	1.41
31-45	-	-	-	-	-	-	-	1.63
46-60	-	-	-	-	-	-	-	1.13
b. Chemical properties								
pH	Electrical conductivity (dS/m)	Total N (%)	Total organic C (%)	Available P (ppm)	Soluble ions (meq per 100 g soil)			
					K^+	Ca^{++}	Mg^{++}	Na^+
7.38	0.32	0.19	2.26	26.25	4.26	25.72	16.60	4.30

FC = Field capacity; PWP = Permanent wilting point; **Source**: (ZSTLC, 2011).

a rate of 92 kg P_2O_5 per ha and urea was applied at a rate of 82 kg N per ha. Fertilizer applications were in splits during crop growing period by the ring application method. Weeds were controlled by tillage and hand weeding. Insect pests were controlled using Thionix, Carbaryl, whereas diseases were controlled with Ridomil. Harvesting of the tomatoes was done from 05 November to 07 December 2010 (Experiment 1) and from 03 February to 04 March 2011 (Experiment 2).

Agronomical water use efficiency (AWUE, Mg/m^3) was calculated using the relationship (Van Cleemput, 2000):

$$\text{AWUE} = \text{Fresh fruit yield}\left(\frac{\text{Mg}}{\text{ha}}\right) \div \text{water consumed by the crop}\left(\frac{\text{m}^3}{\text{ha}}\right)$$

where AWUE = the ratio of fresh fruit yield to irrigation water consumed by the crop.

Biological water use efficiency (BWUE, kg/m^3) was calculated using the relationship

$$BWUE = \text{Dry fruit yield}\left(\frac{\text{kg}}{ha}\right) \div \text{cycle irrigation volume}\left(\frac{\text{m}^3}{\text{ha}}\right)$$

where BWUE= Biological water use efficiency (kg/m^3) was calculated as the ratio between dry fruit yield kg/ ha to seasonal or cycle irrigation volume (m^3/ha).

Growing conditions

Experiment 1: Average seasonal maximum daily temperature was 26.7 ^{o}C with a corresponding average minimum daily temperature of 13.4 ^{o}C. Average seasonal total sunshine was 8.6 hours per day. Seeds of varieties Chali, Miya and Malkashola were sown on the 3rd of August 2010 in a seedbed under grass shade conditions (to protect seedlings from hot and cold weather). After hardening, seedlings were transplanted on the 4th of September, 2010, on sandy clay loam soils (NMSA, 2011; ZSLTC, 2011). These were grown under open-field conditions subjected to two irrigation systems (furrow and drip) along with three strategies (local empirical practice, according to crop water requirement, and deficit irrigation). Differential water application was started at two weeks after transplanting.

Experiment 2: Average seasonal maximum daily temperature was 27.8 ^{o}C with a corresponding average minimum daily temperature of 13.1 ^{o}C. Average seasonal total sunshine was 9.5 hours per day. Seeds were sown on 04 November, 2010, under similar nursery conditions as in Experiment 1, and the seedlings transplanted on 04 December, 2010, in similar soils. Tomato plants were cultivated under open-field situations with two irrigation systems (furrow and drip) along with three strategies (local empirical practice, based on estimated crop water requirement, and deficit irrigation).

Differential water application and standard crop management practices were as in Experiment 1.

Laboratory analyses

Fruit dry matter content determination was done using 5 g of homogenized tomato sample which was dried in a conventional oven at 105 ^{o}C to constant weight. The pH was measured using a pH meter (Model-UK, England). Fruit soluble solids and organic acid were determined using five fruit samples following AOAC (1995a); soluble solids (°Brix) was estimated at 20 ^{o}C by a refractometer (model-Bellingham + Stanley 45-02, UK, England) illuminated with sodium light and fruit acid content by titrating tomato juice with 0.1 N standardized NaOH to a pH 8.1 (NaOH meq per100 ml juice) expressing the results in grams of anhydrous citric acid per 100 g (AOAC, 1995b). Citric acid is the commonly found organic acid in tomato fruit (Davies and Hobson, 1981).

Statistical analysis

In order to study the effects of deficit irrigation on fruit quality and water use efficiency of tomatoes, all data were subjected to Analysis of Variance (ANOVA) to determine the significance of the difference between treatments using the SAS statistical software version 9.2 (SAS Institute Inc., 2008). When treatment combinations were found to be significant mean separations for two-way and three-way interactions were computed by using the Method of Least Squares Means (lsmeans). Pearson's correlation test was used to analyze the relationships between growth and development variables.

Results and discussion

Water savings and tomato yields under deficit irrigation in the Central Rift Valley

If deficit drip irrigation (DDI) or deficit furrow irrigation (FDI) was successfully practiced, about 1201 m^3 water/ha could be saved per season, amounting to $US 3341/ha per season compared to the local empirical drip irrigation (DLE) used by International Development Enterprise (Table 8.2). DDI or FDI saved irrigation water by about 54%, whereas local empirical furrow irrigation (FLE) could only save irrigation water by 15% (equivalent to 339 m^3 water/ha per season) compared to DLE. Given the relatively limited yield loss associated with such a large water saving (Table 8.2), these water savings might imply that increasing the areas irrigated with the water saved would compensate for the yield loss, provided land is not scarce. Furthermore, using drip irrigation according to crop water requirement (DETc) or furrow irrigation according to crop water requirement (FETc) would save about 9% (189 m^3 water/ha per season) irrigation water compared with DLE.

Deficit irrigation is widely used as a means to reduce agricultural water use without reducing yield too much, while improving fruit quality (Fereres and Soriano, 2007). Prieto *et*

Table 8.2. Irrigation per season, water saving relative to local empirical drip irrigation, length of growing period (LGP), and commercial yield (CY) of field-grown tomato under different irrigation management practices in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Irrigation system	Irrigation strategy	Irrigation per season (m^3/ha)	Water saving per season (m^3/ha)	Money saved per season ($US/ha)	LGP (days)	CY (Mg/ha)
2010						
Furrow	Local empirical	1875	339	943	125	57.4d
	ETcrop	2026	189	524	125	70.6c
	Deficit	1013	1201	3341	125	33.9f
Drip	Local empirical	2214*	-	-	125	82.2b
	ETcrop	2026	189	524	125	94.1a
	Deficit	1013	1201	3341	125	46.0e
2010/2011						
Furrow	Local empirical	1875	339	943	125	45.5D
	ETcrop	2026	189	524	125	58.3C
	Deficit	1013	1201	3341	125	26.8F
Drip	Local empirical	2214*	-	-	125	71.7B
	ETcrop	2026	189	524	125	82.3A
	Deficit	1013	1201	3341	125	36.3E

* = indicates irrigation water amount used by International Development Enterprise on 200 m^2 growers field converted to (m^3/ha) and used as a reference point. Water cost estimated at 1 ETB for 20 L and 17.98 ETB (Ethiopian Birr) equals to $US1 during experimentation. Means within columns in each variable and year followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) or $p \leq 0.01$ (upper case letter).

al. (1999) also reported that introducing a moderate water deficit with drip system involving estimation of the tomato water requirements allowed significant water saving of 17% and 49% during vegetative growing and flower initiation, respectively, whereas it concurrently improved the °Brix value.

Maintaining a plant water deficit can improve the partitioning of carbohydrate to fruit and control excessive vegetative growth (Chalmers *et al*., 1981). As Guichard *et al*. (2001) stated, great care has to be taken in deficit irrigation, as dry soil constrains growth and development and exacerbates physiological disorders in tomatoes.

Commercial yield

DDI decreased commercial yield (CY) relative to FLE, FETc and DLE in both experiments (Table 8.2). However, DDI increased CY relative to FDI in both experiments (Table 8.2).

In DDI and FDI, the observed CY was less by 51% and 52% in Experiment 1 and by 56% and 54% in Experiment 2 compared with DETc and FETc, respectively (Table 8.2). Other studies (Colla *et al*., 1999) reported that deficit irrigation (DI) of 50% ETc in two growing seasons led to a decrease in numbers of flowers and fruits and ultimately in a lower CY. Pulupol *et al*. (1996) observed a significant reduction in dry mass yield under DI for a glasshouse variety, whereas Mitchell *et al*. (1991a) reported no reduction in CY for a field-grown processing tomato. Contrary to this finding Quadir *et al*. (2005) reported that irrigation according to crop water requirement influenced the fruit soluble solids and also resulted in having excess moisture in the root zone, causing root inactivity contributing to lower CY and delayed maturity.

A research report by Zegbe *et al*. (2006) showed that water savings and gains in quality might compensate for the eventual losses in fresh and dry weight of fruits in regions where water is an expensive input. Contrary to this, Zegbe-Dominguez *et al*. (2003) in their glasshouse experiment with a processing tomato, revealed that there was no decrease in dry mass yield under DI relative to full irrigation, and a 50% water saving and 200% increase in irrigation WUE, with improved fruit quality attributes under DI.

Yield reduction due to diseases, improper fertilization and suboptimal management practices are much greater (Gemechis *et al*., 2014) under full irrigation compared to those expected under DI. Although reduction in irrigation water led to a decrease in CY, the gain by shifting the water saved via DI to grow other crops for which water is insufficient to fill demands under normal irrigation practices, often outweighs yield losses of the original crop.

On the other hand, the local empirical furrow irrigation resulted also in lower CY as compared to DETc and FETc (Tables 8.2 to 8.4), which is in line with previous findings for tomato CY (Yohannes and Tadesse, 1998; Birhanu and Tilahun, 2010). Franco *et al*. (1999) showed that at higher irrigation levels there was a high yield potential and less blossom end rot affected fruit.

Fruit dry yield

The reduction in fruit dry yield (FDY) with FDI was more than with DDI in both experiments (Table 8.3). Reductions in FDY with DDI relative to FLE, FETc, DLE and DETc were only 5%, 12%, 20% and 33%, respectively, in Experiment 1, and 8%, 16%, 28% and 40%, respectively, in Experiment 2.

Similarly, Tables 8.4 and 8.5 indicate that reduction in FDY with DDI compared with full-irrigation was lower for the fresh market variety 'Miya' than for the processing varieties Chali and Malkashola. The declines in FDY for Miya irrigated with DDI compared with FLE, FETc, DLE and DETc were 2%, 7%, 14.7% and 28%, respectively. But the decreases in FDY for Chali with DDI compared with FLE, FETc, DLE and DETc were 4%, 13%, 22% and 41%, whereas for Malkashola they were 0%, 15.3%, 23% and 29% respectively, in Experiment 1 (Table 8.4).

In Experiment 2, also the reduction in FDY with DDI relative to FLE, FETc and DLE for Miya was similar to the patterns observed in Experiment 1, albeit with a slightly greater reduction. The decrease in FDY with FDI compared to full-irrigation was greater than with DDI in all varieties across seasons. The reduced GLAI and vegetative growth observed in Miya (Gemechis and Struik, 2012) might imply that photosynthesis assimilates were predominantly distributed to sink organs so that significant fruit weight and fruit dry yield reduction were tolerated under DDI (Tables 8.4 and 8.5). This is consistent with findings by Gautier *et al*. (2001).

Table 8.3. Comparison among irrigation strategies under two irrigation systems on fruit weight, fruit dry matter yield, water use efficiency (WUE) and some fruit quality of field grown tomatoes in 2010 (Experiment 1) and 2010/2011 (Experiment 2).

Irrigation system and strategy	Yield, WUE and some fruit quality variables								
	2010								
	Cycle irrigation volume (m^3/ha)	FDMC (%)	FDY (kg/ha)	AWUE (kg/m^3)	BWUE (kg/m^3)	AFW (g)	pH	TA (%)	TSS (°Brix)
FLE	1875	12.1C	2615D	30.6d	1.39d	45.0c	4.05bc	0.73C	5.1CD
FETc	2026	10.9D	2812C	34.9c	1.39d	49.8b	4.04bc	0.74C	4.9DE
FDI	1013	13.5B	2212F	33.5c	2.18b	35.3d	4.07ab	0.86B	5.7B
DLE	2214	9.7E	3102B	37.1b	1.40d	48.7b	4.08ab	0.67D	5.3C
DETc	2026	9.0F	3717A	46.4a	1.84c	53.7a	4.04bc	0.66D	4.6F
DDI	1013	15.2A	2487E	45.4a	2.46a	46.3c	4.10a	1.02A	6.6A
2010/2011									
FLE	1875	11.6c	2133D	24.3f	1.14ef	47.7b	4.05c	0.52C	5.3c
FETc	2026	10.7d	2342C	28.8d	1.16e	50.8a	4.07abc	0.51C	5.1d
FDI	1013	13.0b	1758F	26.5e	1.74b	35.2d	4.09ab	0.54B	5.6b
DLE	2214	9.0f	2731B	32.4c	1.23d	48.2b	4.08abc	0.46D	4.6f
DETc	2026	9.7e	3251A	40.6a	1.60c	51.3a	4.10a	0.47D	4.9e
DDI	1013	14.8a	1957E	35.8b	1.93a	43.3c	4.07abc	0.61A	6.0a

FLE = Local furrow empirical; FETc = Furrow crop evapotranspiration; FDI = Deficit furrow; DLE = Local drip; DETc = Drip crop evapotranspiration; DDI = Deficit drip. AFW = Average fruit weight; AWUE = Agronomical water use efficiency; BWUE = Biological water use efficiency; CY = commercial yield; FDMC = Fruit dry matter content; FDY = Fruit dry yield; TA = Titratable acid; TSS = Total soluble solid.

Means within columns in each variable and year followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter) or $p \leq 0.01$ (upper case letter).

Table 8.4. Comparison among irrigation strategies under two irrigation systems on yield, water use efficiency (WUE) and some fruit quality variables of field grown tomatoes in 2010 (Experiment 1)

Treatments			**Yield, WUE and some fruit quality variables**								
Irrigation	Cycle irrigation volume (m^3/ha per season)	Variety	CY (Mg/ha)	AWUE (kg/m^3)	BWUE (kg/m^3)	FDM (%)	FDY (kg/ha)	AFW (g)	pH	TA (%)	TSS (°Brix)
FLE	1875	Chali	58.1g	31.0i	1.40i	12.4e	2617fg	44.3h	4.07bcd	0.78e	5.13fgh
		Miya	54.3h	28.9j	1.38ij	11.8ef	2582g	45.5gh	4.03def	0.63g	5.06ghi
		Ma/Shola	59.7g	31.8hi	1.41i	12.0e	2646efg	45.1gh	4.04cdef	0.79de	5.07ghi
FETc	2026	Chali	69.5f	34.3fg	1.35ij	11.3f	2733e	50.1c	4.00f	0.75ef	5.00hij
		Miya	66.9f	33.0gh	1.33j	10.4g	2699ef	49.9cd	4.05cde	0.72f	4.83j
		Ma/Shola	75.4d	37.2e	1.48h	11.2f	3004d	49.4de	4.06bcde	0.75ef	4.87ij
FDI	1013	Chali	28.7l	28.4j	2.08e	13.9c	2104k	34.1j	4.03def	0.84d	5.63d
		Miya	39.7j	39.2d	2.29c	13.2d	2318ij	36.5i	4.08bc	0.82d	5.56e
		Ma/Shola	33.3k	32.9gh	2.18d	13.4cd	2212j	35.4i	4.10b	0.91c	5.83d
DLE	2214	Chali	82.6c	37.3e	1.38ij	9.9gh	3053d	49.4de	4.08bc	0.65g	5.33f
		Miya	77.8d	35.1f	1.33j	9.4hij	2956d	48.8de	4.08bc	0.64g	5.20fgh
		Ma/Shola	86.1c	38.9de	1.49h	9.7hi	3297c	48.0ef	4.07bcd	0.72f	5.33f
DETc	2026	Chali	98.4a	48.6a	2.00f	8.8j	4052a	57.1a	4.08bc	0.63g	4.53k
		Miya	90.4b	44.6b	1.73g	9.1ij	3507b	52.5b	4.02ef	0.57h	4.50k
		Ma/Shola	93.5b	46.1b	1.77g	8.9j	3593b	51.5bc	4.02ef	0.77ef	4.67jk
DDI	1013	Chali	42.4j	41.8c	2.36b	14.9b	2388i	48.6de	4.17a	1.06b	6.50b
		Miya	49.5i	48.8a	2.49a	15.8a	2522h	46.5fg	4.04cdef	0.83d	6.27c
		Ma/Shola	46.0i	45.4b	2.52a	14.8b	2551g	43.9h	4.08bc	1.18a	6.93a

FLE = Local furrow empirical; FETc = Furrow crop evapotranspiration; FDI = Deficit furrow; DLE = Local drip; DETc = Drip crop evapotranspiration; DDI = Deficit drip. AFW = Average fruit weight; AWUE = Agronomical water use efficiency; BWUE = Biological water use efficiency; CY = commercial yield; FDMC = Fruit dry matter content; FDY = Fruit dry yield; TA = Titratable acid; TSS = Total soluble solid.

Means within each variable and variety followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter).

Water use efficiency of deficit-irrigated tomatoes

Tables 8.2 and 8.3 illustrate that if DDI was successfully applied a larger agronomic water use efficiency (AWUE) could be obtained. Differences could be as high as 48%, 30%, 22% and 36% compared with FLE, FETc, DLE and FDI, respectively. In Experiment 2, however, these percentage gains over FLE, FETc, DLE and FDI were smaller: 1%, 6%, 11% and 1%, respectively. See also the in-depth analysis of Gemechis and Struik (2014).

Response of varieties to deficit irrigation varied. Increases in AWUE for Chali, Miya and Malkashola with DDI were 22%, 48% and 22% (Experiment 1), and 13%, 50% and 14% (Experiment 2), respectively, compared to FETc (Tables 8.4 and 8.5). Similarly, an increase in AWUE for Chali, Miya and Malkashola with DDI relative to DLE was 12%, 39% and 17% in Experiment 1, but by 0%, 30% and 5% in Experiment 2. However, DDI increased AWUE only by 9% compared to DETc for Miya (Experiment 1), whereas it decreased AWUE by 0.5% in Experiment 2. The decreases for Chali and Malkashola were 14% and 1.5% (Experiment 1) and 25% and 9% (Experiment 2), respectively (Tables 8.4 and 8.5). This may imply that Miya is better than the two other varieties in terms of AWUE. In general, a greater AWUE was observed for both DDI and FDI than for the other irrigation treatments in all varieties during both seasons (Tables 8.4 and 8.5).

The gains in biological water use efficiency (BWUE) with DDI in relation to FLE, FETc, DLE and DETc were 77%, 77%, 76% and 34%, but for FDI 57%, 56%, 55% and 18%, respectively, in Experiment 1. Similarly, in Experiment 2, the increase in BWUE with DDI was 69%, 66%, 57% and 21%; however, under FDI it was 53%, 50%, 41% and 9% compared to FLE, FETc, DLE and DETc, respectively (Table 8.3).

DDI was 18%, 44% and 42% greater than DETc for Chali, Miya and Malkashola during the first season. Likewise in the second season BWUE was about 13%, 28% and 21% higher for these varieties in the same order. Tables 8.4 and 8.5 show that with DDI, the BWUE increase was 71%, 87% and 69% (Experiment 1), and 56%, 69% and 47% (Experiment 2) higher than DLE for Chali, Miya and Malkashola, respectively. Similarly, the decrease in BWUE with FETc was 75%, 87% and 70% (Experiment 1), and 69%, 70% and 60% (Experiment 2) lower than DDI for Chali, Miya and Malkashola, respectively.

Also, the decrease in BWUE when FLE was applied could be 69%, 80% and 79% (Experiment 1), and 66%, 75% and 67% (Experiment 2) compared with DDI. Furthermore, when FDI was used, BWUE gains for Chali, Miya and Malkashola were 54%, 72% and 47% (Experiment 1) and 45%, 60% and 44% (Experiment 2), respectively, relative to FETc. This greater BWUE of Miya confirms earlier records of Miya's better water productivity.

Fruit dry matter content, average fruit weight, pH, titratable acidity and total soluble solid of fresh market and processing tomatoes produced under deficit- and full-irrigation management strategies

A well-managed drip irrigation system can improve quality of tomato as well as saving water (Rudich *et al*., 1977). Frequent light irrigation improved the size, shape, juiciness and colour of the fruit, but reduced total solids (dry matter content) and acid content. In selecting the best irrigation strategy, consideration must therefore be given to the type of end product required. Prolonged water deficits lead to fruit cracking while frequent irrigation results in fruit rotting and should be avoided during the period of yield formation. Water deficit improves fruit quality, whereas it reduces photosynthesis and transpiration of the plant (Shinohara *et al*., 1995).

In this study, variation in response between varieties was observed with reference to fruit dry matter content (FDMC), average fruit weight, titratable acidity and TSS. Deficit irrigation management promotes the photosynthate translocation into fruit and improves the product quality.

Similar values were observed with DDI and FLE for average fruit weight in Experiment 1. Besides, DDI increased fruit weight by 31% and 23% compared with FDI in Experiments 1 and 2, respectively.

With DDI average fruit weight was lower by 15%, 11% and 15% for Chali, Miya and Malkashola, respectively relative to DETc in Experiment 1. In Experiment 2, the reduction in fruit weight was 16%, 14% and 17% for Chali, Miya and Malkashola, respectively relative to DETc. However, the increase in fruit weight relative to FDI was 43%, 27% and 24% for Chali, Miya and Malkashola, respectively in Experiment 1. In Experiment 2, this increase was 27%, 21% and 21% for these varieties, respectively. Generally, the reduced fruit weight with DDI in relation to FETc and DLE was minimum, and in the range of 2-16% (Chali), 5-13% (Miya) and 9-17% (Malkashola) in both experiments (Tables 8.4 and 8.5).

In line with these results, Lapushner *et al*. (1986) reported that water deficit reduced fruit weight but improved commercial yield, fruit colour, TSS and reducing sugar. Other research reports indicated that restricting water to 60% and 80% of the crop requirements checked vegetative vigour but reduced yield by 20% and 4%, respectively, due to reduction in fruit size (Adams, 1990). Ho and Hewit (1986) also argued that water availability affected the fruit size which in general less negatively affected by the deficit irrigation (Davies *et al*., 2000; Mingo *et al*., 2003; Topcu *et al*., 2007).

Fruit dry matter content

Fruit dry matter content (FDMC) significantly increased with DDI or FDI compared with the other irrigation treatments. Plants grown under DDI increased FDMC by 26%, 39%, 57%, 69% and 13% compared with those grown with FLE, FETc, DLE, DETc and FDI, respectively, in Experiment 1, whereas the increases in Experiment 2 were 28%, 38%, 14%, 64% and 53% compared with FLE, FETc, DLE, DETc and FDI, respectively (Table 8.3). Moreover, FDI increased FDMC by 12%, 24%, 39% and 50% (Experiment 1), and by 12%, 22%, 44% and 34% (Experiment 2) compared with FLE, FETc, DLE and DETc, respectively. Such increases of FDMC under DDI or FDI treatment matches the findings of Bhattarai and Midmore (2005), who reported that highest values of dry matter content, pH, TSS and titratable acidity were found in deficit irrigated tomatoes fruits.

There was no significant difference between varieties in FDMC with FLE during both experiments. Significant difference in FDMC was observed between Miya and the processing varieties under DI and ETcrop treatments during the first season (Table 8.4). During the second season, however, significant difference was registered between Malkashola and the two varieties in the FDI and DLE treatments (Table 8.5).

In this study (Tables 8.4 and 8.5), it was observed that with DDI the increase in FDMC was 68%, 74% and 65% for Chali, Miya and Malkashola, respectively, during Experiment 1, and 67%, 41% and 51% for Chali, Miya and Malkashola, respectively, compared with DETc during Experiment 2, respectively. Besides, FDI improved FDMC by 23%, 27% and 20% for Chali, Miya and Malkashola, respectively, in Experiment 1, but during Experiment 2, by 16% 26% and 22% for these varieties, respectively in relation to FETc.

Among the three varieties an increase in FDMC was observed for Miya with DDI compared with FLE, FETc, DLE and FDI (Table 8.4). Increases in FDMC with DDI

Table 8.5. Comparison among irrigation strategies under two irrigation systems on yield, water use efficiency (WUE) and some fruit quality variables of field grown tomatoes in 2010/2011 (Experiment 2)

Treatments			Yield, WUE and some fruit quality variables								
Irrigation	Cycle irrigation volume (m^3/ha per season)	Variety	CY (Mg/ha)	AWUE (kg/m^3)	BWUE (kg/m^3)	FDMC (%)	FDY (kg/ha)	AFW (g)	pH	TA (%)	TSS (°Brix)
FLE	1875	Chali	46.4h	24.7f	1.14i	11.6e	2133ij	48.5c	4.09ab	0.53de	5.33f
		Miya	41.3i	22.0g	1.12i	11.6e	2091j	47.0d	4.04cd	0.49f	5.27f
		Ma/Shola	48.7h	26.0f	1.16hi	11.8e	2175i	47.6cd	4.03d	0.53de	5.43ef
FETc	2026	Chali	58.4f	28.8e	1.12i	10.9f	2259h	51.0ab	4.05cd	0.53de	5.07g
		Miya	52.5g	25.9f	1.15i	10.2g	2323h	50.5b	4.09ab	0.48fg	5.00g
		Ma/Shola	64.1e	31.6d	1.21h	11.0f	2444g	50.8b	4.08bc	0.52e	5.10g
FDI	1012	Chali	22.4m	22.1g	1.62de	12.7d	1645n	34.5g	4.07c	0.54d	5.60d
		Miya	31.7k	31.3d	1.85b	12.8d	1869l	36.1f	4.10ab	0.53de	5.57de
		Ma/Shola	26.3l	26.0f	1.74c	13.5c	1761m	35.1fg	4.11ab	0.54d	5.73cd
DLE	2214	Chali	72.1d	32.8d	1.21h	8.7i	2686e	48.7c	4.09ab	0.46gh	4.57i
		Miya	66.2e	29.9e	1.16hi	8.8i	2574f	48.2cd	4.08bc	0.45h	4.46i
		Ma/Shola	76.3c	34.5c	1.32g	9.4h	2932d	47.8cd	4.07c	0.47g	4.83h
DETc	2026	Chali	87.7a	43.3a	1.67d	9.5h	3376a	52.2a	4.10ab	0.48fg	4.92gh
		Miya	79.0bc	39.0b	1.53f	9.9gh	3108c	50.8b	4.12a	0.45h	4.90gh
		Ma/Shola	80.4b	39.7b	1.61e	9.6h	3269b	51.1ab	4.09ab	0.49f	4.93gh
DDI	1013	Chali	33.0k	32.6d	1.89b	15.9a	1918lk	43.7e	4.04cd	0.60b	5.97b
		Miya	39.3ij	38.8b	1.96a	13.9c	1988k	43.8e	4.07c	0.58c	5.80c
		Ma/Shola	36.6j	36.1c	1.94a	14.5b	1965kl	42.5e	4.10ab	0.64a	6.28a

FLE = Local furrow empirical; FETc = Furrow crop evapotranspiration; FDI = Deficit furrow; DLE = Local drip; DETc = Drip crop evapotranspiration; DDI = Deficit drip. AFW = Average fruit weight; AWUE = Agronomical water use efficiency; BWUE = Biological water use efficiency; CY = commercial yield; FDMC = Fruit dry matter content; FDY = Fruit dry yield; TA = Titratable acid; TSS = Total soluble solid.

Means within each variable and variety followed by different letters are statistically different from each other at $p \leq 0.05$ (lower case letter).

compared with FLE, FETc, DLE and FDI, respectively, were for Chali 20%, 32%, 50%, 7%; for Miya 35%, 53%, 68%, 20%; and for Malkashola 23%, 32%, 52% 10%, in Experiment 1. But in Experiment 2, the increase in FDMC with DDI relative to these treatments was larger for Chali followed by Miya (Table 8.5). Significant differences between Chali and other varieties were also noted in DDI during the same season. Similar FDMC values with no significant difference among the three varieties were also observed in DETc (Table 8.5).

Average fruit weight

Fruit size is expressed as fresh fruit weight (g). It is a direct indicator of the produce quality according to the market grading standards, and it is also an indirect indicator of tomato taste quality, as 50% of the FDMC are soluble solids and fruit dry matter represents 4% to 8% of the fruit fresh weight (Heuvelink and Dorais, 2005).

According to Table 8.3, about 7% and 5% less fruit weight was obtained with DDI compared with FETc and DLE in Experiment 1, while 9%, 15% and 10% less fruit weight was observed with this treatment compared with FLE, FETc, and DLE, respectively, during Experiment 2.

pH

Except with DDI no significant differences were observed among treatments in Experiment 1. However, during the second season FDI and DETc showed significant and high values (statistically at par) and these were also statistically at par with FETc, DLE and DDI treatments (Table 8.3). Similarly, during the same experimentation significant differences among varieties were observed with DDI for processing tomato. This result is in line with the work of Miguel and Del Amor (2007).

Variety Chali showed higher values than Miya and Malkashola. However, no significant varietal differences were observed with FLE and FETc. Also in Experiment 2, for most irrigation practices no significant differences were found among varieties showing an unclear effect of DDI on pH in this work. Nuruddin (2001) also found that water stress level had no significant effect on pH of the fruit. Contrary to this, Tan (1995) reported a pH decline with no irrigation compared to the irrigation treatment.

Titratable acidity

Most acid in tomato fruit is contained in the locules and pH ranges between 4 and 5. A pH < 4.5 is required in processing tomato for microbial growth inhibition. A high acid content imparts a sour taste that is desirable for some consumers. High and significant difference was observed between DDI and the other treatments for titratable acid content (Table 8.3).

With DDI fruit titratable acid increased by 55% and 30% whereas with FDI it increased by 16% and 6% compared to DETc and FETc for Experiments 1 and 2, respectively. In line with this result, increased fruit acid content under water deficit condition was reported in another country (Miguel and del Amor, 2007). Moreover, an earlier study conducted in the Malkassa area of this valley showed that TSS and acid content of tomato varieties Malkashola and Malkassa Marglobe increased under DI (Birhanu and Tilahun, 2010). However, no significant difference between DLE and DETc, FLE and FETc were found in either experiment (Table 8.3). Giardini *et al.* (1988) found also that acidity decreased with higher irrigation rates, although other researchers found the opposite. Sanders *et al*. (1989) found no effect.

Except with FETc fruit acid content was varied in all irrigation treatments for all varieties (Table 8.4). For acidity, Malkashola revealed a significantly higher value than Chali and Miya with DDI in both experiments, and with FDI during Experiment 1, implying differential variety response to water deficit (Tables 8.4 and 8.5).

Table 8.4 also shows an increase in fruit acid content with DDI compared with FLE (36%, 32%, 49%), FETc (41%, 15%, 57%), DLE (65%, 30%, 64%) and FDI (26%, 1%, 30%) for Chali, Miya and Malkashola, respectively in Experiment 1. A similar trend with a slight decrease in this variable was noted in Experiment 2 (Table 8.5).

Total soluble solids (TSS)

As May (1993) observed, tomato fruit contains about 95% water and 4-5% organic compounds called solids. With the consumer's increasing preference for mature and sweet tomato fruit, high sugar content tomato production has increased (Parks and Newman, 2005). Although limiting irrigation affects physiological processes, growth and yield (Nahar and Gretzmacher, 2002), it increases sugar content (Imada *et al*., 1989). Water deficit decreases the movement of solutes into fruits reducing fruit size increase, which results in higher sugar concentration (Ehret and Ho, 1986).

Fruits from plants subjected to DDI had significantly greater TSS than the other treatments in both experiments (Tables 8.3 and 8.5). Table 8.3 shows that deficit furrow irrigated fields had lower Brix values than deficit drip irrigated fields (0.9 and 0.4 °Brix lower in Experiments 1 and 2, respectively). Contrary to these findings, previous research reports indicated that drip irrigated fields have lower Brix values than furrow irrigated fields (0.2-0.5 °Brix lower) (Hartz, 2001). Significant differences between irrigation treatments were also observed. The TSS of the Experiments 1 and 2 increased with DDI to about 43% and 22% compared with DETc, whereas that of TSS observed with FDI relative to FETc were 16% and 10%, respectively. Previous research results revealed that DI (50% ETc) in two growing seasons led to higher tomato soluble solids and acid contents (Colla *et al*., 1999).

The increase of °Brix was similar in the three varieties in treatments FLE, FETc, and DETc in both seasons (Tables 8.4 and 8.5), whereas Malkashola showed higher TSS than Chali and Miya with FDI and DDI (in both Experiments) and with DLE (in Experiment 1).

With DDI, fruit TSS concentration, measured as °Brix, was about 43%, 39% and 48% higher than TSS obtained with DETc for Chali, Miya and Malkashola, respectively in Experiment 1. Similarly, in Experiment 2, DDI recorded TSS of 21%, 18% and 27% higher than with DETc for these varieties in the same order. These results agree with May's (1993) opinion that low water deficit resulted in maximum yield and best viscosity with low soluble solids, whereas high water deficit caused lower yield, highest TSS and poorer viscosity. Sezen *et al*. (2010) reported also that increasing the irrigation amounts resulted in increased total yield in general, but decreased TSS.

Sanders *et al*. (1989) asserted an increase in TSS from 4.9% to 6.6% and an increase in TSS from 5.6% to 7.5% via a combination of DI and early water cutoff; however, red fruit yields were reduced from 94.2 Mg/ ha to 30.5 Mg/ ha. In another study, Birhanu and Tilahun (2010) reported an increase in TSS by 15% and 10% for fresh market type (Malkassa Marglobe) and processing (Malkashola) tomatoes, respectively, whereas frequent light irrigation improved the size, shape, juiciness and colour of the fruit, with reduced TSS, dry matter and acid content, under Malkassa field situations. Furthermore, Patane and Cosentino (2010) and Bhattarai *et al*. (2005) reported that applying DI (50% ETc) restoration, throughout the tomato growing period (from flowering onwards), contributed by enhancing fruit quality (TSS content, dry matter and ratio of TSS to total titratable acidity) with highest BER and minor losses in °Brix yield and variations of TSS.

Increases in TSS with DDI compared with FLE were more by 27%, 24% and 37% for Chali, Miya and Malkashola, respectively (Table 8.4). Similarly, the observed TSS with DDI were more when compared with FETc by 30%, 30% and 42%; DLE by 22%, 21% and 30%; and FDI by 16%, 13% and 19% for Chali, Miya and Malkashola, respectively in Experiment 1. In Experiment 2, however, increases in TSS with DDI compared with FLE were more by 12%, 10% and 16%; with FETc were more by 18%, 16% and 23%; with DLE were more by 31%, 30% and 30% and with FDI were more by 7%, 4% and 10%, for Chali, Miya and Malkashola, respectively (Table 8.5).

Conclusions

The effects of deficit drip irrigation (DDI) on fruit quality, water use efficiency (WUE) and commercial yield were found significant. DDI can allow growers to sustain fruit quality and yield, concurrently saving irrigation water in the sandy clay loam soils of the Central Rift Valley area. It seems that 50% of full crop water requirement under drip irrigation in the present study demonstrated a way to save water for agricultural purposes and to increase the WUE and improve fruit quality traits. DDI provides higher WUE enabling growers to use the water saved for other purposes, provided land and other resources are available. With DDI one could expect an increase in soluble solids, titratable acidity of fruits and an improvement in the FDMC of tomatoes. Because higher solid contents are desirable for tomato processing, a processor may select this irrigation strategy.

There was no clear influence of DDI on pH of the fruits in this study. Perhaps increasing the DDI level could permit one to address this question. Although it appeared that DDI increased the pH of the fruit juice which affects the shelf life of tomato products, a non-deficit strategy throughout the growing season is a good option for the growers that might provide a good yield, but would not necessarily be best for the processor. Growing tomato using DDI resulted in improved quality, greater WUE and higher yield than the FDI system. This study might serve as a starting reference for irrigation management under field conditions in the Central Rift Valley and similar ecologies and could provide insight to produce an economical and high-quality tomato product.

In the Central Rift Valley where water scarcity is a constraint, smallholder growers should adopt DDI to manage their irrigation schemes to sustain tomato production. In doing so DDI ensures optimum and sustainable tomato production and maximizes the income of the growers when irrigation water is limited.

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Chapter 9

General discussion

Introduction

The drip irrigation saves water while the others waste them and it is well suited for use with raised bed production cultures (Feng *et al*., 2005). Drip irrigation, provides merit in using saline water because this system maintains low salt accumulation in the wetting zone, by maintaining a low salinity level in the root zone (Hanson *et al*., 2006). Higher yield of tomato was observed from drip irrigation compared with furrow irrigation (Singandhupe *et al*., 2003; Yohannes and Tadesse, 1998). Drip irrigation has shown great promise for raising tomato productivity and water-use efficiency. Its combination of water savings and yield increases produced at least a doubling of water productivity, yield per unit water, and makes it a leading technology in the global challenge of boosting crop production in the face of serious water constraints (Postel, 1999).

Tomato (*Solanum lycopersicum* L.) is one of the most widely grown vegetables in the world (Passam, 2008). Irrigation is required in most of tomato production regions to sustain food security and commercially viable tomato production. Improving irrigation management by smallholders in tomato growing ecoregions is important in these growing zones. The pace at which irrigation development has been progressed has only been gradual compared to the growing demand for food. Thus, the general objectives of this study, carried out in Batu (Ziway), Oromia, were:

- to contribute to the understanding of irrigated tomato by smallholders in Ethiopia as a case study;
- to survey and to characterize irrigated tomato in different growing ecoregions and seasons; and
- to analyse yield limiting and yield reducing factors by using combination of survey of farm households and field experiments.

The specific research objectives were:

1. Are current status and constraints of irrigated tomato by smallholder growers in growing ecoregions of Ethiopia properly characterized for future research and development intervention?
2. Is tomato productivity in growing ecoregions mostly limited by weather conditions or by inadequate management or by both?
3. Do empirical irrigation practices by smallholder growers result in suboptimal yield and quality in tomato growing zones of Ethiopia?

4. How do varying ways of water supply impact on tomato physiological processes and yielding ability in the Central Rift Valley of Ethiopia?
5. Do combinations of irrigation systems and strategies in producing processing or fresh market tomatoes affect yield and quality? Which of the alternative strategies (i.e. based on local empirical knowledge, according to crop water requirement, deficit irrigation) give the optimal combination of yield, quality and water use?

Keeping in mind the above research questions, this thesis aims to answer production problems of irrigated tomato by smallholder growers in various tomato growing ecoregions and different seasons; and by exploring the research questions whether tomato production limited by weather conditions or by inadequate management or by both. Although tomatoes are sources of food, nutrition and income for smallholder growers and contribute to the national economy as a regional export crop, factors affecting yield and quality, particularly in relation to water management are not well understood in the contrasting ecoregions under field conditions. Therefore, we carried out a survey of tomato production to identify and to describe constraints in ecoregions and to characterize crop management practices (Chapter 2).

Chapters 4, 5, 6, 7 and 8 of the thesis present the results of field experiments addressing research questions 2, 3, 4 and 5. The field experiments are used to analyse and to identify irrigation systems and strategies in producing processing or fresh market tomatoes for the optimal combination of yield, quality and water use. From these experiments promising outcomes for intervention were identified. In order to answer the above research questions, the theoretical and analytical discussions are presented. Smallholder tomato growers brief of theoretical and analytical work explained in Chapter 1, survey at farm household level presented and discussed in Chapter 2 are answering research question 1. This Chapter describes different growing seasons, identifies main features and major yield constraints for future research and development intervention. Finally, achievements of research objectives and questions, and analysis of the findings are explained in this Chapter 9.

Area, production and features of irrigated tomato by smallholders in different eco-regions

This study describes the tomato production system in Ethiopia during various growing seasons in contrasting ecoregions, analyzed by combined use of field survey and field experiments. This approach allows the identification of crop yield limiting factors or yield reducing factors. Based on the information obtained from the field survey and field experiments possible strategies can be developed.

Area and production at the national level

From 2001 to 2003 the area and production of tomato increased, but there was a sharp decrease in both area and production in 2004 (cf. Chapter 3). By the following year area increased, however, production was decreased because of shortage of fertilizer supply in most areas. In 2006 both area and production declined, but in the following season, tomato acreage increased while production appears to fall because of losses by leaf diseases. In 2008 there was an increase in area and production as a result of favourable climate. However, in the following year there was a decrease in both area and production, because growers were faced with shortage of inputs as a result of exorbitant input prices.

Average fruit yields varied during 2001 through 2010 (Fig. 3.2b, Chapter 3) due to agro-climatic conditions and culture (Table 3.3, Chapter 3) hindering consistent tomato production and productivity (cf. Chapter 3). Tomato cultivation is usually undertaken under full and supplemental irrigation and the crop is grown in various growing periods in different eco-regions with different levels of technology (Table 9.1).

Area, production and features of irrigated tomato by smallholder in growing eco regions

The large tomato production comes from the late season (November-March), due to the large area cropped during that season, whereas highest productivity is from the intermediate late (February-June) season followed by the late season in East Shawa zone (Table 9.1), because of suitable agro-climatic conditions compared with other seasons. During 2001-2010 the areas in the sample zones were fluctuating.

East Hararge zone

About 744,050 ha of land is suitable for tomato production in this zone, which is characterized by soil types of suitable soil depth, drainage, light wind erosion, but with high water erosion (Table 9.2). Currently, 896 ha is under tomato cultivation with a productivity range of 6.5-12.7 Mg ha^{-1}(cf. Chapter 3). There was a remarkable increase in area and production during the first five years because of suitable climate and market access. Area and production decreased in 2006 as a result of poor access to irrigation water and biocides to control diseases.

Table 9.1. Planting and harvesting time, technological level, area, production and yield of irrigated tomato by smallholders for different growing seasons in eco regions of Ethiopia

Growing season	Administrative zone or ecoregion	Planting time	Harvesting time	Technological level *	Area (ha)	Production (Mg)	Yield (Mg ha^{-1})
Early	East Wollega	December	April	Low	518	77045	13.6
Mid-early	East Hararge	February	June	Low	376	4775	12.7
	East Shawa			Low	325	4550	14.0
	North Walo			Low	91	1429	15.7
	East Wollega			Low	117	1111	9.5
Mid-late	East Hararge	August	December	Very low	251	1619	6.5
	East Shawa			Low-medium	67	1608	24.0
Late	Jimma	November	March	Low	637	6071	9.5
	East Shawa			Low-medium	240	5400	22.5
	East Wollega			Low	389	4279	11.0

*[Medium = use of fertilizer, improved seeds, biocides but substandard culture; Low = use of fertilizer, biocides but recycle seeds and substandard culture; Very low = use of suboptimal quantities of inputs and substandard culture].

Table 9.2. Soil types, main features, total and suitable area (thousand ha) and actual area of tomato for different growing zones of Ethiopia

Administrative zone	Locations	Soil types	Main features					Area (ten thousand ha)		Actual area grown, ha (% of suitable)
			A layer (m)	O.M. (%)	Drainage	Water erosion	Wind erosion	Total	Potentially suitable	
East Hararge	Haramaya	cambisols	1-1.5	3-5	good	High	Light	251.6	74.4	896 (0.12)
	Kombolcha	nitosols vertisols	1-1.5	3-5	good	High	Light			
Jimma	Karsa	nitosols vertisols	>1.5	3-10	good	Medium to high	None	173.0	103.8	1275 (0.12)
	Dedo		>1.5	1-3	Moderate	High	None			
East Shawa	Adama	cambisols	1-1.5	5-7	good	None	None	137.7	46.0	1489 (0.30)
	Batu	fluvisols nitosols vertisols	1-1.5	5-7	good	None	None			
North Walo	Habru	cambisols	1-1.5	1-3	Moderate	High	None	127.4	31.3	379 (0.12)
	Raya Kobo	vertisols	>1.5	1-3	good	Medium	None			
East Wollega	Bako Tibe	nitosols	>1.5	3-10	good	Medium	None	208.7	160.4	1297 (0.10)
	Gobu Sayo	vertisols cambisols	ND	ND	good	Medium	None			

Source: FAO (1984; 1997); (Own survey, 2011), O.M. = Organic matter; ND = data not available. Numbers in bracket indicate % of suitable area under tomato production.

Jimma zone

An estimated suitable area of 1,030,100 ha was identified for tomato production (Table 9.2), whereas 1275 ha with a yield range of 6.5-9.5 Mg ha^{-1} is grown currently. This area is featured by having nitosols and vertisols soil types with soil depth greater than 1.5 m, well drained and, with intermediate water erosion. During the first three cropping years area and production increased but both decreased in the following years (Fig. 3.3i, Chapter 3) because of damage by late blight (Ocho, 2006; JZBoA, 2011). From 2005-2008 in area and production increased as a consequence of more access to inputs; then area and production decreased in 2009. In 2010 area and production increased again.

East Shawa zone

Currently, about 0.3% of suitable land is under cultivation with tomato having a productivity range of 10.6-24.0 Mg ha^{-1}(cf. Chapter 3 and Table 9.2). Area and production increased over the first three years (Fig. 3.3e, Chapter 3), but later the area declined due to poor product price in the previous season and shortage of improved seeds (Dessalegn, 2006). In 2006 area and production also decreased as a result of poor access to credit and fertilizer supply, however, they increased again in the following year (own survey, 2011).

North Walo zone

Tomato production in this zone is characterized by high water erosion, moderate drainage, cambisols and vertisols soil types with a layer of suitable depth. Only 0.12% of suitable land is under tomato production with low productivity (cf. Chapter 3 and Table 9.2). Area and production increased (2001-2007), but from 2007 onwards the area declined because of shortage of irrigation water associated with extended drought for some growers, while production increased as a result of fertilizer adoption by resource-rich growers.

East Wollega zone

An estimated potential area of 1,604,300 ha for tomato production was identified in this zone. The actual acreage of tomato under production found is 1297 ha with low level of production technology (Tables 9.1 and 9.2). Area and production increased from 2001-2003 because of suitable climate and high demand for the product, but in the preceding year both declined as a result of late blight damage (cf. Chapter 3). There was a gradual increment in area and production due to poor access to credit and irrigation water and inputs (2005-2008), but a decrease in area and production occurred in 2009 as a consequence of soaring input prices and low product price with a slight increase in area and production in the following year.

General highlights of smallholders' irrigated tomato production constraints in ecoregions

Development of technologies have allowed a progress in agricultural output per unit of land, improving per capita food availability. However, a decrease in per capita agricultural land area, rural poverty and food insecurity to remain in the country (Tesfaye *et al*., 2008). Despite semi-modern smallholder irrigation development started several decades ago in response to droughts and food insecurity, smallholder growers are facing food insecurity related to challenges in irrigation management and climate changes. Challenges in irrigated crops or tomatoes production are related to institutional issues, research gaps and support services (credit and extension), land use rights and holding size, and irrigation policy and strategy. The survey work results demonstrate that the education level of the household head, seed type, use of irrigation, biocides and commercial fertilizers and drought variables were found as major constraints of irrigated tomato by smallholder in the different ecoregions.

Education level of the household head

Education is one of the major factors that influence input adoption decisions. Information is scanty about effect of education level of household heads on the tomato productivity and about its impact on production technology adoption decision under contrasting eco-regions conditions of Ethiopia (own survey, 2011). Education affects tomato productivity by increasing the ability of growers to produce more output from given resources and by enhancing their capacity to obtain and analyze information and to adjust quickly to conditions. Educated growers are expected to produce with higher efficiency and are more likely to adopt new technologies in a shorter period of time than uneducated ones because educated growers can gather, process, and interpret available information, differentiate between promising and unpromising investment areas, and make decisions easily (World Bank, 1990; Appleton and Mackinnon, 1993; Asfaw and Admassie, 2004).

For every 1% increment in the education level of a household head the amount of yield increased highly significantly by 0.57%, 0.40%, 0.32% and 0.07% in East Hararge, Jimma, North Walo and East Wollega zones, respectively keeping other factors constant

(Table 3.3, Chapter 3). This may imply that education is a main constraint in tomato productivity. However, no significant difference was observed for East Shawa zone as a result of uneducated growers' long growing experiences and access to information from the Research Centre. Similar role of education on adoption of inorganic fertilizer in central part of the country was also reported (Asfaw and Admassie, 2004).

Seed type

Seed is one of the yield determining factor of crop production in each ecoregion (Penning de Vries and Rabbinge, 1995). The quality of seeds has profound effects on the economic production of agricultural crops of all species. The events in seed imbibition, the process of germination resulting in radicle emergence from the seed, and post germination growth to emergence can affect crop yield, because each is uniquely influenced by seed quality (Finch-Savage, 1995). Seedling emergence is the result of a large number of preceding processes which occur against the often hostile background of the seedbed environment. Under such circumstances, the chance of successful seedling emergence greatly affected by seed quality (Perry, 1984).

For each 1% increase in improved seed there is a yield increment of 0.30% and 0.27% in East Shawa and Wollega, respectively keeping other variables constant. But insignificant difference was observed between improved and recycled seed users for the other zones. This is probably due to seeds poor tolerance to sub-optimal conditions, low seedling growth rates (Powell *et al*., 1984) because growers may apply sub-optimal management practices, and lowest percentage seed germination and seedling emergence obtained from seeds produced on primary branches (Dias *et al*., 2006).

Use of irrigation

Tomato producing moisture deficit areas with high average temperatures and low average rainfall levels is associated with use of irrigation to increase yield (Campos, 1998; Yohannes and Tadesse, 1998; Kamara *et al*., 2002; Malash *et al*., 2005). In general, the climatic conditions of growing ecoregions vary from place to place; and the topographic and altitudinal diversity of the country accounted for wide variation in climate (Setotaw, 2006). Water is a highly limiting factor in crop production. About 57% population of Ethiopia inhabit in the 76% area of the country, which is featured by moisture deficit where productivity has remained low (Awulachew *et al*., 2010).

Smallholder growers would double the crop output and income if they had access to water (Bala, 2003). In semi-arid and arid regions, access to irrigation water is critical to boosting and stabilizing crop production. With a secure water supply, growers can choose to invest in higher-yielding seeds, produce higher-value crops, and harvest an additional crop or double each year (Postel, 1999).

For every 1% of increment in the use of irrigation the yield increased by 0.18%, 0.36%, 0.16% and 0.15%, keeping other variables constant in East Hararge, Jimma, East Shawa and East Wollega, respectively. But no significant difference was recorded between irrigation users and non-users for North Walo zone (Table 3.3, Chapter 3) perhaps because of lack of knowledge on irrigation management practices for obtaining greater returns to irrigation via improved water management and use. Majority of growers in this zone use uncontrolled flooding irrigation which probably caused lower yield due to nitrate-nitrogen leaching.

Biocides use

Productivity of agricultural crops is at risk due to incidence of pests, particularly pathogens, insect pests and weeds. Yield losses because of such pests can be substantial and may be reduced by crop protection means (Oerke, 2005). Ineffectiveness of resistant varieties to delay inoculum build-up and susceptibility of most varieties to pests or diseases may give quantitatively or qualitatively inferior yields. Thus, pest management in tomato production largely depends on biocides use (Abebe *et al*., 2005; Ocho, 2006).

The total global potential losses due to pathogens (fungi and bacteria) varied from about 7-24% (Oerke, 2005). Late blight (*Phytophthora infestans*), bacterial wilt (*Ralstonia solanacearum*) and Fusarium wilt (*Fusarium oxysporum*) are known to cause serious yield losses in Ethiopia (Abebe *et al*., 2005; Ocho, 2006). Tomato yields ranged from 6.5 to 24.0 Mg ha^{-1} across ecoregions (own survey, 2011). Yield losses because of diseases may account for more than 25% of the total seasonal production, and losses under smallholder growers are usually greater (Mamuye, 2011, personal communication).

Smallholder tomato growers are affected by poor access to credit (Table 2.3, Chapter 2), high biocides price and low product price most of these factors are outside their control (Woldeab, 2003; Emana and Gebremedhin, 2007; Joosten *et al*., 2011). For every 1% of increment in the use of biocides the yield increased by 0.13%, 0.23%, 0.41%, and 0.13%, in

East Hararge, Jimma, North Walo and East Wollega, respectively keeping other variables constant (Table 3.3, Chapter 3). But no significant difference was recorded for East Shawa zone perhaps due to the occasional presence of diseases and pests and because of favourable agro-climatic conditions for tomato production (own survey, 2011).

Commercial fertilizers use

Fertilizer has significant influences on fruit yield and has linear relationship with tomato yield during years when sufficient soil water will be available (Ronald, 1990; Heeb *et al.*, 2006). The narrow rotation with nutrient demanding vegetables like onions, carrot and potato; inefficient use of commercial fertilizers due to an exorbitant price of fertilizers and lack of credit as a result of lack of land right for mortgage are main constraints (Ambaye, 2001; Emana and Gebremedhin, 2007; CSA, 2011; own survey, 2011).

For each 1% increase in commercial fertilizer the amount of yield increased by 0.16%, 0.33%, 0.16% and 0.30% for Jimma, East Shawa, North Walo and East Wollega, respectively. However, no significant difference was obtained for East Hararge (Table 3.3, Chapter 3) because it was influenced probably by a combination of fertilizer management practices (rate, frequency, time of application) and often due to adoption of manure by non-users.

Drought effects

A crop's yield depends on processes occurring at different times during plant growth and development. Processes such as leaf area growth, intensity of flowering and root growth or depth can be influenced rapidly affecting the final fruit yield (Heuvelink and Dorais, 2005). For each 1% increase in drought there was a decrease of yield by 0.34% in East Hararge zone. This is consistent with report of FARC (2011). Effect of drought was also significant in East Wollega zone whereas its influence was insignificant for Jimma, East Shawa and North Walo.

Cold effects

Temperature affects metabolic rates (Dahal *et al.*, 1996). Air temperature is the most important factor in limiting tomato production. It directly affects fruit growth and biomass partitioning (Heuvelink and Dorais, 2005). Tomato is sensitive to cold temperatures (usually 10-15 °C down to 0 °C) showing growth inhibition and reduced photosynthesis and respiration. Temperature fluctuations may affect the pattern of crop yield because the rate of developmental events (fruit maturation) is limited largely by temperature (Adams, 2001). The influence of cold damage is significant only in East Hararge zone from July-November (Table 3.3, Chapter 3). For each 1% occurrence of cold there was a decrease of yield by 0.19% in this zone.

The four major input constraints *viz.,* biocides, commercial fertilizers, irrigation water and seed cost are decreasing return to scale for pooled data. The estimated coefficients for biocides, commercial fertilizers, irrigation water and seed cost were -0.02, 0.42, 0.06 and -0.25 with a corresponding t-value equal to -0.99, 15.82, 3.40 and -7.86, respectively. Except for biocides these t-values are highly significant at 1%. Nevertheless, factors constraining yield varied across ecoregions in each zone and there exists some inefficiency in the tomato production features. The negative elasticity of irrigation in East Hararge zone, and the insignificance of some constraints in other zones showed that the estimated production function may be unstable. As is presented (cf. Chapter 3), the estimated coefficients for irrigation in East Hararge, drought effect in Jimma, cold damage in Walo and Wollega are -0.18, -0.11, -0.10 and -0.06 with corresponding t-values of -2.67, 1.19, -1.36 and -1.70, respectively. The negative t values for constraints probably suggest that the matching relationship between these constraints and tomato production is vulnerable to other factors like agroclimatic conditions.

Growth and yield related traits, physiological processes and yielding ability of tomato as influenced by irrigation management practices

Growth and production of agricultural crops are greatly affected by water shortage (Wahb-Allah *et al.,* 2011). Management of irrigation strategy should consider factors such as plant types, plant varieties, types of salt, agro climatic and soil conditions, salt levels, water management practices and irrigation systems (Shannon and Grieve, 1999; Bustan *et al*., 2004). Water volume, its distribution throughout the crop growth period and the irrigation system have important effects both on yield and quality (Dumas *et al*., 1994; May, 1994; Prieto, 1996; Rodriguez *et al*., 1993). The volume of water available to the plant may influence negatively the dry matter content, with higher energy costs for the dehydration, and too much water availability for the plant can result in low soluble solid content and the percentage of reducing sugar in the fruit (Favati *et al*., 2009). On the other hand, under irrigation volumes may cause the development of small size fruits, lower yields, early senescence of the plants and greater susceptibility to various diseases (Hanson *et al*., 2006).

Water deficit reduces photosynthesis by limiting leaf area development, stomatal opening, and reducing the carbon fixation efficiency (Kramer, 1983). In doing so, a water shortage limits plant growth, yield and quality in most areas of arid and semi-arid regions. Drip irrigation is an effective way to supply water to the plant roots and save water, maintain high yield and quality (Boyhan and Kelley, 2001), whereas in furrow irrigation system, water is used inefficiently and large nutrient losses occur through seepage (Locascio *et al*. 1997). Reducing irrigation volume increased the incidence of blossom end rot (BER) in pepper plants, which may be attributed to calcium deficiency in fruit induced by water deficit conditions (Dorji *et al*., 2005).

Growth and yield related traits

Water deficit is a limiting factor for plant growth and development as well as for a range of physiological processes including photosynthesis. In order to explain the influences of irrigation system and strategy on growth and development, measurements on plant growth components and development were conducted (cf. Chapters 4 and 5). Plant-type trait (plant height), constitutive trait (root depth) and integrative traits (dry matter of plant part) were decreased when the amount of water was reduced. Plant height modifies the expression of secondary and integrative traits by influencing transpiration demand. Varieties with greater plant height are often larger in overall plant size, intercept more light and use water faster by transpiration, leading to lower plant water status (Kamoshita *et al*., 2004). The research results show that with deficit furrow irrigation (FDI), the reduction was 20% for plant height and 16% for root depth compared to plants grown in drip irrigation according to crop water requirement (DETc).

Root functions are anchorage, absorption of water and minerals, synthesis of nitrogen compounds and growth regulators (abscisic acid, cytokinins, and gibberellins), which have roles in shoot growth and functioning. Roots play a role as sensors of water stress which causes them to send biochemical signals to shoots that reduce leaf growth and stomatal conductance even before there is reduction in leaf turgor (Brouwer, 1982). Depth and spread of root systems are controlled by heredity and environment, varying among species and with water content, temperature, and aeration of the soil.

Maximum values for the constitutive trait root depth (RD) were registered with DETc (36.6 cm) followed by drip local, DL (35.1 cm) and furrow according to crop water requirement, FETc (33.8 cm) in Experiment 1. Correspondingly, in Experiment 2 similar trends were observed. Smaller RD was observed by DDI (31.6 and 29.0 cm) and FDI (30.6 and 26.4 cm) in both Experiments 1 and 2, respectively (Table 4.1, Chapter 4). This is probably because of roots failing to develop where soils are devoid of adequate levels of moisture. Tomatoes grown with deficit irrigation (DI) may exhibit a small root system configuration and decreased root system size equivalent to the magnitude of irrigation volume applied as presented in the tables in Chapter 4 in which DI strategy results in a decrease in the constitutive trait e.g., RD and integrative trait e.g., RDMA because the pattern of root distribution was similar to that of the moisture distribution (Levin *et al*., 1979; Kramer 1995). The roots grew deep downward (36.6 and 34.2 cm depth) with DETc in Experiments 1 and 2, respectively to a high soil moisture content resulting in a higher RD compared to the FDI and DDI treatments (Table 4.1, Chapter 4).

RD of tomato with deficit furrow irrigation (FDI) and deficit drip irrigation (DDI) reduced to about 84% and 86% (Experiment 1) and to 77% and 85% (Experiment 2), respectively of the DETc (Table 4.1, Chapter 4). Reduced RD might be related to smaller number of growing root tips and reduced synthesis of growth regulators e.g., abscisic acid (Atkinson, 1991). FDI reduced RD in both Experiments 1 and 2 with consequent decreases in LA (Table 4.2, Chapter 4), which in turn decreased photosynthesis (cf. Chapter 7). Kramer (1995) elucidated that a reduction in sink (root) size may also reduce photosynthesis by feedback inhibition. From this result we can propose that DETc for RD trait contributes to better growth (cf. Chapter 4) and higher commercial yield increase (cf. Chapter 6), important to the success of plants, as this treatment also promotes shoot growth.

Green leaf area index (GLAI) is related to processes of photosynthesis, evapotranspiration, plant water condition and respiration (Malone *et al*., 2002b). The increase in GLAI with DETc (Table 4.1, Chapter 4) was associated with enhances in leaf size (Table 4.2, Chapter 4) and leaves number (data not shown). But tomato plants grown under furrow system had fewer leaf and lower leaf area development. Similar to this result greater GLAI value for potato with drip irrigation than with furrow has been reported by Chawla and Narda (2000).

Significant differences were observed between treatments for GLAI during experiments; values were about 6.64 for DETc; 5.28 for DL, and only about 2.60 for the DDI treatment during Experiment 1. However, it was decreased to 5.53 for DETc; 4.39 for DL, and 2.55 for DDI in Experiment 2 (Table 4.1, Chapter 4) because of increased temperatures and incidence of Fusarium wilt (*Fusarium oxysporum*) (Chapter 5). As Venema *et al*. (1999) reported, growth of tomato in the suboptimal temperature range was also reduced. The relative performance due to irrigation system and variety had small effect while that of irrigation strategies and interaction contributed large effects (Table 9.3). The observed GLAI values in Experiment 1 were similar to values previously published in literature (Jones *et al*., 1989) for sub-irrigated field grown, and for drip irrigated greenhouse tomatoes (Marlowe *et al*., 1983). Abdel Gawad *et al*. (2005) reported also maximum GLAI under drip irrigation (5) compared with furrow irrigation (3).

Lower GLAI values with FDI and DDI crop might have been attributed to deficit irrigation used in the studies. Consistent with Scholberg *et al*. (2000) report, GLAI below 3.00 in tomato may be ascribed to poor crop growth because of water deficit. From Tables 4.1 and 4.2 (Chapter 4) it is possible to state that DoN and GLAI exhibit similar response under same irrigation treatment e.g., DETc resulted in greater values, whereas FDI in lowest values of DoN and GLAI. Scholberg *et al*. (2000) argued, this may indicate that increases in DoN relate to the formation of both primary and secondary axillary branches with an associated exponential increase in leaf development.

It is shown by this study (Chapter 5) that FDI significantly reduced integrative traits such as plant growth components (dry matter accumulation, DMA) by different plant parts and also decreased plant development i.e. DoNs, number of flowers, trusses and fruits in tomato plants. In this thesis (Chapter 5), significant differences were observed among irrigation treatments that had a marked influence on number of flowers and fruits per truss, percentage fruit set, number of trusses per plant and average fruit weight. Greater fruit weight was observed for DETc than for FDI indicating irrigation systems and strategies effects on fruit weight during both experiments (Table 9.3), and this result is consistent with Hanson *et al*. (2006).

The relative performance of irrigation systems vary from small to large effects for most integrative traits, whereas irrigation strategies and interaction had large to very large effects (Table 9.3). Tomato irrigated with FDI reduced integrative traits like number of flowers per truss, fruits per truss, percentage fruit set, number of trusses per plant and average fruit weight by 41%, 50%, 14%, 44% and 34% respectively, relative to DETc in Experiment 1 (Table 9.3). In Experiment 2, however, the reduction was more by 8% (flowers per truss), 6%

Table 9.3a Summary of relative performance of irrigation systems, strategies and varieties for the various traits of fresh market or processing tomato types (Experiment 1)

Traits category	Irrigation systems **(Furrow: drip) (1)**	Irrigation strategies **(Deficit: ETc) (2)**	Variety (Chali, Malkashola, Miya) **(3)**	Interaction **(1 x 2 x 3)**
Primary traits: *Constitutive traits*				
AWUE	++	++	+	++
BWUE	++	+++	0	++
SLA	+	++	+	++
GLAI	+	++	+	++
RD	+	++	+	++
Induced traits				
F_v/F_m	+	+++	+	++
A	++	+++	+	+++
PAR_{absorb}	+	++	+	++
Secondary traits: T_l	0	+	0	+
Integrative traits				
No. of trusses $(plant)^{-1}$	++	+++	+	+++
No. of flowers $(truss)^{-1}$	+	+++	+	+++
No. of fruits $(truss)^{-1}$	++	+++	+	+++
Fruit set (%)	+	+	+	++
Average no. of fruits $(plant)^{-1}$	+++	+++	++	+++
Average fruit weight (g)	+	+++	+	++
FDMI	+	++	+	++
RDM	+	+++	+	+++
SDM	+	+++	+	+++
LDM	+	+++	0	+++
Phenology: DTF	+	++	+	++
Plant type: plant height	+	++	+	++

0 = no effect (< 3%), + = small effect (>3%), ++ = large effect (>10%),+++ = very large effect (>25%), AWUE = agronomical water use efficiency, BWUE = biological water use efficiency, A = Stress induced change in rate of photosynthesis, PAR_{absorb} = Stress induced change in PAR_{absorb}, T_l = leaf temperature, SLA = Stress induced change in specific leaf area, GLAI = Stress induced change in green leaf area index, RD = Stress induced change in root depth, FDMI = Stress induced change in fruit dry matter indices, RDM = Stress induced change in root dry matter, SDM = Stress induced change in stem dry matter, LDM = Stress induced change in leaf dry matter.

Table 9.3b Summary of relative performance of irrigation systems, strategies and varieties for the various traits of fresh market or processing tomato types (Experiment 2)

Traits category	Irrigation systems	Irrigation strategies	Variety (Chali,	Interaction
Primary traits: *Constitutive traits*	(**Furrow: drip**) **(1)**	**(Deficit: ETc) (2)**	Malkashola, Miya) **(3)**	**(1 x 2 x 3)**
AWUE	+	++	+	++
BWUE	++	+++	0	++
SLA	+	++	+	++
GLAI	+	++	+	++
RD	+	++	+	++
Induced traits				
F_v/F_m	+	+++	+	+++
A	++	++	+	++
PAR_{absorb}	+	++	+	++
Secondary traits: T_l	0	+	0	+
Integrative traits				
No. of trusses $(plant)^{-1}$	++	+++	+	+++
No. of flowers $(truss)^{-1}$	+	+++	+	+++
No. of fruits $(truss)^{-1}$	++	+++	+	+++
Fruit set (%)	+	+	+	++
Average no. of fruits $(plant)^{-1}$	+++	+++	++	+++
Average fruit weight (g)	+	+++	+	++
FDMI	+	++	+	++
RDM	+	+++	+	+++
SDM	+	+++	+	+++
LDM	+	+++	+	+++
Phenology: DTF	+	++	+	++
Plant type: plant height	+	++	+	++

0 = no effect (< 3%), + = small effect (>3%), ++ = large effect (>10%),+++ = very large effect (>25%), AWUE = agronomical water use efficiency, BWUE = biological water use efficiency, *A* = Stress induced change in rate of photosynthesis, PAR_{absorb} = Stress induced change in PAR_{absorb}, T_l = leaf temperature, SLA = Stress induced change in specific leaf area, GLAI = Stress induced change in green leaf area index, RD = Stress induced change in root depth, FDMI = Stress induced change in fruit dry matter indices, RDM = Stress induced change in root dry matter, SDM = Stress induced change in stem dry matter, LDM = Stress induced change in leaf dry matter.

(trusses per plant), but with no change to the other three traits (Table 5.2, Chapter 5). As Shinohara *et al*. (1995) and Pervez *et al.* (2009) stated, deficit irrigation decreased leaf number, plant height, fruit yield, and average fruit weight (AFW), but did not change average number of fruits and percent of commercial fruit. Other published literature showed also that water deficit can influence the yield of tomatoes by its effect on either number of flowers per plant, percentage fruit set, or fruit size (cf. Wudir and Henderson, 1985; Rahman *et al*., 1999). Wudir and Henderson (1985) have reported also that average number of fruits set per truss decreased with increasing water deficit (75% to 25% ETc) both under greenhouse and field conditions.

Similar to these authors' reports, in this study (Chapter 5), a decrease in growth and yield related traits was observed with FDI or DDI in all varieties. Such a decrease in growth and yield related traits under DDI was less for Miya variety than for processing varieties (Chali and Malkashola) (Table 5.4, Chapter 5). Miya variety grown under DDI reduced integrative traits such as flowers per truss, fruits per truss, percentage fruit set, number of trusses per plant and average fruit weight by 27%, 28%, 1%, 32% and 11% respectively, relative to DETc in Experiment 1, but the decrease was more by 3% (flowers per truss), 4% (fruits per truss), 2% (percentage fruit set) and 2.4% (average fruit weight) (Table 9.3) probably because of water stress and variation in temperature during this season.

A reduction in average fruit weight of 6.4% (Chali), 5% (Miya), and 4.8% (Malkashola) occurred compared to 50% reduction in volume of water applied during Experiment 1. However, the reduction in average fruit weight in Experiment 2 was more 1.2% (Chali) and 2.2% (Malkashola) (Table 9.4). Favati *et al*. (2009) reported also a decrease in the fruit mean weight of 14% with respect to that found in tomatoes under well irrigated conditions.

The research findings (cf. Chapter 4) show that leaf area ratio (LAR), specific leaf area (SLA), net assimilation rate (NAR) and relative growth rate (RGR) were influenced by the irrigation system and strategy; greater values were observed for plants grown with DETc than in those grown with FDI (Table 4.1, Chapter 4). In broad leaved plant species including tomato SLA decreases and leaf thickness increases with high solar radiation and temperature in general, whereas leaf density relates negatively to precipitation (Niinemets, 2001). As decreases in a constitutive trait e.g., SLA result normally in higher induced trait e.g., photosynthesis per unit of LA, the correlation between leaf density and increased aridity

Table 9.4 Comparative performance of fresh market and processing tomato varieties under full- and deficit-drip irrigation practices during Experiments 1 and 2.

Irrigation system and strategy	Yield and some fruit quality variables									
	Variety	AFW (g)	AWUE (kg/m^3)	BWUE (kg/m^3)	CY (Mg/ha)	FDMC (%)	FDY (kg/ha)	pH	TA (%)	TSS (°Brix)
	Experiment 1									
DETc	Chali	57.1a	48.6a	2.00f	98.4a	8.8i	4052a	4.08bc	0.63h	4.53k
	Miya	52.5b	44.6b	1.73g	90.4b	9.1h	3507b	4.02def	0.57i	4.50k
	Malkashola	51.5bc	46.1b	1.77g	93.5b	8.9i	3593b	4.02def	0.77efg	4.67jk
DDI	Chali	48.6de	41.8c	2.36b	42.4i	14.9b	2388g	4.17a	1.06b	6.50b
	Miya	46.5fg	48.8a	2.49a	49.5h	15.8a	2522f	4.04cdef	0.83de	6.27c
	Malkashola	43.9h	45.4b	2.52a	46.0h	14.8b	2551f	4.08bc	1.18a	6.93a
RP (%)	Chali	-15	-14	+18	-57	+69	-41	+2	+68	+44
	Miya	-11	+9	+44	-45	+74	-28	+1	+46	+39
	Malkashola	-15	-2	+42	-51	+66	-29	+2	+53	+48
	Experiment 2									
DETc	Chali	52.2a	43.3a	1.67d	87.7a	9.5h	3376a	4.10ab	0.48fg	4.92gh
	Miya	50.8b	39.0b	1.53f	79.0bc	9.9gh	3108c	4.12a	0.45h	4.90gh
	Malkashola	51.1ab	39.7b	1.61e	80.4b	9.6h	3269b	4.09ab	0.49f	4.93gh
DDI	Chali	43.7e	32.6d	1.89b	33.0k	15.9a	1918lm	4.04de	0.60b	5.97b
	Miya	43.8e	38.8b	1.96a	39.3i	13.9c	1988k	4.07bcd	0.58c	5.80c
	Malkashola	42.5e	36.1c	1.94a	36.6ij	14.5b	1965kl	4.10ab	0.64a	6.28a
RP (%)	Chali	-16	-25	+13	-62	+67	+43	+2	+25	+21
	Miya	-14	-1	+28	-50	+40	+36	+1	+29	+18
	Malkashola	-17	-9	+21	-54	+51	+40	+ 0.2	+31	+27

- , + = indicate decrease and increase, respectively by drip deficit irrigation (DDI) relative to drip according to crop water requirement (DETc). RP = Relative performance. AFW = average fruit weight; AWUE= agronomical water use efficiency; and BWUE= biological water use efficiency; CY= commercial yield; FDMC= fruit dry matter content; FDY= fruit dry yield; TA = titretable acid; TSS= total soluble solid. Means within columns in each variable and year followed by different letters are statistically different from each other at $p \leq 0.05$.

(moisture stress) is that water use efficiency and photosynthetic nitrogen use efficiency increase with decreasing SLA.

We found similar patterns with the decreases in SLA due to water deficit conditions (Chapter 4), but increases in biological water use efficiency, BWUE (Chapter 6). Meziane and Shipley (2001) stated also that SLA as forcing variable directly affects both leaf N and net photosynthetic rate (*A*); leaf N then directly affects net *A*, which in turn affects g_s. They also asserted that *A* increases with decreased SLA and increased thickness, in contrast to our findings that increases in *A* increased SLA under same treatment (Chapters 4 and 7).

It was also observed in this study (Table 4.1, Chapter 4) that under FDI growth decrease was caused by a lowering of the LAR or NAR or both. The decrease in LAR with FDI was caused mainly by a reduction in SLA. The decrease in LAR and NAR with FDI relative to DETc was 32.6% and 32.8% respectively, in Experiment 1, whereas in Experiment 2, the decrease was 30% (LAR) and 68% (NAR) (Table 4.1, Chapter 4). For FDI grown plants a lower SLA (thicker leaves) resulted in less light absorption, PAR (cf. Chapter 7) and thus in growth reduction (same Table). Heuvelink (1989) in his work on temperature effect on tomato reported also that lower LAR values of tomato were due to lower SLA under low temperature. Flexas *et al*. (1999) argued further that the slow development of water stressed plants might enable the activation of different acclimation mechanisms such as osmotic adjustment, leading to the maintenance of photosynthetic capacity. Reduction of plant growth observed under FDI or DDI confirmed earlier works in four tomato varieties by Rahman *et al*. (1999).

Changes in RGR due to irrigation system and strategy are caused by changes in LAR and NAR in Experiment 1 because of proportional influence of irrigation. However, the larger decrease in NAR than LAR with FDI in Experiment 2, may be an indication of dominant NAR influence on growth rate in Experiment 2. This was further supported by the lower rate of photosynthesis observed in this Experiment (Chapter 7). Similar findings (Van der Ploeg and Heuvelink, 2005) were reported on decrease in RGR as a result of a decrease in NAR in tomato grown under low temperature. As Poorter and Van der Werf (1998) in their research review reported, under this field experiment, the influence of irrigation system and strategy on RGR was largely influenced through changes in NAR possibly due to high irradiances.

Dry matter accumulation, dry matter partitioning and yield

To determine use of combination of irrigation scheduling, irrigation systems and strategies for optimum dry matter accumulation and partitioning, commercial yield and water use efficiency, experiments were conducted in 2010 and 2010/2011. Irrigation scheduling is an important element in improving water use efficiency, with a focus on evapotranspiration (ET) estimation methods (Howell, 1996). Yield is affected by the scheduling, volume and frequency of irrigation applied (Roth, 1990).

The findings of this study (Table 4.2, Chapter 4) ultimately indicate that a decrease in dry matter accumulation (DMA) of roots, stems, leaves and fruits was related to decreased water volume (Table 6.2, Chapter 6). A decrease in integrative traits such as DMA of roots, stems, leaves and fruits was observed with FDI (1013 m^3 ha^{-1}) followed by DDI (1013 m^3 ha^{-1}), FLE (1875 m^3 ha^{-1}), and DL (2214 m^3 ha^{-1}) in descending order. The lowest values of DMA of plant parts were observed with FDI in both experiments (cf. Chapter 4). Our findings were also in line with Razavi *et al*. (2008), who reported that moisture stress significantly reduced both fresh and dry biomass, leaf area, and leaf number in strawberry. Similar findings were also reported for cucumber (Ayas and Demirtas, 2009).

According to this study (Tables 4.2, Chapter 4 and cf. Chapter 6), maximum RDMA was observed for shorter irrigation intervals with DETc followed by DL and FETc in both Experiments. Greater shoot DMA was also observed with DETc using three day (DS), two day (DS-MS), four day (MS-LS) and six day interval (LS), whereas increasing irrigation interval using DL with every day (DS-MS) and 3-4 day interval (MS-LS) reduced DMA (Table 6.2, Chapter 6).

According to Marcelis (1996), dry matter (DM) distribution is the distribution of DM between plant organs or distribution between different processes like synthesis and hydrolysis of sugars, exports, respiration, or all processes acting on DM in the plant, whereas DM partitioning is the end result of the processes acting on DM. Dry matter partitioning (DMP) of Chali and Malkashola (processing type) was similar, but slightly differed from that of Miya (fresh market type) (Table 4.3, Chapter 4).

The DMP of roots, stems and leaves with FDI were 6%, 12% and 28% respectively, compared with DMP under DETc (16%, 12% and 28%) for these plant parts in Experiment 1 (Table 4.2, Chapter 4). Similarly, DMP of roots, stems and leaves grown under FDI were 8%, 12% and 28% respectively, compared with DETc (17%, 14% and 27%) in Experiment 2. Influence of irrigation system (furrow) and strategy (50% ETc) on DMP of roots seemed high compared with its effects on shoots during both experiments.

As presented in this study (Table 6.2, Chapter 6), varieties Chali, Miya and Malkashola that were grown with FDI decreased commercial yield (CY) by about 59%, 41% and 44% respectively, relative to FETc, whereas FLE grown crop decreased by about 16%, 19% and 21% compared with FETc irrigated plants. Similarly, the decreases in CY with DDI were 57% (Chali), 45% (Miya) and 51% (Malkashola) compared to that with DETc. Moreover, the decreases in CY with DL were also 16% (Chali), 14% (Miya) and 8%% (Malkashola) compared to that with DETc. Miya variety was more water deficit tolerant than the two other varieties in both experiments.

In this thesis (Chapter 6), it was revealed that tomato grown with DETc recorded significant and more CY by 25% and 39% compared with FETc and FLE, (Experiment 1) and CY increase of more by 29% and 45% compared with FETc and FLE (Experiment 2), respectively. This result is in agreement with earlier findings of Prieto *et al*. (1999) that stated furrow irrigation had lower fruit yields when a high soil moisture level was maintained.

The yield increases with DETc were related to the increase in average fruit number per plant and average fruit weight with drip irrigation in both seasons Experiment (cf. Chapter 5). Ho (1996) elucidated that the potential yield of tomato is indeed determined by the fruit number and size; Badr *et al*. (2010) reported also that tomato total yield of 58.6 Mg ha^{-1} with drip irrigation and solid NPK fertilizers than furrow irrigation with same fertilizers (47.4 Mg ha^{-1}), amounting to 24% yield increase. It was also reported that the application efficiency of water with drip irrigation (0.9) is higher than that with furrow irrigation (0.7) (Abdel Gawad *et al*., 2005). The outcomes presented in this study and previous literature results show that drip irrigation is best for optimizing yield and WUE.

Irrigation management practices and tomato yield reducing factors

Yield reducing factors such as diseases late blight (*Phytophthora infestans),* bacterial wilt (*Ralstonia solanacearum*), powdery mildew (*Leveillula taurica*), Fusarium wilt (*Fusarium oxysporum*); and insect pests including African ball worm (*Helicoverpa armigera)*, white fly (*Bemisia tabaci*), red spider mite (*Tetranychus cinnabarinus*) have great impact in the growing zones (cf. Dessalegn, 2002). Most of these diseases occurred as a result of mismanagement of irrigation water. Yield losses because of diseases may account for more than 25% of the total seasonal production, and losses under smallholder growers may be greater (Mamuye, 2011, personal communication).

As presented in Table 5.8 in Chapter 5, greater damages by Phytophthora root rot on tomatoes was observed in FLE than FETc and drip irrigation treatments due to over-watering during DS-MS crop development phase. Occurrence of *Phytophthora* root rot in FLE plants increased 7.5, 8.1 and 7.6 times for Chali, Miya and Malkashola, respectively compared with DETc irrigated plants. Occurrence under DL was less by 1.6, 1.9 and 1.8 times for these varieties in the same order. This is probably because seedlings do not require as much water instantaneously or because seedlings appear more susceptible to severe disease under furrow irrigation.

Certainly, Aissat *et al*. (2008) argued that irrigation system can impact the development of pathogens responsible for soil borne diseases. It was demonstrated that in this thesis (Table 5.8, Chapter 5), higher incidence of Fusarium wilt, *Fusarium oxysporum* (FO) occurred under FDI plants followed by DDI, maybe as a result of water deficit. During Experiment 2, temperature was higher than in Experiment 1 (cf. Chapter 6 materials and methods), resulting in stress in the plants. FO was first observed in the FDI irrigated plants, at 67 days after plant (DAP) on leaves and petioles (Table 5.8, Chapter 5), whereas in the DDI plants, the first symptoms were observed five days later and were less frequent than in FDI plants.

Leaf water deficits caused by FO may have accounted for the decreases in gas exchange variables. From this study (cf. Chapter 5), it is evident that drip irrigation reduced disease incidence relative to furrow-irrigation. Provision of a light, frequent and uniform water application through drip system may be the case for such reduction of disease incidence under drip system than furrow irrigation system.

Corresponding to the high incidence of FO in FDI irrigated plants with consequent lowering of leaf photosynthetic rate in this study (cf. Chapter 7), Nogues *et al*. (2005) reported also that FO induced decreases in photosynthetic capacity of the tomato leaves, which were accompanied by reductions in both carboxylation efficiency and regeneration of RuBP. Reductions in RuBisCO content and activity induced by abiotic stresses have also been reported in other plant species (Allen *et al*., 1997; Harmens *et al*., 2000; Nogues and Baker, 2000).

Number of affected fruits by blossom end rot (BER) per plant was greater under FDI than in other treatments. Number of affected fruits by BER increased 9.2, 7.0 and 6.3 times more for Chali, Miya and Malkashola, respectively under FDI plants relative to that under DETc plants. However, it was less by 3.4, 2.0 and 3.3 times more, respectively for these same varieties in the same order under DDI plants (Table 5.8, Chapter 5).

According to Gebremariam (2005) *Orobanche ramosa* caused a yield loss ranging from 37-45% even in resistant varieties in this valley while soil moisture stress occurred. It was also observed (Table 5.8, Chapter 5) that there was a higher infestation of this weed species under furrow-irrigated system than in drip-irrigated plants (Chapter 5). Moreover, more of *Orobanche ramosa* was observed in FDI than in FLE and FETc. This is possibly due to both poor water distribution as well as water deficit on the soil surface in the furrow-irrigated plants (Table 5.8, Chapter 5).

Leaf gas exchange and chlorophyll fluorescence as influenced by irrigation management practices

The physiological condition of plants is indicative of plant productivity, adaptability to stress and a general indication of the environment in which they grow (Zarco-Tejada *et al*., 2002). Plant growth depends on photosynthesis, which is influenced by environmental factors including water shortage. Stress may be apparent in morphological and physiological features, which represent integrated responses to multiple environmental factors (Naumann *et al*., 2007).

What impact does varying ways of water supply have on tomato physiological processes (leaf gas exchange and chlorophyll fluorescence) in the Central Rift Valley? To determine whether varietal differences in photosynthetic rate leaf gas exchange (GE) and chlorophyll fluorescence variables exist, measurements were used for varying irrigation water treatments from 47 to 77 days after plant (DAP). Thus, the aim of this study was to identify performance under varying irrigation management practices through analysis of photosynthetic traits in tomato (*Solanum lycopersicum* L.) for improvements in open field production.

Many studies have defined that photosynthetic rate (*A*) is the rate at which CO_2

assimilation takes place in order to increase plant DM. Photosynthetic rate of an intact tomato leaf, which is enclosed in a chamber, was measured by detecting the reduction in CO_2 concentration as a function of time i.e. by measuring the quantity of CO_2 used per unit time. But various factors influence the *A* of a tomato plant of which water amount is one (Kramer, 1983). Plants of same tomato species function differently if cultivated under different water levels (Wudir and Henderson, 1985). In this study (cf. Chapter 7), it was observed that average *A* during the experiments was greater for tomato grown with DETc compared to the other treatments.

The results of this study (cf. Chapter 7) demonstrated that induced traits i.e. physiological variables such as *A*, stomatal conductance (g_s), chlorophyll fluorescence (F_v/F_m) and photosynthetically active radiation absorbed ($PAR_{absorbed}$) of tomatoes were significantly smaller for deficit furrow irrigation (FDI) or deficit drip irrigation (DDI) irrigated tomatoes compared to the other treatments in both experiments. Relative performance of irrigation strategies and interactions for *A* and F_v/F_m had very large effects, whereas also $PAR_{absorbed}$ exhibited large effects (Table 9.3). The findings of this research further show that Miya variety had greater tolerance to water deficit than Chali and Malkashola. Under such deficit irrigation stomatal closure is the most likely mechanism responsible for reductions in photosynthesis in all varieties (Chapter 7).

With regards to local empirical practices versus drip crop water requirement the increase in *A* for FLE was 74.8% (Experiment 1) and 72.2% (Experiment 2) of DETc, whereas the increase for DL was 90.6% (Experiment 1) and 90.5% (Experiment 2) of plants grown with DETc (Table 7.1, Chapter 7). In this study (cf. Chapter 7), the high and positive correlation (r = 0.95**) between g_s and *A* may show a decrease in the g_s leading to a decrease in *A*. Increases in leaf internal CO_2 (C_i) with inundating water brought about by a loss of function of PSII may close the stomata. This is due to increased C_i in the leaves of flooded plants (Yordanova and Popova, 2007) and of damage to light-harvesting mechanisms in inundated tomato (Janowiak *et al*., 2002) and soybean (Ahmed *et al*., 2006).

Correspondingly, other researchers (Bradford, 1983; Pezeshki, 1994; Yordanova and Popova, 2007) alluded also increased photorespiration and reduced ribulose bisphosphate (RuBP) activity as a result of decreased capacity to regenerate during sharp decreases in nitrate supply from roots. Ahsan *et al*. (2007) reported significant degradation of RuBP and RuBP activase in 35 days-old tomato plants after three days soil water logging due to oxidative damage to membranes by H_2O_2. In a study with leaves of field bean (*Vicia faba* L. minor), Pociecha *et al*. (2008) elucidated waterlogging also decreased chlorophylls a and b concentrations; and the photosynthesis activity may also be changed by biochemical reactions including reduced activity of RuBPCO.

In this study leaf g_s was affected by water level and lower g_s was associated with deficit irrigation (FDI or DDI), whereas higher g_s was associated with drip irrigation according to crop water requirement (Table 7.1 and Fig. 7.1, Chapter 7). Stomatal closure decreases photosynthesis with mild to moderate water stress and restricts CO_2 entry into leaves thus decreasing CO_2 assimilation and reducing water loss from the leaves (Cornic, 1994; Cornic and Massacci, 1996). Bartholomew *et al*. (1991) elucidated also deficit irrigation in tomato leads to a rapid decrease in the abundance of RuBisCO small unit transcripts, which may indicate decreased synthesis.

Decreases in g_s with DDI (0.12 mol m^{-2} s^{-1}) compared with DETc (0.20 mol m^{-2} s^{-1}) was corresponded by a decrease in A with DDI (8.0 µmol m^{-2} s^{-1}) and DETc (10.9 µmol m^{-2} s^{-1}) in Experiment 1. Similar pattern of dependency of A on g_s was also observed in Experiment 2. This may suggest stomatal limitations to A under deficit irrigation conditions. A increases also gradually to about 51% for FDI and 62% for DDI relative to DETc irrigated tomato (Fig. 7.1, Chapter 7).

Corresponding to these findings a similar pattern of dependence of A on g_s was reported on grapevines (Medrano *et al*., 2002). These authors in their review of literature on regulation of photosynthesis of C_3 plants to drought suggested that dependence of photosynthetic processes on g_s pattern is general for C_3 plants including tomato under water deficit conditions. Contrary to this, Farquhar *et al*. (2001) argued that regulation of g_s is related to variations among species and varieties, leaf relative water content, and abscisic acid (ABA) making it difficult to define a pattern of photosynthetic responses to water stress emphasizing a greater degree of co-regulation of g_s and A.

The results of this thesis (Fig. 7.1-7.2, Chapter 7) indicated that while g_s decreased by 73% and 72%, F_v/F_m was decreased by less than 44% and 42% and $PAR_{absorbed}$ (data not shown) was decreased by less than 51% and 48% under FDI relative to DETc in Experiments 1 and 2, respectively. With regards to DDI treatment, the decrease was 58% and 61% for g_s; 19% and 21% for F_v/F_m; and 17% and 21% for $PAR_{absorbed}$ relative to DETc in Experiments 1 and 2, respectively. Hence, stomatal closure both under FDI as well as DDI seems the major cause of decreased *A*. Correspondingly, this low performance of plants under FDI in relation to DDI evidenced that deficit furrow irrigation is discouraging as a means for economic tomato production despite saving water.

Decreases in g_s with water deficit could be attributed to decreases in soil moisture as a result of deficit irrigation; which led to lower g_s, with FDI (27% of Experiment 1 and 28% of Experiment 2 peak values) imposing a reduction in CO_2 supply to the mesophyll cells, and resulting in a decrease (73% for Experiment 1 and 72% Experiment 2 of the DETc) in the rate of leaf photosynthesis of tomato grown with FDI. This is similar to earlier reports on tomato (Carvaja *et al*., 1998) and *Arbutus unedo* L. in dry climates (Manter *et al*., 2000).

The relationship between *A* and g_s (r = 0.95**) (Table 7.2, Chapter 7) may support that stomatal control of CO_2 diffusion plays an important role in controlling photosynthesis. As Baker and Rosenqvist (2004) explained, such stomatal limitations imposed on photosynthesis will be accompanied by a decrease in the rate of consumption of ATP and NADPH for CO_2 assimilation, which could result in decreases in the rate of linear electron transport and, consequently, in PSII operating efficiency (the quantum yield of PSII photochemistry for a leaf in light). Moreover, Mielke *et al*. (2003) elucidated that the decrease of plant biomass production may be directly related to stomatal limitations on net photosynthesis which reduces carbon assimilation due to soil drying.

Leaf temperature (T_l) and leaf transpiration rate (E)

In these experiments, increased leaf temperatures do have a significant influence on carbon gain during experimentation (Fig. 7.1 and Tables 7.1, 7.3, 7.4, 7.5, Chapter 7). Rise in T_l up to 26.5 °C did decrease *A* to 8.2 µmol m^{-2} s^{-1} with FDI in Experiment 1, indicating high temperature inhibition of *A* (Table 7.1, Chapter 7). At this same T_l, inhibition of *A* was accompanied by reduced g_s (0.20 mol m^{-2} s^{-1}) (Table 7.1, Chapter 7). On the other hand, T_l values of ≤ 25.3 ^{o}C were maintained with DETc, DL and FETc because of regulated water supply resulting in lowering in T_l fluctuation under full irrigation requirement thereby raising the *A* of leaves (Fig. 7.1). Thus plants irrigated according to crop water requirements and with local drip had less water loss as compared to their counterparts, those grown under deficit irrigation. Similarly, T_l of tomato leaves that were irrigated with FDI and DDI was significantly higher than that of tomato irrigated by DETc, DL and FETc (Tables 7.3, 7.4, 7.5, Chapter 7).

An increase of T_l registered in deficit irrigation (DI) caused subsequent lowering of g_s that is induced by elevated CO_2 concentration in the mesophyll cell possibly resulting in lower *A* under DI compared with full irrigation requirements (Tables 7.1, 7.3, 7.4, Chapter 7). This indicates that DI does not result in a sustained increase of *A*. This is also supported by the work of (Farquhar and Sharkey, 1982) who explained that high temperatures reduce electron transport capacity and increase the rates of CO_2 evolution from photorespiration and other sources resulting in assimilation rate to decrease.

Transpiration is the evaporation of water from the surface of actively growing tomato leaf cells. The process of transpiration provides the tomato with evaporative cooling, nutrients, carbon dioxide entry and water to provide plant structure. Although stomatal movement is highly responsive to those factors influencing the rate of water loss from leaves (Farquhar and Sharkey, 1982), in this study (cf. Chapter 7) leaf transpiration rate and stomatal conductance were significant and negatively (r = -0.98) correlated with each other. Transpiration rate (E) was increased for tomatoes grown with deficit irrigation. Leaf transpiration rate (*E*) associated with T_l (Tables 7.1, 7.3, 7.4, Chapter 7) and this was supported by highly significant and positive correlation (r = 0.86*) with each other (Table 7.2, Chapter 7) in line with Konis (1950; cf. Bote, 2007) who reported that the leaf temperature has marked influence on rate of leaf transpiration. According to this report, the temperature increment of the leaves of a plant is capable of raising *E* by as much as over 30%. Also, consistent trend was found for *E* in drip and furrow irrigation in Experiment 1. Greater *E* was recorded in FDI followed by FLE but with a minimum value under FETc and in drip irrigation higher *E* was recorded under DDI followed by DL and lower value in DETc. A similar pattern was noted with both irrigation systems with higher *E* for deficit followed by local empirical practice and full irrigation requirements in descending order (Fig. 7.1) in Experiment 2.

Chlorophyll fluorescence (F_v/F_m)

Chlorophyll fluorescence provides insight about the ability of a plant for leaf photosynthetic performance to adapt under water deficit as well as into the extent to which those stresses have damaged the photosynthetic apparatus (Maxwell and Johnson, 2000; cf. Razavi *et al*., 2008). Many studies have indicated that conventional measurements of leaf internal CO_2 concentration (C_i) using gas exchange techniques during water deficit may over-estimate as a consequence of both patchy stomatal response and an under-estimation of cuticular transpiration, and thus, use of F_v/F_m helped to identify effects of water deficit on stomatal closure and consequent effect on carboxylation (Meyer and Genty, 1999).

F_v/F_m has been widely used to detect stress-induced perturbations in the photosynthetic apparatus, because decreases in F_v/F_m can be an outcome of the development of slowly relaxing quenching processes and photodamage to PSII reaction centres, both of which reduce the maximum quantum efficiency of PSII photochemistry.

It is well known that from F_o theoretical explanation, an increase of F_o can be expressed as a reduction of the rate constant of energy trapping by PSII centres (Havaux, 1993), which could be the result of a physical dissociation of light harvesting complex from PSII core observed in several plant species under environmental stresses (Armond *et al*., 1980). Such a decrease in F_o could reflect damage to regulatory processes external to P680 (reaction centre of PSII), such as impairment of the photo protective processes that facilitate the dissipation of excess energy with the leaf (Angelopoulous *et al*., 1996; Hong and Xu, 1999).

According to our research results (Table 7.1-7.4, Chapter 7), the decreases in F_v/F_m with FDI could be ascribed to decreases in water volume in the soil as a result of deficit irrigation, leading to lower F_v/F_m, which is with FDI (71% of Experiment 1 and 70% of Experiment 2 DETc values). The positive and highly significant relationship between A and F_v/F_m ($r^2 = 0.93$**) may support this result.

Matching with these findings, several researchers (Greaves and Wilson 1987; Araus and Hogan 1994; Hakam *et al*., 2000; Percival and Sheriffs 2002; Baker and Rosenqvist 2004; Valladares *et al*., 2005) revealed that chlorophyll fluorescence variables were strongly correlated with whole-plant mortality in response to environmental stresses and were reliable indicators of stresses. Furthermore, as Krause and Weiss (1991), Schreiber *et al*. (1994) and Baker and Rosenqvist (2004) reported, a decrease in F_v/F_m values could show the possibility of photoinhibition. Significant declines in F_v/F_m occur as water deficit increases (Liberato *et al*. (2006), Souza *et al*. (2004), whereas Marques da Silva and Arrabaca (2004), Miyashita *et al*. (2005) and Subrahmanyam *et al*. (2006) stated that no significant change in F_v/F_m occurred during moisture stress or only after severe water stress in coastal plant species.

In my study (cf. Chapter 7), the observed declines in F_v/F_m with FLE may be accounted for by irregular supply of water amount around root zone of plants due to inundating water during application and water shortage between successive irrigation intervals leading to reduced F_v/F_m, with FLE (88.6% of Experiment 1 and 86.5% of Experiment 2 DETc values).

As demonstrated by Yan *et al*. (1996) and Yordanova and Popova (2007) decreases in F_v/F_m in flooded tomato are associated with damage to PSII (Else *et al*., 2009), because with less CO_2 available for photosynthesis, the surplus reducing power is diverted to O_2 and the generation of damaging superoxide anions (O_2^-) and H_2O_2. Else *et al*. (2009) adding to this, asserted that the changes in photosynthetic fluorescence variables resulting from flooding are the consequence of stomatal closure rather than its cause and are induced by restricted availability of CO_2 for photosynthetic reduction.

Photosynthetically active radiation absorbed ($PAR_{absorbed}$)

Tomato yield is limited by the amount of intercepted light (Newton *et al*., 1999) and assimilate partitioning (Ho, 1996). Decreases in $PAR_{absorbed}$ with water deficit might be attributed to deficit irrigation which led to lower absorbed radiation, (427 µmol m^{-2} s^{-1}), with FDI resulting in a decrease of 22% for Experiment 1 and 24% for Experiment 2 of the DETc. On the other hand the decrease in $PAR_{absorbed}$ (466 µmol m^{-2} s^{-1}), due to irregular water supply with FLE was 15.3% for Experiment 1 and 19% for Experiment 2 relative to DETc (cf. Chapter 7).

Adopting irrigation systems and strategies for water saving and improving tomato yield and quality

Maximum benefit from irrigation will be obtained only by adding proper amounts of water at the right time to reduce moisture stress. Tomatoes irrigated with right volumes of water require also less energy to dehydrate water from the fruit while producing tomato paste or concentrated juice (Favati *et al*., 2009). Irrigation management and scheduling are based on management skills, however, they may be improved when factors such as plant evaporative demand, irrigation systems, soil characteristics and root distribution are considered as well (Fereres *et al*., 2003).

To answer the research question whether irrigation system and/or strategy affect (s) water saving, yield, and fruit quality of tomato two-season field experiments were conducted in Ziway area. Higher fruit yield was obtained by applying water according to crop water requirement throughout the growing season.

With the same volume of water and irrigation strategy, DETc recorded more yields by 41%, 35% and 24% than FETc for Chali, Miya and Malkashola, respectively in Experiment 1, whereas 9%, 16% and 1% more yields were obtained for these same varieties in the same pattern during Experiment 2 (Tables 6.2 and 6.3, Chapter 6).

This study (cf. Chapter 6) indicated that commercial yield (CY) under drip irrigation was significant and greater than the traditional furrow irrigation system for all water management strategies. The influence of irrigation systems on tomato yield also varied between years. In Experiment 1, greater CY (Mg ha^{-1}) was observed for DETc (94.1) followed by DL (less by 12) and FETc (less by 23), whereas during Experiment 2, for DETc (82.3) followed by DL (less by 10) and FETc (less by 24). This yield variation between years was possibly, because of the variation in temperatures between seasons (cf. Chapter 6 materials and methods), which contributed to decrease in yield and yield related traits via decreased flower per truss may be as a result of pollen abortion (data not shown).

Water use efficiency (WUE) at a crop scale is expressed as the ratio of production of total biomass, or shoot biomass, harvested yield to evapotranspiration or crop transpiration (ETcrop) (Loomis and Connor, 1992). According to Tables 6.2, 6.3 and 6.6 (Chapter 6), WUE and CY for different varieties varied with the irrigation strategy, water volume and irrigation scheduling. The adoption of frequent but low volume irrigation applications through drip irrigation is superior to furrow empirical practices, the more traditional scheduling by smallholders growers with large applications. This result is matching with Locascio (2005) reporting on drip irrigation according to crop water requirement in Florida. The use of moderate water deficit with drip system improved water saving and fruit soluble solids value (Prieto *et al*., 1999). In these experiments, irrigation according to local empirical drip (DL) did not correspond to the actual water requirements of tomato plants, and led to excess water application.

Despite shorter irrigation intervals used, AWUE showed more than 27% decrease with FDI in relation to DETc (Experiment 1) and 34% (Experiment 2) (Tables 6.4 and 6.5, Chapter 6) as a result of no uniform and shortage of water which may result in a decline in photosynthetic capacity and increased transpiration rates (Chapter 7), but BWUE was increased more than 18% (Experiment 1) and 8% (Experiment 2). Similarly, AWUE decreased by about 2% (Experiment 1) and 12% (Experiment 2), whereas BWUE increased more than 33% (Experiment 1) and 20% (Experiment 2) with DDI.

The results of this study (Tables 6.4 and 6.5, Chapter 6) demonstrated that increasing irrigation interval with FLE reduced plant water consumption, whereas decreasing irrigation intervals with FDI and DDI increased WUE. Using FLE, longer irrigation intervals with too much water inundated over entire field resulted in smaller WUE because of plant water stress (water logging during application and water shortage between successive irrigation intervals).

Implication of deficit irrigation strategy for water-limited areas and improvement of fruit quality

As Musick *et al*. (1994) elucidated, by deficit irrigation (DI) crops are purposefully under irrigated during growth stages that are relatively insensitive to water stress as regards to the quality and quantity of harvestable yield. Adding to this, Zegbe-Dominguez *et al*. (2003) stated that DI involves irrigating the root zone with less water than required for evapotranspiration, so it can improve the partitioning of carbohydrate to reproductive structures (e.g. fruit) and control excessive vegetative growth (Chalmers *et al*., 1981).

Previous studies on irrigation management practices under water scarcity situations, pertaining to tomato crops have also been reported elsewhere. The findings of those studies would be useful under similar production situations of tomato. DI effects have also been studied on several crops (Sepaskhah and Kamgar-Haghighi, 1997; Dorji *et al*., 2005), including tomato, though with contrasting results (Obreza et al., 1996; Pulupol *et al*., 1996; Kirda *et al*., 2004).

As the crop performance is sensitive to the irrigation practices, an extended severe water deficit limits growth and reduces yields, which cannot be corrected by heavy watering later on. Highest demand for water is during flowering. However, withholding irrigation during this period is sometimes recommended to force less mature plants into flowering in order to obtain uniform flowering and ripening.

Several studies have reported that limitation of irrigation during culture is generally adopted in order to increase the sugar content. But this treatment affects many physiological processes and the growth and yield apt to decrease along with extended stress (Aloni *et al*., 1991). Restricting water to 50% of the requirements with drip and furrow irrigation controlled vegetative vigor but reduced final yield by about 20% and 4%, respectively. These decreases were mainly because of a reduction in fruit weight and number. It is evidenced that at higher irrigation levels there was a high yield and less blossom-end rot (BER) affected fruit.

DI approach can improve water use efficiency, and is a potential strategy to increase water savings in tomato production by allowing crops to withstand mild water stress or by limiting water application to 50% ETcrop with no or only marginal decreases of yield and quality.

On the other hand, under limited water supply and drought, DI can lead to better economic gain by maximizing water use efficiency (WUE). Increasing the amount of water used by the plant or increasing the yield of the plant can change WUE. In this context, DI provides a means of reducing water consumption while minimizing adverse effects on yield. However, this approach requires precise knowledge of crop response to water as drought tolerance varies considerably by growth stage, species and varieties.

DI improved soluble solids and dry matter of tomatoes compared with full irrigation (Hanson *et al*., 2006; Zegbe-Dominguez *et al*., 2003). DI imposed by reducing irrigation volume by 50% of ETc, in two growing seasons: led to a decrease in the number of flowers and that of fruit number and ultimately to less marketable yield, however, soluble solids and acidity were improved (Colla *et al*., 1999). DI can also improve tomato quality and save water via well managed drip irrigation systems (Rudich *et al*., 1977). The ascorbic acid content of tomato was positively affected by less frequent irrigation (Mitchell *et al*., 1991a).

Other studies also reported that crop water status was strongly influenced by the water regime, and the dry matter accumulation was gradually reduced with the increase of water deficit (Perniola *et al*., 1994). Lapushner *et al*. (1986) observed also that fruit weight was reduced by water deficit but commercial yield, fruit colour and total soluble solids and reducing sugar were improved.

From the findings of this thesis (cf. Chapter 8), we have shown that DI saved irrigation water and improved fruit quality by allowing photosynthate translocation because of reduction in volume of water. Although deficit irrigated plants received 50% of crop water requirement (ETc), the deficit drip irrigation was not severe enough to decrease plant growth and development (Chapter 4), yield and yield related traits (Chapters 5 and 6), and photosynthesis (Chapter 7) in Experiment 1. Although furrow local empirical irrigation practices (FLE) adopted in this study (cf. Chapters 4-8), used about 85% more water than deficit drip irrigation (DDI), it only yielded 25% more than DDI (Table 6.4 and 6.5, Chapter 6).

Turner (1990) asserted that crops can withstand considerable soil water depletion before water deficits affect leaf area development, photosynthesis and other physiological processes. This thesis (Table 4.2, Chapter 4) indicated that reducing irrigation volume to half of the ETc with drip system decreased LA (29%), DoN (9%), FDMA (32%), and FDMI (13%) during Experiment 1, whereas in Experiment 2, the decrease was 28.5%, 22.6%, 40.0% and 12.9% for these traits in the same order (Table 4.2, Chapter 4). In the same way, the research findings (cf. Chapters 6 and 8) showed that the effects of DI was significant for tomato yield, quality and WUE. Differences in response to DI between varieties were also observed Tables 6.2, 6.3 and 6.6 (Chapter 6) and Tables 8.4 and 8.5 (Chapter 8). In this thesis (Table 9.4), about 45% (Experiment 1) and 50% (Experiment 2) yield decrease was observed in Miya variety compared with Chali and Malkashola.

Greater conversion of starch to sugars for tomatoes grown under DI could also be a reason for greater TSS and dry matter in tomatoes (Zegbe-Dominguez *et al.*, 2003). The results of this research (Table 9.4) demonstrated that with DDI, an increase in the BWUE 18% (Chali), 44% (Miya) and 42% (Malkashola), and that of FDMC 68% (Chali), 73.7% (Miya) and 65% (Malkashola) were observed relative to DETc during Experiment 1. In the same way, an increase in titratable acidity (TA) 68.3% (Chali), 45.6% (Miya) and 53.2% (Malkashola), and that of total soluble solids (TSS) 43.5% (Chali), 39.3% (Miya) and 48.4% (Malkashola) were obtained during the same year (Table 9.4).

During Experiment 2, however, increase in BWUE was less: 5% (Chali), 16% (Miya) and 21% (Malkashola), and that of FDMC was less by 1% (Chali), 33% (Miya) and 14% (Malkashola). Furthermore, increase in TA was less by 43% (Chali), 17% (Miya) and 23% (Malkashola), and that of TSS was less by 22% (Chali), 21% (Miya) and 21% (Malkashola).

Favati *et al*. (2009) reported a mean value of 5.78 ^{o}Brix soluble solids for tomatoes cultivated under DI and 4.30 ^{o}Brix for the full water application. Birhanu and Tilahun (2010) reported also that DDI of 75% ETc improved TSS of Malkashola and Malkassa Marglobe by

10% and 15%, respectively with less decrease in CY relative to full irrigated plants. With regards to pH, no significant difference between irrigation treatments was observed (cf. Chapter 8).

Combining amount of water and irrigation interval gave useful indications on the possibility to improve tomato nutritional quality by reducing irrigation water during tomato cropping (Favati *et al*., 2009). DI limited water uptake, as result relatively promoted translocation of photosynthesis into fruits and decreased water content of fruits and hence increased fruit sugar concentration (Shinohara *et al*., 1995).

A decrease in AWUE was observed for Chali (14%) and Malkashola (1.5%), but an increase in Miya (9%), whereas the decreases in fruit dry yield were 41% for Chali, 28% for Miya, and 29% for Malkashola compared to 50% reduction in volume of water applied during Experiment 1. However, in the following year the decrease in AWUE was more by 10.7% for Chali, 9.5% for Miya, and 7.5% for Malkashola, whereas the increases in fruit dry yield were more for Chali (43%), Miya (36%), and Malkashola (40%) (Table 9.4). These results indicate that deficit drip irrigation saved water, improved fruit quality and only mildly decrease in yield. This is consistent with the findings of Birhanu and Tilahun (2010).

In this study (cf. Chapter 6), Miya variety was shown tolerant to deficit irrigation. Drought-tolerant species control stomatal function to permit carbon fixation at stress, hence improving WUE, or open stomata rapidly when water deficit is relieved (Yordanov *et al*., 2003). WUE of 31 kg tomato per m^3 was obtained with ETc of 710 mm in California (Phene, 1999). Plants which are exposed to limited availability of resource for growth viz. water, nutrient, or light usually exhibit specific responses to overcome the stress condition, such as increased allocation of biomass to the structures involved in resource uptake, increased organ duration to decrease resource losses and increased resource use efficiency (Chapin *et al*., 1987). WUE usually increases with reduced water supply (Osorio *et al*., 1998; Ponton *et al*., 2002) and varieties with a high WUE are frequently better adapted to water-limited conditions (Silim *et al*., 2001).

In Ethiopia, population increase increases pressure on irrigated land. The average population density is over 18, 118 and 143 people per km^2 in pastoralist, moisture deficit and high rainfall zones respectively while the average national land holding per household is 0.96 ha (CSA, 2011); soils are often degraded in quality and marginal in fertility. Besides to this riskiness of practices to increase land productivity water quantity and distribution over cropping season is another constraint. Household food insecurity is further accentuated by poor rural infrastructure and marketing services. While water supply is limited or irrigation costs are high, growers' general attitude is either towards practice of full irrigation over a smaller area or they do not irrigate at all. No intermediate solutions are available.

On the other hand, the increasing water scarcity and the need of irrigation for large areas and many crops require a different approach to irrigation practice based on economic optimization. On top of this, water stress cause low yields and total crop failures in semi-arid areas of Ethiopia. A field survey carried out in different eco-regions areas of Ethiopia indicated that problems relative to semi-arid areas are either seedling drought stress, mid-season stress, terminal stress, or a combination of any two or three of these (Own survey, 2011). Seedling drought stress occurs during the early to middle part of the rainy season. This can result in delayed transplanting of seedlings or seedlings may not be planted at all. Terminal stress develops towards the end of the growing season or before flowering.

According to this study (Chapter 2), an irregularity of yield between 7 and 14.6 Mg ha^{-1} was observed from 2001-2010 due to substandard water management practices. Ten years (2001-2010) average productivity under Ethiopian conditions was 9.9 Mg ha^{-1}, which is very low in contrast to the high average yield for various countries mentioned elsewhere (Chapter 1). Tomato is often cropped in areas with high water deficit during crop cycle and choice of watering system strongly governs the WUE (Phene *et al.*, 1983; Birhanu and Tilahun, 2010).

General conclusions

It was argued from the survey work that growers adopt varied water management practices e.g. irrigation practices with varying frequencies and volumes of water for the same crop under similar ecology, viz. in irrigated tomato production, some growers use drip irrigation, with scheduling of twice every day at application rate of 4 L m^{-2} day^{-1} before fruit development and 3-4 day during fruit development, while others empirically adopted every two days scheduling for drip, but twice in a week for furrow irrigation is practised. Most of growers in the sample zones are illiterate. Yields varied across ecoregions and were low due to agro climatic conditions, access to resources and culture. Although growers are attempting to check these constraints, the majorities are beyond their capacity requiring due attention from research, extension and policy makers. The same variety performed differently across and within ecoregions because of varied management practices and agroclimatic conditions. Education and extension services are crucial for smallholder growers to use improved agricultural technologies. Poor irrigation management results in important social, economic and environmental problems. Hence, ensuring the sustainability of irrigated tomato requires an improvement in the performance of irrigation practices. Growers must also be able to maintain their existence in order to sustain and possibly get improve the development of irrigated tomato farming. This implies they must not only utilize irrigation for tomato production, but such production must yield profits as well for continued involvement and increased growers tomato production.

This study provides analysis of irrigated tomato production systems by smallholders in Ethiopia. It surveys and characterizes the crop in different selected growing ecoregions and seasons from survey work carried out in different zones and field experimentations conducted in Ziway, Oromia region, Ethiopia. The approach of the study facilitated the combination of quantitative and qualitative data gathering and analysis from the survey and field experimentations. We analyzed irrigated tomato production systems by smallholders, surveyed and characterized the crop in different selected growing ecoregions and seasons, and determined yield limiting or yield reducing factors by using combination of survey work and field experiments. This thesis contributes to developments in smallholders irrigated tomato production. The study also contributes to societal food security in general through the determination of the crop yielding ability, recommendation of better alternative means of water supply and describing tomato potential growing zones and seasons.

Recommendations

There is a necessity for research on irrigation water management technologies, crop water requirement research, how to successfully improve traditional smallholders into modern ones including organizational issues linked to water user association formation. Enhancing water availability for production and modernization of existing irrigation that can lead to food security and intensification of cropping via increasing cropping intensity, and improving land productivity by improving households' access to extension service are crucial to reduce food insecurity. For Ethiopian smallholders to be productive and profitable: low effective demand for agricultural products due to poverty, poor and un-remunerative markets, limited access to technology and low rate of technology adoption, low level of investment in rural infrastructure resulting in high transaction costs and weak support services need to be addressed.

In Central Rift Valley, particularly where water scarcity is a constraint, smallholder growers should adopt deficit drip irrigation to manage their irrigation schemes to sustain tomato production. In doing so deficit drip irrigation ensures optimum quality and sustainable tomato production and maximizes the income of the growers when irrigation water are limited.

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Summary

Development of agricultural technologies contributed to unprecedented global food production. Minimizing the effects of physiological stresses such as water and nutrient stresses that prevent crops from reaching their theoretical yield potential is a crop grower challenge. Tomato is among the top list of major vegetable crops most popular with a role in food security, human nutrition and national economy of a large number of countries. Because it is very versatile and the crop can be used as salad (fresh market) and processed (processing type), its demand is increasing. However, tomato is sensitive to water stress, and its production is limited by water unavailability. At establishment, water stress affects seedlings and decreases plant stand, whereas at vegetative phase, it limits growth and expansion of leaves thereby resulting in stunted growth. With water stress, the dry matter production of the crop decreases by reducing cell division and enlargement and indirectly through reducing rate of photosynthesis. On the one hand, excessive irrigation at flowering increases flower drop and reduces fruit set and so causes excessive vegetative growth and a delay in ripening. Light and frequent irrigation, well-distributed during the growing period, promotes optimum growth and results in high yield and good quality.

Ethiopia receives an apparently adequate average annual rainfall for crop production for the 24% of the area inhabiting 43% of the population of the country. However, for the 76% of the area inhabiting 57% of the population, sustainable production and reliable food supply is challenged by temporal and spatial imbalance in the distribution of rainfall. The consequential non-availability of water at required time during crop growth periods often results in crop failure because of unavailability of water.

Understanding the current status and challenges of irrigated tomatoes by smallholders and determining water management for better crop performance will help to improve yield, quality and water productivity. These require proper irrigation management, an irrigation practice whereby water supply is regulated according to crop water requirement. Optimization of yield and quality of tomato can be understood mechanistically by studying the effects of water management on plant growth, yield related traits, leaf photosynthetic rates, yield and quality variables. Such studies may lead to future research and development interventions.

Thus, considering the lack of information on tomato water requirement in the valley, scarcity of irrigation water in arid area of Ethiopia, poor water infrastructure in the Central

Rift Valley and similar ecologies of Ethiopia, and the sensitivity of tomato crop to moisture stress, the general research question and its general scientific and social perspectives were proposed and conducted to determine the optimal irrigation strategy under drip and furrow irrigation for optimal yield and quality of fresh market and processing tomatoes under field conditions in the Central Rift valley, Oromia region, as a case study in Ethiopia. On the basis of that the candidate conceptualized the research programmes and drafted the general discussion aiming:

1. to review literature on smallholders irrigated crop production with emphasis on tomato in selected tomato growing zones of Ethiopia using published and unpublished sources to understand research and development gaps (Chapter 2).

2. to survey tomato production and possible yield constraints in Ethiopia. A survey was designed including a questionnaire for interviews and discussed irrigated tomato production systems by smallholders by surveying selected ecoregions in Ethiopia (Chapter 3).

3. to assess in a mechanistic way which irrigation system and strategy would be best in terms of growth and dry matter partitioning of field-grown tomatoes (Chapter 4).

4. to compare drip and furrow irrigation practices for their impact on yield-related characteristics and growth components, and the development of disease, blossom end rot and weeds and their effects on fresh market and processing tomatoes (Chapter 5).

5. to determine the irrigation scheduling and volume of water used for optimum commercial yield and water use efficiency of irrigated tomato by smallholders in Ziway area, Central Rift Valley (Chapter 6).

6. to determine the effects of irrigation management practices on physiological changes of fresh market and processing tomatoes under open field in a semi-arid area in Oromia, Ethiopia (Chapter 7).

7. to evaluate the deficit irrigation strategy as a means of saving water and improving fruit quality under drip and furrow irrigation for both fresh market and processing tomatoes (Chapter 8)

The analysis of yield constraints carried out in this thesis is based on survey of 400 randomly selected farm households which were equally distributed among sample ecoregions where tomato is a co-staple, for field survey; and based on data collected from two different seasons of field experiments conducted in Batu/Ziwai (07'96^o N and 038'72 ^{o} E), Central Rift Valley during 2010 and 2010/2011. The plant material used in the study consisted of one fresh market (Miya) and two processing (Chali and Malkashola) tomatoes obtained from Malkassa Agricultural Research Centre.

This thesis is composed of nine chapters. Chapter 1 outlines the general background of the research, such as justification, problem statement, research question and objective, survey approach and organization of the thesis. Chapter 2 presents a review literature on smallholders irrigated crop production with emphasis on tomato in selected tomato growing zones of Ethiopia using published and unpublished sources to understand research and development gaps. It begins with the explanation on the irrigation potential and development since the 1960s, followed by the current status of smallholders irrigation in the country. The review discusses land use rights and holding size, growers' diverse income behaviour, irrigation policy and strategy and physical factors influencing irrigation efficiency of irrigation systems. This chapter ends by elucidating those challenges and opportunities for irrigation development in Ethiopia.

Chapter 3 illustrates and details area, production and yields in the selected major tomato growing zones and at national level. It presents and analyzes crop cycle along with actual growing period and tomato cultivars used in sample growing zones using 400 farm households, and discusses tomato production (yield) constraints and analyzes production characteristics of sample ecoregions in Ethiopia.

The next five Chapters (Chapters 4, 5, 6, 7 and 8) report the outcomes of the field experiments carried out in Central Rift Valley, Oromia region. Chapters 9 deals with a general discussion and general conclusion of the study. Chapter 4 provides assessment of irrigation system and strategy in a mechanistic way on growth and dry matter partitioning of field-grown tomatoes in Central Rift Valley. The outcomes of this study revealed that maximum rate of node appearance was 0.49 nodes d^{-1} and maximum green leaf area index (GLAI) was attained 77 days after plant (DAP), about 5.23 and 6.64 with furrow- and drip-irrigation based on crop water requirement, respectively. Lower GLAIs were observed with deficit irrigation.

Greater root depth (36.6 cm), plant height (80.6 cm), leaf area (6465 cm^2 $plant^{-1}$), specific leaf area (883 cm^2 g^{-1}), leaf area ratio (499 cm^2 g^{-1}), leaf weight ratio (0.57 g g^{-1}), crop growth rate (1.93 g m^{-2} d^{-1}) and net assimilation rate (2.01 mg cm^{-2} d^{-1}) were recorded for drip-irrigation based on crop water requirement. Peak dry matter accumulation (DMA) by roots, stems and leaves with drip-irrigation based on crop water requirement were 10.02, 7.74, and 17.98 g plant^{-1}, respectively. DMA by roots accounted for 16-20% of total biomass for Chali and Malkashola, and for 16-18% for Miya during 47-57 DAP, but accounted for 11, 10 and 11% for Chali, Miya and Malkashola from 57 and 77 DAP. DMA by stems accounted for 31-20, 31-19 and 30-19% of total biomass for Chali, Miya and Malkashola, respectively between 47-77 DAP, but decreased to 22-16 % afterwards. DMA by leaves accounted for 53-69, 53-70 and 54-70% of total biomass for Chali, Miya and Malkashola, respectively from 47-67 DAP, but decreased to 39% (Chali and Miya) and 38% (Malkashola) from 77 DAP onwards.

Chapter 5 presents comprehensive comparison between fresh market and processing tomatoes performance in terms of various characteristics related to yield under different irrigation management practices. Tomato plants were examined individually every seven days interval to observe the occurrence of *Phytophthora* root rot, *Fusarium* wilt (*Fusarium oxysporum*), Blossom end rot and *Orobanche ramosa* on roots or leaves, stems or fruits, and were recorded during experimental period until the end of harvest. To compare the growth components of tomatoes two representative plants per plot were sampled. These were collected and weighed and then separated into roots, stems, leaves and fruits. Fresh matter of collected plant parts (root, stem, leaf and fruit) were measured right after harvesting, whereas dry matter yield was determined for 48 h at 65.8 ^{o}C (vegetative organs) and 105 ^{o}C (fruits) to a constant weight. To determine and compare fresh market and processing tomatoes relative performances under different irrigation management practices were calculated per strategy and per season.

The findings of the study evidenced that greater performance for truss and fruit per plant, flower and fruit per truss, fruit set percentage and weight, stem diameter growth, dry matter production by root, stem, leaf and fruit were observed with drip irrigation according to crop water requirement. Delayed days to 50% flower initiation, occurrence of *Fusarium oxysporum*, Blossom end rot and *Orobanche ramosa* were observed with deficit irrigation. From these results it was concluded that drip irrigation according to crop water requirement could be useful for increasing yield related traits and growth components and reducing occurrence of yield reducing factors compared to furrow irrigation in both fresh market and processing tomatoes.

Chapter 6 examines influences of irrigation scheduling and irrigation systems and volume of water on commercial yield, agronomical water use efficiency (AWUE) and biological water use efficiency (BWUE) of tomatoes in the Central Rift Valley. The findings demonstrated that the main factor in regulating fruit yield was the amount of water applied during the growing period and the method used for water application. Average commercial yield for drip irrigation based on crop water requirement implemented with proper scheduling increased by 51% (94.1 Mg ha^{-1}) for Experiment 1 and by 56% (82.3 Mg ha^{-1}) for Experiment 2 compared with the respective deficit drip irrigation. Similarly, with furrow irrigation based on crop water requirement a yield increase by 52% (70.6 Mg ha^{-1}) and 54% (58.3 Mg ha^{-1}) compared with the respective deficit furrow irrigation were also observed in Experiments 1 and 2, respectively.

Moreover, with deficit drip irrigation 46.0 Mg ha^{-1} and 36.3 Mg ha^{-1} was obtained for Experiments 1 and 2, respectively, whereas yields for deficit furrow were 33.9 Mg ha^{-1} and 26.8 Mg ha^{-1} in both seasons, respectively. Compared to drip irrigation system along with three strategies minimum yields were observed with furrow irrigation. BWUE decreased by about 43% and 36% in Experiments 1 and 2, respectively, with the increasing irrigation water volume from 1013 to 2214 m^3 ha^{-1}. In contrast, AWUE increased by about 18.2% and 9.6% during Experiments 1 and 2, respectively.

Chapter 7 explains the outcomes based on measurements of photosynthetic gas exchange and chlorophyll fluorescence, aiming to determine the effects of irrigation management practices on physiological changes of fresh market and processing tomatoes under open field in a semi-arid area in Oromia, Ethiopia. The measurements were undertaken from 18 September to 18 October 2010 and 28 December 2010 to 27 January 2011 for Experiments 1 and 2, respectively. The chlorophyll fluorescence data was collected on the same leaves used for gas exchange using a portable fluorometer OPTI-SCIENCES model OS-30 (Opti-sciences Inc., Tyngsboro, MA, USA) simple portable device for measuring plant stress (F_v/F_m). Two young and fully expanded leaves of same plant in each plot were measured five times a day approximately every 2 h between 07:00 and 17:00 h for gas exchange and chlorophyll fluorescence.

Increasing leaf photosynthetic rates seems a direct way of increasing crop yields. The results indicated that combined leaf gas exchange/chlorophyll fluorescence measurements differentiated the treatments effectively. Irrigation treatments demonstrated varied and significant results on physiological responses of one fresh market (Miya) and two processing (Chali and Malkashola) tomatoes. A decrease in photosynthetic rate (*A*), stomatal conductance (g_s), the maximum quantum efficiency of photosystem II (F_v/F_m) and absorbed photosynthetically active radiation ($PAR_{absorbed}$) were varied across seasons in green leaves of all cultivars, however, transpiration rate and leaf temperature increased by deficit irrigation in all cultivars. Noticeable decrease under deficit irrigation in *A* and F_v/F_m was noted in Chali while reductions in g_s and $PAR_{absorbed}$ were observed in Malkashola and Miya respectively. Stomatal limitation of *A* increased significantly suggesting a stronger influence of stomatal factor. Reduction in leaf gas exchange variables were varied across growing periods and irrigation practices for all cultivars. Among leaves of all varieties studied, Miya was found most tolerant to deficit irrigation.

Chapter 8 demonstrates deficit irrigation as a way to save water and improve quality of tomato. Studies were conducted on fresh market and processing tomatoes to evaluate the deficit irrigation strategy as a means of saving water and improving fruit quality under drip and furrow irrigation for both fresh market and processing tomatoes from August 2010 to March 2011 in Central Rift Valley.

The findings indicated that deficit drip (DDI)/deficit furrow (FDI), local empirical furrow (FLE), and full drip (DETc)/furrow irrigation (FETc) saved irrigation water by 54% 15% and 9%, respectively compared with local drip irrigation (DL). DDI was the best management strategy to optimize water use and tomato quality. DDI increased AWUE by 48%, 30%, 22% and 36% compared with FLE, FETc, DL and FDI, respectively in Experiment 1, with similar performance in Experiment 2. DDI increased BWUE by 77%, 77%, 76% and 34% compared with FLE, FETc, DL and DETc, whereas FDI increased by 57%, 56%, 55% and 18% compared with these treatments in the same order in Experiment 1. This is also consistent with Experiment 2. On the one hand, DDI produced commercial yield (CY) of 49% and 44% of DETc in Experiments 1 and 2, respectively. Similarly, FDI produced CY of 48% and 46% of FETc during the same experiments respectively. Improvements in fruit dry matter content, acid content and total soluble solids were obtained with DDI compared with other treatments. There was no clear influence of DDI on pH in this study.

In general, increase in water supply increases tomato fruit yield but reduces fruit quality attributes due to high fruit water content. Contrary to this, DDI results in decrease in

CY in general, but increases total soluble solids, acid content and fruit dry matter content. Restricting water to 50% of the crop water requirements with drip and furrow irrigation controls vegetative vigour but reduces CY on average by 53% and 65%, respectively in relation to DETc. These decreases were mainly because of a reduction in fruit weight and number. It is evidenced that at greater irrigation levels there was a high yield and less blossom-end rot (BER) affected fruit.

DDI approach can improve water use efficiency (WUE), and is a potential strategy to increase water savings in tomato production by allowing crops to withstand intermediate water deficit (by limiting water application to 50% ETcrop) with only certain level decreases of yield and quality. On the other hand, under limited water supply and drought, DDI can lead to better water saving by maximizing WUE. Increasing the amount of water used by the plant or increasing the yield of the plant can change WUE. In this chapter, DDI provides a means of reducing water consumption while minimizing adverse effects e.g., yield reducing factors (Chapter 5) on yield. However, this approach requires precise knowledge of crop response to water as drought tolerance varies considerably by growth stage, species and cultivars.

Chapter 9 discusses the previous chapters in a wider view by reflecting on the theoretical and analytical aspects; filling the research gap mentioned in the research questions, explaining the general implication of the study for optimization of irrigated tomato productivity and quality, and water conservation.

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Ambecha Olika Gemechis

PE&RC PhD Training Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Optimization of productivity and quality of irrigated tomato (*Solanum lycopersicum* L.) crop by smallholders in Ziway Area of Ethiopia

Writing of project proposal (4.5 ECTS)

- Optimization of productivity and quality of irrigated tomato (*Solanum lycopersicum* L.) crop by smallholders in Ziway Area of Ethiopia

Post-graduate courses (3 ECTS)

- Multivariate analysis (2010)
- Linear model (2010)
- Mixed linear model (2010)

Laboratory training and working visits (3 ECTS)

- Plant tissue-N analysis; Jimma University Col. of Agric. (2010/2011)
- Visits to research centres; Ambo, Malkasa, Bako Res centres, Ziwat soil lab. testing centre (2010)

Deficiency, refresh, brush-up courses (3 ECTS)

- Crop ecology (2010)
- Designing sustainable cropping systems (2010)

Competence strengthening / skills courses (2.7 ECTS)

- Techniques for writing and presenting scientific paper (2012)
- Agricultural and natural resource management: a multi-criteria approach (2010)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.4 ECTS)

- PE&RC Weekend (2010)
- PE&RC Day (2010/2013)

Discussion groups / local seminars / other scientific meetings (7.5 ECTS)

- Annual group meetings in Ethiopia (2010-2012)
- Annual group meetings in the Netherlands (2010-2012)

International symposia, workshops and conferences (3.2 ECTS)

- Ethiopian Crop Science Society (2012)
- Tropentag; Goettingen, Germany (2012)

Lecturing / supervision of practicals/ tutorials; 48 days (3 ECTS)

- Vegetable seed science and technology (2011)

Curriculum Vitae

Ambecha Olika Gemechis was born in Gidami, Oromia region, Ethiopia, on 6th February, 1969. He studied at Asmara University of Eritrea and Haramaya University from September 1987 to November 1991 obtaining a B.Sc. Degree in Arid Land Crop Production. In February 1992 he was employed as a junior agronomist by the Ministry of Coffee and Tea Development for Manasibu district where he served for eight months. Between October 1992 and July 1993 he served as a manager for Gidami district Coffee and Tea Development. From July 1993 to August 1999 he worked as agronomist at West Wallaga zone Coffee and Tea Development which later on was merged with Ministry of Agriculture (MoA). From September 1999 to July 2001 he pursued a M.Sc. Degree with scholarship from his country sponsored by United Nations Development Programme at Haramaya University where he graduated in Horticulture. Then after serving for 10 months in the earlier organization, in July 2002, feeling the need for career change, he resigned his job with MoA and joined Jimma University College of Agriculture, Horticulture and Plant Sciences department. Since then he has been working as a teacher and partly as a researcher at Jimma University until October 2004. He also participated in Advanced Profession Training in *'Environmentally sound plant production and protection and soil management*' in Germany and Portugal between November 2004 and November 2005. While teaching, he worked as a Horticulture and Plant Science department head from December 2005 to February 2008. He also wrote a teaching text on '*Indigenous root and tuber crops of Ethiopia'* for the course he taught for about seven years. Ambecha has been the recipient of numerous awards and honours including those from Oromia Bureau of Agriculture, Nedjo TVET College, Jimma University and other institutions. In December 2009 he joined Wageningen UR Plant Science group to pursue his PhD study under the supervision of Prof. Dr *ir.* Paul C. Struik (Centre for Crop Systems Analysis, CSA) and Dr Bezabih Emana (SID Consult Support, Ethiopia).

List of Publications

Regasa, M., W. Garedew and A. O. Gemechis (2017) Effect of Seed tuber size and Intra row spacing on Yield and Quality of Potato (*Solanum tuberosum* L.) Varieties at Nono Benja, Jimma Zone. *Proceedings of the Sixth Ethiopian Horticultural Science Society.* Haromaya University *(in press)* p. 28.

Gemechis, A. O., P. C. Struik and B. Emana (2012) Tomato production in Ethiopia: constraints and opportunities. http://www.tropentag.de/2012/abstracts/full/659.

Gemechis, A. O. (2011) Root and Tuber Crops: A teaching text on '*Indigenous root and tuber crops of Ethiopia.* p. 237.

Gemechis, A. O. and Y. Ujoro (2001) Influence of nitrogen and phosphorus on yield, yield related and some quality traits of two sweet potato (*Ipomoea batatas* (L.) Lam.) cultivars. http://hdl.handle.net/123456789/2146

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