STUDY ON PRODUCTION PRACTICE AND EFFECT OF GENOTYPE, IRRIGATION AND ZINC FERTILIZATION ON PRODUCTIVITY AND QUALITY OF POTATO IN SEMI-ARID ENVIRONMENT OF TIGRAY, ETHIOPIA

PhD DISSERTATION

NIGUSE ABEBE MISGINA

HAWASSA UNIVERSITY, HAWASSA. ETHIOPIA

November 2025

STUDY ON PRODUCTION PRACTICE AND EFFECT OF GENOTYPE, IRRIGATION AND ZINC FERTILIZATION ON PRODUCTIVITY AND QUALITY OF POTATO IN SEMI-ARID ENVIRONMENT OF TIGRAY, ETHIOPIA

NIGUSE ABEBE MISGINA

A DISSERTATION SUBMITTED TO SCHOOL OF PLANT AND HORTICULTURAL
SCIENCES, COLLEGE OF AGRICULTURE, SCHOOL OF GRADUATE STUDIES,
HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF
DOCTOR OF PHILOSOPHY IN AGRICULTURE
(SPECIALIZATION: HORTICULTURE)

Advisory committee:
MAJOR ADVISER: Derbew Belew (PhD, Prof)
CO- ADVISER: Hussien Mohommed (PhD, Asso.Prof)
Gebre Hadgu (PhD, Lead Researcher)

November 2025

ADVISORS APPROVAL SHEET-1

SCHOOL OF GRADUATE STUDIES

HAWASSA UNIVERSITY ADVISORS APPROVAL SHEET

(SUBMISSION SHEET-1)

ADVISORS APPROVAL SHEET-2

SCHOOL OF GRADUATE STUDIES
HAWASSA UNIVERSITY ADVISORS APPROVAL SHEET
(SUBMISSION SHEET-2)

DEDICATION

This work is dedicated to the resilient farmers of the Tigray Regional State and throughout Ethiopia, whose livelihoods face increasing threats from the adverse effects of climate change and variability. Despite contributing the least to its causes, they continue to bear its most severe consequences. I hope this work raises awareness and fosters support for vulnerable communities striving to sustain their livelihoods in challenging conditions

STATEMENT OF THE AUTHOR

I declare that this dissertation is the product of my own original work and that all sources of materials used have been duly acknowledged. This dissertation has been submitted in partial fulfillment of the requirements for the PhD degree at Hawassa University, and has been deposited in the University Library to be made available to borrowers under the library's rules. I solemnly declare that this dissertation has not been submitted to any other institution for the award of any degree, diploma, or certificate.

Brief quotations from this dissertation are allowable without special permission, provided that the source is accurately acknowledged. The Head of the Major Department may grant requests for permission to quote extensively from or reproduce this manuscript in completely or in part or the Dean of the School of Graduate Studies, if they judge the proposed use of the material is for scholarly interest. In all other instances, permission must be obtained from the author.

Name: Niguse Abebe
Signature: _____________
Place: Hawassa University
Date of Submission: ____________________

ACKNOWLEDGMENTS

Above all, I thank the Almighty God for keeping me healthy and strong from the start to the end of this work. I am grateful to the Tigray Agricultural Research Institute (TARI) for granting me study leave and providing financial support. I appreciate Hawassa University for enrolling me as a PhD student in the School of Plant Science and Horticulture. The financial support given by the Food System Resilience Programme (FSRP) at TARI is also duly appreciated. I express my gratitude to my major advisor, Professor Dr. Derbew Belew, Professor at Jimma University, as well as to my co-advisors, Dr. Hussien Mohammed Beshir, Associate Professor at Hawassa University, and Dr. Gebre Hadgu, Lead Researcher in Agronomy at Tigray Agricultural Research Institute, for their consistent professional guidance and invaluable suggestions and comments throughout the thesis work. I have no words to express my appreciation to my advisors for their psychological treatment and technical support, especially when I was under siege during the Tigray war, as they helped me to continue my studies. In general, the successful completion of this work would have been difficult without the unreserved, positive, and friendly support of my advisors.

I am indebted to all the staff at the Mekelle Soil Research Center who contributed technically and administratively to my laboratory research work, notably Gebremedhin Berhe, Ligalem, Hagos Weldegebriel, and Keshi Girmay Hailu. I am grateful to Hailesilase Amare, the operational research coordinator, for his financial support during laboratory work at Ezana Mining Development PLC. I would also like to extend my sincere gratitude to Dr. Haile Tesfay, Dr. Beyene Dimitsu, and Mersiet Hadush from the CIP project at the Mekelle branch for their technical and financial support.

Furthermore, I am glad to those who made my study and work challenging, as those things contributed greatly to my growth and development. Last, but not least, I would like to extend my gratitude and appreciation to all those whose names I may not have listed here.

PAPER/MANSCRIPT TITLE

CHAPTER III.

Assessment of potato production practice, opportunities, and constraints, in Semi-arid areas of Tigray, Northern Ethiopia:

Submission to Journal of Science and Development (Hawassa University) Completed: Under process

CHAPTER IV.

Analysis of Farmers' Perception and Observed Climate Variability: Implication for Potato Production in Semi-Arid Areas of Tigray, Northern Ethiopia

Published as: Abebe, N., Hadgu, G., Belew, D. and Mohammed, H., 2025. Analysis of farmers' perception and observed climate variability: implication on potato production in semi-arid areas of Tigray, Northern Ethiopia. Vegetos, pp.1-12.

CHAPTER V.

Growth, Yield, and Water productivity of Potato Genotypes under Supplemental and Non-supplemental irrigation Conditions of Semi-Arid areas of Northern Ethiopia

Published as: Misgina, N.A.; Beshir, H.M.; Yohannes, D.B.; Gebreyohanes, G.H. Growth, Yield, and Water Productivity of Potato Genotypes under Supplemental and Non-Supplemental Irrigation in Semi-Arid Areas of Northern Ethiopia. Agronomy 2025, 15,72.https://doi.org/10.3390/ agronomy15010072

CHAPTER VI.

Effect of Irrigation level and genotypes on growth, yield and quality of potato under Semi-Arid growing conditions of Tigray, Northern Ethiopia

Published as: Misgina, N.A., Yohannes, D.B., Beshir, H.M. et al. Effect of Irrigation Level and Genotype on Growth, Yield and Quality of Potato Under Semi-Arid Growing Conditions of Tigray, Northern Ethiopia. Potato Res. (2025). https://doi.org/10.1007/s11540-025-09894-6

CHAPTER VII.

Effects of Zinc fertilizer rates and irrigation levels on growth, yield and quality potato genotypes under screen house condition Submitted to Indian Journal of Agricultural Science publication: Under review

ABBREVIATIONS AND ACRONYMS

ATA	Agricultural Transformation Agency
ANOVA	Analysis of Variance
CEC	Cation Exchange Capacity
CIP	Centro Internacional de la Papa/International Potato Center
CSA	Central Statistical Agency
CV	Coefficient of variation
CWR	Crop Water Requirement
DM	Dry Matter
DMRT	Duncan's Multiple Range Test
DTI	Drought Tolerance Index
EC	Electrical Conductivity
EIAR	Ethiopian Institute of Agricultural Research
Eq	Equation
ETa	Actual Evapotranspiration
ETc	Crop Evapotranspiration
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FC	Field Capacity
Fig	Figure
GDP	Gross Domestic Product
HH	Household
IPCC	Intergovernmental Panel on Climate Change
IPI	International Potato Improvement
IWR	Irrigation Water Requirement
IWUE	Irrigation Water Use Efficiency
Kc	Crop Coefficient
LGP	Length of Growing Period
MARC	Mekelle Agricultural Research Center
Max	Maximum
Min	Minimum
MP	Mean Productivity
MTY	Marketable Tuber Yield

NGOs	Non-Government Organizations
NMSA	National Meteorological Service Agency
NPK	Nitrogen: Phosprouse: Potassium
NPRP	National Potato Research Program
NUE	Nutrient Use Efficiency
OC	Organic Carbon
OM	Organic Matter
PCI	Precipitation Concentration Index
PC	Protein Content
Pe	Effective Rainfall
PPI	Potash and Phosphorous Institution
PWP	Permanent Wilting Point
RWS	Relative Water Satisfaction
SAI	Standardized Anomaly Index
SAS	Statistical Analysis System
SC	Starch Content
SG	Specific Gravity
SIR	Supplement Irrigation Requirement
SPSS	Statistical Package for the Social Sciences
SSI	Stress Susceptibility Index
STI	Stress Tolerance Index
TARI	Tigray Agricultural Research Institute
TAW	Total Available Water
TOL	Tolerance Index
TSP	Triple Supper Phosphate
TTY	Total Tuber Yield
TWP	Total Water Productivity
USDA	United State Development of Agriculture
UTY	Unmarketable Tuber Yield
WFP	World Food Program
WPc	Crop Water Productivity
WUE	Water Use Efficiency
YSI	Yield Stability Index

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Study on Production Practice and Effect of Genotype, Irrigation and Zinc Fertilization on Productivity and Quality of Potato in Semi-Arid Environment of Tigray, Ethiopia

Niguse Abebe Misgina

Hawassa University, College of Agriculture, Hawassa, P.O.Box 5, Ethiopia,

General Abstract

Potato is the fourth most important world food crop after wheat, rice, and maize because of its great yield and high nutritional value. It is also an important crop among the root and tuber crops grown in Tigray. However, productivity is very low due to moisture stress, climatic variability, traditional agronomic practices that growers undertake, the use of low-yielding varieties and other production constraints. A series of studies were conducted to assess the current potato production practices of smallholder farmers, identify key opportunities and constraints, analyze climate variability and its implications for potato production, and evaluate the relationship between historical climate data and farmers' perceptions. The studies also aim to optimize potato yield by evaluating suitable genotype both under supplement and under non-supplement irrigation conditions, assess the effects of genotypes and irrigation levels on growth, yield, quality, water use efficiency, and drought tolerance, and examine the effect of Zn fertilizer rates, genotypes, and irrigation levels on yield, quality, and nutrient use efficiency in potatoes. The study used surveys, long-term climate analysis, and field experiments on various potato genotypes and irrigation levels. Survey was conducted in major potato production areas. Long-term daily rainfall and temperature data analysis as well as an interview were carried. For the field experiment five potato genotypes with two and three irrigation levels were used as treatments under rain-fed and irrigation condition, respectively arranged in split plot using randomized complete block design with three replications. Furthermore, three potato genotypes, three-irrigation levels and five Zn fertilizer rates were used as treatments arranged in a factorial complete randomized design with three replications, conducted under controlled screen house conditions . Mann–Kendall test and Sen's slope estimator statistical trend analysis techniques were used to analyze the climate variability , SPSS , and SAS software were used to analyze the qualitative and quantitative data/.

The survey result confirmed that potato is the main horticultural crop in the study areas, serving as a source of cash, food, and seed under both irrigation and rain-fed conditions. The average tuber yield under irrigation ranged from 12.6 to 15.0 tons per hectare, while under *rainfall conditions, it ranged from 12.4 to 14.6 tons per hectare. Key opportunities for potato production in the study areas include suitable agro-ecological conditions, good soil types, access to irrigation water, and available labor. However, persistent challenges, including diseases and pests, a lack of improved varieties, drought, and limited market access were identified. The study revealed that rainfall patterns in the study areas are showing decreasing trends in annual and seasonal rainfall, coupled with rising temperatures. The seasonal rainfall in the study areas was also highly variable and unevenly distributed. This variability negatively affects the kiremt season, characterized by lateonset and early cessation of rainfall, ultimately shortening the growing period. Farmers have also perceived these changes, noting reduced rainfall and increased temperatures that adversely affected crop production. The study indicates that the interaction between irrigation and potato genotypes significantly affected maturity, yields and water use efficiency under both rain-fed and irrigation conditions. The highest marketable and total tuber yields, along with shorter days to flowering and maturity, were obtained from the genotypes CIP-394611.112 and CIP-390478.90 under both supplemental and full irrigations. Under full irrigation, CIP-394611.112 produced the highest total tuber yield (29.87 t ha*$^{-1}$*). Under rainfall with supplemental irrigation, CIP-390478.90 produced the highest yield (28.71 t ha*$^{-1}$*).A pot experiment also revealed that the genotype CIP-394611.112 with 100% and 75% irrigation levels produced the highest total (0.28 and 0.256 kg pot*$^{-1}$* respectivly) and marketable tuber yields (0.267 and 0.247 kg pot*$^{-1}$* respectivly). The study recommends strengthening extension services for Integrated Pest Management (IPM) and promoting water-harvesting techniques to address the primary constraints of pests and drought. Furthermore, it advocates for building a robust seed system by supporting local seed multipliers and strengthening the formal seed sector. A key long-term strategy is breeding improved varieties with enhanced drought tolerance and resistance to local diseases. Research institutions and NGOs should also focus on developing high-yielding drought-tolerant varieties and producing high-quality seed tubers of improved varieties through the establishment of a potato seed multiplier association. In summary, the studies provide valuable insights and recommendations for mitigating the effects of climate change and improving potato production in the Tigray region and other similar areas of Ethiopia. Key interventions include developing and disseminating drought-tolerant potato genotypes, as well as adopting efficient water management practices like small-scale irrigation and rainwater harvesting to offset rainfall variability*

Key words: Climate variability, Genotypes, Irrigation, Potato, Rainfall, Temperature, Tuber Yield

CHAPTER 1

1. GENERAL INTRODUCTION

1.1 Background and Justification

Potato (*Solanum tuberosum* L.), belonging to the Solanaceae family and genus Solanum (Spooner *et al*., 2014), is a staple crop of global importance, playing a critical role in human nutrition and food security as one of the world's major food crops (FAOSTAT, 2022). Potato is one of the most important agricultural products worldwide, consistently ranking as the fourth most important food crop after rice, wheat, and maize. It holds the position of the number one non-grain food commodity globally (FAO, 2021). Among root and tuber crops, potato is the leading crop in terms of both production volume and consumption, followed by cassava, sweet potato, and yam (Scott & Ambler, 2023). In Ethiopia, potato is a critical food security and cash crop, primarily cultivated by smallholder farmers in the highlands (MoA, 2019). Its short growing cycle makes it an excellent crop for ensuring food availability and generating income within a relatively short period (Gebremedhin et al., 2008).

Potato production provides food, employment, and income as a cash crop, helping to increase food availability while contributing to a more more efficient land-use ratio by enhancing the aggregate efficiency of agricultural production systems (Gastelo et al., 2014). Potato has excellent nutritional value containing well-digestible carbohydrates, important vitamins, as well as one of the best mixes of plant proteins with a high content of lysine (Pęksa et al., 2013), which is an important essential amino acid often lacking in crops like cereals and vegetables (Waglay et al., 2014). It provides more edible food than the combined world output of fish and meat (Dzwonkowski et al., 2010). Due to its optimal balance between protein and calories, it is considered a good weaning food, and these traits make it an efficient crop in combating world hunger and malnutrition (Thiele et al., 2010; Haverkort and Struik, 2015). Furthermore, potato is a very efficient food crop in terms of yield and water use, having a greater consumable part of dry matter as well as more protein and minerals per unit area in comparison to cereals (Birch et al., 2012). It is also suitable for many crop systems as a main crop or an early crop adaptable to different conditions and different lengths of the crop cycle. In addition, there is wide variability in nutrient levels among the tubers of different potato varieties (Mouillé et al., 2008). This diversity makes the potato crop important for various sectors, including human food, animal feed and industry (both food and non-food products). According to Kirkman (2007), the commercial value of potato increased considerably when they are processed into edible products that appeal to consumers in terms of flavor, texture, appearance, and, most of all convenience.

Potato is suitable for areas with limited land and abundant labor, which characterize many developing regions (Lutaladio and Castaldi, 2009). Potato requires a consistent water supply to ensure high-quality yields (Levy et al., 2013). However, its shallow root system makes it susceptible to drought stress, leading to decreased tuber yield and quality, or even total loss of the harvest (Devaux et al ., 2010). Under water stress, roots are unable to efficiently uptake nutrients due to reduced root activity and slow ion diffusion and water movement (Dubey and Pessarakli, 2001). Drought can also cause nutrient deficiencies in fertilized fields, as the soil's physicochemical properties can limit nutrient mobility and absorption (Amtmann and Blatt, 2009). Potato requires all essential macro and micro nutrients, supplied at the right rate, time, and location, to reach its yield potential, however, any deficiency can result in decreased tuber yield and quality.

Potato is one of the staple crops growing in Tigray. In Tigray, potato is an important crop for smallholder farmers, serving as a commercial and food crop as well as business opportunities for cooperatives, engaged in seed tuber multiplication. There are legal potato seed producer cooperatives, which produce potato seed tubers and distribute them in the region, as well as other parts of the country. The average yield of potato in Tigray is (7.85t ha^{-1}), which is far below the national average of 14.18 t ha^{-1} (CSA, 2018/19) and other countries like New Zealand (50.2 t ha^{-1}) and North America (41.2 t ha^{-1}) (Grewal et al., 1992), which indicates the prospect of the crop to feed the rising population. While in Tigray, progressive farmers, who use improved varieties of potato and agronomic practices obtained tuber yield of 19-24 t ha^{-1} and this increased to more than 30 t ha^{-1} under research management. A wealth of evidence confirms that with improved varieties and basic good practices, Ethiopian potato farmers can realistically achieve yields of 25 to 40 tons per hectare, far exceeding the current national average (Gebremedhin et al., 2020; CIP, 2019).

Despite its importance, potato production and productivity in Tigray are hindered by numerous defined and undefined production constraints, including drought, low soil fertility, a lack of drought-tolerant genotypes, disease and pests, among others. Moreover, there is a lack of area-specific information on potato production practices, potentials, and constraints in the study areas. The complexity of these production constraints intensified with climate change, which further detered potato production in the region. In this regard, being a crop with a shallow root system, potato is susceptible to drought stress, leading to a decrease in tuber yield and quality, or in severe cases, even to total loss of the harvest (Devaux et al., 2010). Moreover, high temperatures delay and impede tuber initiation (Minhas et al., 2006) and reduce yield by inhibiting starch synthesis in tubers (Mohabir and John, 1988). According to Foti et al. (1995) and Haverkort et al. (1990), water stress and moderate rise in temperature generally lead to yield and tuber quality losses. Water is also another crop production-limiting factor, as the rainfall in the region is erratic, torrential, highly variable in space and time, and poorly distributed over the growing season (mainly confined between July and August) (Hagos et al., 2002; Nyssen et al., 2005). This precipitation variability in the region has been manifested by an extended dry spell, resulting in recurrent drought and famine (WFP, 2009). Araya et al. (2010) also indicated that the rainy season in Tigray is shorter than the cropgrowing period often not exceeding 65 days. Notably, early cessation of rainfall, implying water stress at later development stages (during the reproductive stage), negatively affects crop productivity in the region. Drought conditions affect nutrient transport to the root surface by inducing root shrinkage and subsequent loss of the soil-root contact (Ahmad et al., 2013). Potato regularly suffers transient water deficit in most of the rainfed growing regions due to erratic rainfall or inadequate supplemental irrigation with its appropriate techniques.

Higher temperatures increase the crop water requirement, which, together with changing rainfall patterns, could bring about greater drought stress risks for potato. Crop growth models suggest that potato yield decreases in consequence of climate change by up to 32% on a global scale until 2050 (Schafleitn et al., 2011). In dry land environments, late onset and early withdrawal of rain fall are important problems in reducing yield of crops and/or yield failure. The erratic rain fall pattern and its poor distribution over the growing season in such areas, limit the probability of receiving optimum rain for the growth and development of crops; thus, drought and yield failure are important problems for farmers in the region. On the other hand, the major potato production opportunities and constraints have not been well studied to mitigate the problem of low productivity. This yield reduction and failure could be alleviated by identifying the major potato production opportunities and constraints, as well as their possible solutions. This can be achieved through an analysis of farmers' perceptions and observed climate data, as well as the use of drought-resistant genotypes, supplementary irrigation, effective water management, and the application of fertilizers. Fertilizer application is likely to increase the efficiency of crops in utilizing available water. Efficient use of limited water and better growth under limited water supply conditions are important traits for crops in drought-prone environments (Guendouz et al ., 2012).

Nutrient depletion is another important factor limiting crop productivity in the Tigray region. The phenomenon is a cumulative effect of topsoil erosion on the steep slopes of the region, neglect of fallow, continuous cultivation of the arable land with limited external input, less crop residues, continuous removal of nutrients with the crop, less manure from the cattle and overgrazing (Alemtsehay, 2012). According to the Agricultural Transformation Agency (ATA,2014), the soils of most potato-growing areas in Tigray, show multi-nutrient deficiencies, including N, P, S, and Zn. Reduced water uptake also decreases the nutrient absorption rate (He and Dijkstra, 2014). Poor nutrient and water management leads to low nutrient and water use efficiency, respectively and often to large nutrient losses and low nutrient use efficiency due to high nutrient leaching losses. More sustainable agricultural practices are needed to enhance crop yield performance and to mitigate environmental risks (Montemurro et al., 2016). Nutrient use efficiency (NUE) is significantly affected by fertilizer management, and soil- and plant-water management. Similarly, plant nutrient status can markedly influence water use efficiency. Several studies have shown that the addition of P mitigates the addverse effect of drought stress on yield (Faye et al., 2006). Sun et al. (2015) reported that P fertilization enhanced potato growth and WUE whilst slightly reducing PUE. The application of mineral nutrients can alleviate the problem of water stress, but there is a gap in determining at what level of water stress and fertilizer rate can improve the stress. Therefore, it is necessary to apply a sufficient amount of fertilizer with appropriate agronomic options to increase the water and nutrient use efficiency and to achieve optimum yield and high-quality product under water stress condition. Climate change is expected to increase the occurrence and duration of drought in arid and semi-arid regions, leading farmers and governments to face an increasing risk to food security. The earlier studies have focused on variety adaptation, and determining the optimal NPK fertilizer rate for achieving high yield and quality of potato in semi-arid areas of Tigray, Ethiopia. There is no information or study on potato production opportunities and constraints, implication of climate variability on potato production, water and potato crop relation, drought tolerance varieties, water and Zn fertilizer rate relation on potato production in the study area. Hence, there is an urgent need to address these factors to increase potato yield, and this research proposal was therefore initiated to evaluate potato genotypes for water and nutrient use efficiencies under different moisture and nutrient management, in addition to potato production practice and climate variability. The eastern and south eastern parts of Tigray are prone to moisture stress , the rain fall is erratic, heavy, varies in terms of onset and cessation, and poorly distributed over the growing season as a result affecting crop production.

There has been limited research to counterbalance the challenges potato genotypes face and their response to water stress and use efficiency under different moisture and nutrient management practices. There has also been no comprehensive study on climate variability and its impact on potato production in Northern Ethiopia, Tigray. Understanding the trends of climate variability and their effects on potato production, as well as evaluating the opportunities, constraints, and performance of different potato genotypes under varying moisture levels and management practices in the study area, is crucial for optimizing potato production and productivity in the region. According to the United Nations Framework Convention on Climate Change (2014), households with a better understanding of climate variability are better equipped to cope with and adapt to the changing climate compared to those who do not. Similarly, studies conducted in various countries have suggested that incorporating scientific evidence along with farmers' perceptions and their indigenous knowledge is important for designing effective climate change and adaptation strategies (Mkonda et al., 2018). Hence, this study holds profound importance for researchers, government organizations, NGOs, farmers, irrigation water planning professionals, extension experts, and other stakeholders involved in ware and seed potato production and processing.

1.2. Objectives

1.2.1 General objective:

The overall objective of this study was to identify opportunities and constraints, analyze potato production, climate variability, and determine water and nutrient use efficiency of potato genotypes under semi-arid areas of Tigray, Ethiopia

1.2.2. Specific objectives:

1. To assess the production practices of smallholder farmers of potato producers in the study areas and identify the major opportunities and constraints associated with the potato crop production.
2. To analyze climate patterns and their influence on potato production, as well as explore how the historical climate factors relate to farmers’ perceptions of climate change.
3. To optimize potato yield by evaluating suitable genotypes both under supplement and under non-supplement irrigation conditions.

4. To evaluate the effect of genotypes and irrigation levels on potato growth, yield, quality, water use efficiency, and drought tolerance.
5. To assess the effects of different zinc fertilizer rates, irrigation levels, and potato genotypes on yield, quality and nutrient use efficiency.

CHAPTER 2

2. GENERAL LITERATURE REVIEW

Plants need sun light, CO_2, water and nutrient to grow and survival. Among many factors the productivity and quality of any crop is highly influenced by water, nutrients, improved variety and environment under which it is cultivated. These are also crucial to obtain optimum productivity of potato. Water is fundamental to the maintenance of normal physiological activity. Plants obtain a certain amount of water and nutrients from the ground/soil; if these are inadequate to meet the demand for higher production, they may experience stunted growth, reduced yields, and increased susceptibility to diseases and stress. Therefore, it is essential to provide optimum water, major macro and micronutrient in balanced proportion for sustainable crop production.

This literature review focuses on the effects of water stress and nutrient availability on the yield and quality of potatoes, while also providing an overview of potato characteristics and production practices in Ethiopia. This synthesis of existing research underscores the critical importance of effective water management and nutrient optimization strategies in enhancing potato cultivation, ultimately contributing to improved food security and economic stability in the region.

2.1. Description of potato (*Solanum tuberosum L*)

2.1.1. Origin and Distribution

The potato (*Solanum tuberosum L*) is originated in South America, most likely from the central Andes in Peru ((Machida-hirano and Niino, 2017). It was domesticated and has been grown by indigenous farming communities for over 4,000 years. The Spanish introduced it into Europe in the sixteenth century; the crop subsequently was distributed throughout the world (Sukhotu and Hosaka, 2006). Introduction of potato to Ethiopia dates back to 1858 by a German immigrant, Wilhelm Schimper, However, its adoption by Ethiopian farmers occurred very gradually and took several decades (Kidane-Mariam 1980). According to the latest study of geographical distribution (Hijmans and Spooner, 2001), the wild potatoes occurred in 16 countries of Americas, but 88% of the observations were from Argentina, Bolivia, Mexico, and Peru. Peru had the highest number of species. Potato is now grown in more than 149 countries from latitudes 65^{0}N to 50^{0}S and at altitudes ranging from sea level to 4000 m (Hijmans and Spooner, 2001). It is cultivated on 19.2 million ha and its annual production is estimated at 374 million tons (FAO, 2011). Over a billion people worldwide consume potatoes, and 300 million metric tons of potatoes are produced worldwide (International Potato Center, 2024).Potato production increased consistently from 2018 to 2022 globally, reaching its peak at 374.78 million metric tons in 2022 (Sahil et al., 2025)

2.1.2. Botanical description

Potato is a member of the Solanaceae family, a large plant family with more than 3000 species that includes plants such as tomato, eggplant, pepper, tobacco, and petunia (Volkov et al ., 2003). It has one of the richest genetic resources of any cultivated plant, with about 200 wild and primitive species in the section potato of the genus Solanum (Jacobs et al., 2011; Hijmans and Spooner, 2001). Potato can be defined as having an annual cycle and a perennial cycle. In the annual phase, food synthesized in the leaves passes to the ends of the stolons, which swell and form the tubers we call potatoes. Since the potato tuber is a modified stem, it has leaf scars and lateral buds; these constitute the familiar ‘eyes’. Each one of these can produce a new shoot in the following year (the perennial phase), using the food stored in the tuber. The old tubers shrivel and rot away at the end of the season. The tuber is modified portion of the underground stem, termed a stolon. The tips of the stolons produce tubers, or the edible portions of the plant, and initiation of growth occur when the plants are approximately 15.2-20.3 cm high, or about 5-7 weeks after planting (Sieczka and Thornton, 1993).

Potatoes, like their ancestral wild species, reproduce by both sexual means and by setting tubers. Potatoes flower and set true seed in berries following natural pollination by insects capable of buzz pollination, such as some bee species, which can release pollen from the poricidal anthers of potatoes (Scurrah et al ., 2008). Leaf stems are usually green, but they can be red to purple. They are angular in cross section. Late in the growing season, the lower portion may become woody at the base. Secondary branches are common, arising from axillary leaf buds. The leaves are arranged in a spiral pattern around the stem and are pinnately compound, although early leaves of seedlings and the first leaves of plants grown from tubers may be simple. Leaf types differ widely among the many cultivars. Stomata are more numerous on the lower surface of the leaf. Hairs of various types are present on leaves aboveground stems. Some leaf hairs, called trichomes, inhibit insect feeding and ovipostion (Volkov et al., 2003).

2.1.3. Ecology

Potential potato yield in any area is determined by the amount of radiant energy available, number of frost-free days, suitable temperature regimes during the growing season, and the amount and uniformity of the water supply. All other known requirements can be added. The most important factors that determine production can be divided into those in which a grower has some degree of control and those in which control is not possible or very limited. The maximum potential production is constrained by the uncontrollable factors. The ability of each grower to manage the controllable factors and the degree to which they are optimized determine the actual level of production. Factors not controlled by growers include frost-free period, air temperature, soil temperature, light intensity, day length, humidity, and soil type. Grower controlled factors are: soil moisture, crop pests, days grown, fertility, seed quality, seed piece size, plants per acre, timely operation, and soil condition (William and Steven, 2010).

2.1.3.1. Soil Requirements

Potatoes grow well on a wide variety of soils. It grows in all soils except heavy water logged conditions because the underground parts is much affected and decay. In some areas where potatoes are commercially grown, the soils are acid, whereas, in others they are alkaline. Ideal soil for potato growing is deep, well drained and friable. The soil is a water and nutrient reservoir through which air exchange between the soil and atmosphere must readily occur. Without oxygen, the roots do not efficiently absorb either water or nutrients. In areas where potatoes receive moisture entirely from rainfall, the most desirable soils ought to have a high water-holding capacity without a tendency to become saturated when wet or cloddy when dry. In the irrigated areas, especially where sprinkler irrigation is used, soil type is less critical because water can be applied as needed in quantities sufficient to meet the needs of the plants without undue runoff, leaching of nutrients, or saturation (Soussa, 2010).

Soil texture dictates water retention and drainage, fundamentally affecting crop productivity. Sandy soils cause drought stress, while clay soils lead to waterlogging, both limiting yields (Sharma and Kumar, 2023). For potatoes, which require well-drained conditions, heavy clay promotes tuber disease and sandy soils cause drought and nutrient leaching (Osman, 2018). This is a key issue in Ethiopia, where inefficient irrigation on problematic soils like Vertisols lowers water use efficiency. In the drought-prone Tigray region, soil and water conservation practices (e.g., terracing) are critical for harvesting rainwater and sustaining potato production (Gebremedhin et al., 2021).

2.1.3.2 Temperature and Moisture Requirements

Enzymes are essential for governing all metabolic processes in living plants. While the rate of enzyme-catalyzed reactions generally increases with temperature, this only occurs up to an optimum temperature. Beyond this point, the rate decreases sharply as the enzyme's structure is denatured and inactivated. (Arcus and Mulholland, 2020). The potato has long been classified as a short day, cool season crop, but does very well at high temperatures when water is supplied in uniform quantities sufficient to meet evapotranspiration demands. Potatoes can be grown in regions with cool climates, provided there is adequate water from rain or irrigation. They thrive in average daily temperatures between 15°C and 20°C. Temperatures consistently above 25-30°C can stress the plant and hinder tuber formation.A rainfall ranging between 500 and 750 mm, with even distribution during the growing period is generally considered necessary for optimum growth (Govindakrishan and Haverford, 2006). The critical factor is a sufficient water supply to maintain soil moisture, which keeps the leaf stomata open during the heat of the day. Cool night temperatures are also beneficial because they reduce respiration.

As report indicated the vine temperatures change more rapidly and to a greater degree than tuber temperatures because of the latent heat capacity of the soil (Rosen et al., 2020).The interplay between water and temperature is a primary determinant of potato productivity. Rising temperatures increase water demand while simultaneously directly inhibiting tuber formation and growth (Levy & Veilleux, 2007). Ethiopian research, particularly in the vulnerable and strategically important Northern region, highlights the urgent need for climate-smart agriculture using heat-tolerant varieties, mulching, and precision irrigation to enhance Water Use Efficiency and secure potato production for the future (Gebremedhin et al., 2023).

2.2 Nutritional value and quality

The potato is one of the most productive food crops, yielding high amounts of edible energy and high-quality protein per unit of area and time, which allows it to fit well into intensive cropping systems (Food and Agriculture Organization, 2008). Nutritionally, it is considered a well-balanced staple food with a favorable ratio of protein to calories. Additionally, it provides substantial amounts of vitamins, notably vitamin C, as well as minerals and trace elements (US DA, 2019).Furthermore according to United State department of Agriculture (USDA, 2019) report, the nutritional value of potato (100g fresh) have energy 77 kcal, water 79.25 g, carbohydrate 17.49 g, sugars 0.82 g, starch 15.29 g, Dietary fibers 2.1 g, Fat 0.09 g, Ash 0.9%, Protein 2.05 g, Vitamin C 19.7 mg, Calcium 12.0 mg, iron 0.8 mg, magnesium 23 mg, phosphorus 57 mg and potassium 425 mg. Due to its correct balance between protein and calories, it is considered a good weaning food (Berga *et al* ., 1993). Potato produces 54% more protein per unit of land area than wheat and 78% more than rice (FAO, 2008). No other food, not even soybeans, can match the potato for production of food energy and food value per unit of land area. Potatoes are less fattening than others foods in the diet and are excellent source of vitamin C and a good source of potassium, phosphorous and iron. The crop stands out for its productive water use, yielding more food per unit of water than any other major crop. Along with ground nut, onion and carrots," its nutritional productivity "is especially high: for every cubic of water applied in cultivation, the potato produces 5600 calories of dietary energy, compared to 3860 in maize, in wheat 2300 and just 2000 in rice. For the same cubic meter, the potato yields 150g of protein, double that of wheat and maize four times that of rice and 540mg of calcium, double that of wheat and four times that of rice (FAO, 2008). This clearly shows the productive quality of potato and its promising prospect in feeding our alarmingly rising population against the dwindling natural resource base and global climate change (EIAR, 2016)

2.3 Potato production in Ethiopia and Tigray

Potato (Solanum tuberosum L.) is a key tuber crop in Ethiopia. It holds the leading position among root and tuber crops in terms of both production volume and consumption, with cassava, sweet potato, and yam following in that order (CSA, 2021). In Ethiopia, potatoes are mainly cultivated by rural smallholders in Central, Eastern, North Western, and Southern regions at an altitude of more than 1,500 m above sea level (Tesfaye, 2016). It is a high potential food security crop in Ethiopia due to its high yield potential, nutritional quality, short growing period and wider adaptability (Tewodros *et al* ., 2014). In terms of area coverage, 314 652.43 hectares with volum of production 4.19 milion tones and productivity of 13.3 ton per hectar in 2022 it showed an increasing trend in area coverage and volum of production from 2017-2022 (2021/2022) . Root crops covered nearly 13.83% of the area under all Belg crops in the country. Among potato accounted for 82.06% and 87.04 % of total root crop cultivated and production in Ethiopia respectivly . Likewise potato accounted for 68.5.7% and 36.13% of production and area coverage of root and vegetable crops all added together, respectively (CSA, 2021/2022).

Regional distribution of the potato production in Ethiopia: Oromia 54 %, Amhara, 27.4% South Nation Nationalities and People Region (SNNPR) 17.6 % and Tigray 0.94 % , with respect to its productivity 12.4 , 15.4, 15.5 and 8.1 t ha-1, respectively (CSA ,2017). In Tigray, total land allocated to potato production in 2016/17 Meher season was estimated at 622.2 ha with a total production of 5 039.8 tones and total potato growers in the region were estimated at 16 564 households (CSA, 2017). The average yield (8.1 t ha^{-1}) is lower than the national average 13.77t ha^{-1} and other regions of the country (CSA, 2016/17). The low productivity may be due to climate variability especially water stress (drought).

2.4. Crop Evapotranspiration and Water requirements

Crop consumptive water use is the sum of water transpired by the plants, the water evaporated from the soil and the fraction of water held by the plant tissues (Tolessa, 2019). Consequently, in applied approach crop water consumption corresponds to Crop Evapotranspiration (ETc). Potato ETc can be estimated using weather data and is the amount of water to be applied during the growing season in order to assure potential tuber yields at a given site. Potato ETc is important to consider in irrigation as a well-develop strategy to improve the effectiveness of production (Tolessa, 2019). Crop water requirement (CWR) is the total amount of water required by the crop in a given growing season in specific climatic regime, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield (Reta et al., 2024). The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement and irrigation water requirement. Water requirement of the crops depend mainly on the nature and stage of growth of the crop and environmental conditions. Different crops have different water-use requirements under the same weather conditions. The same crop may have different water requirements at different places of the same country; depending upon the climate, type of soil, method of cultivation and useful rainfall (Khavse et al., 2014). The plant roots extract the required water from the soil. Water management and/or rainfall are among the most important factors determining yield and quality of potato. Knobby tubers, growth cracks, internal necrosis, black spot, hollow heart, heat sprouting, and other disorders are directly related to amount and distribution of water during the growing season. Factors to consider are the water application method (rainfall, sprinkler irrigation, furrow irrigation, drip irrigation, or sub-irrigation), irrigation scheduling, and irrigation amount. While the amount of water required for optimum growth of potatoes varies somewhat with cultivar, relative humidity, solar radiation, day length, length of growing season, and other environmental factors, the seasonal requirement for potato in most areas will be at least 460 mm of water. Water should be applied to the soil frequently in light amounts to maintain the crop with an adequate water supply throughout all growth stages of the crop, particularly during tuber initiation and tuber enlargement. Where rainfall is the major source of moisture, water use efficiency can be improved by not planting on steep slopes, by properly preparing the soil so infiltration is enhanced, and by forming small ridges periodically in the furrows to reduce the speed of the water running down the furrows (IUCN, 2006: Clinton, 2010, Khavse et al ., 2014). Considering the above definition the amount of water required by the crop to fulfil its demand is determined FAO CROPWAT program versio.8 (Allen et al ., 1998) as indicated in Equation (2.1)

$$ET_C\,(mm) = Kc * ETo\,(mm) \qquad \text{Eq. 2.1}$$

ETc refers to crop evapotranspiration, Kc denotes the crop coefficient, and ETo represents reference evapotranspiration. The irrigation water requirement of a certain crop is, therefore, the difference between the crop water need and that part of the rainfall, which can be used by the crop (the effective rainfall). It can be expressed mathematically as follows:

$$IR\,(mm) = ETc\,(mm) - Pe\,(mm) \qquad \text{Eq. 2.2}$$

Effective rainfall calculated based on the formula developed by USDA Soil Conservation Service (1999) as followed in equation 2.3 and 2.4.

$$Pe = \frac{TRF}{125(125-0.2*TRF)}\text{, if TRF} \leq 250\text{mm per month} \qquad \text{Eq 2.3}$$

$$Pe = 125 + 0.1 * TRF\text{, if rainfall} > 250\text{ mm per month} \qquad \text{Eq 2.4}$$

TRF is total rainfall on the month and * is multiplication sign

Potato ETc is important to consider in irrigation as a well-developed strategy to improve the effectiveness of production. Local atmospheric conditions, surface soil wetness, crop type, stage of growth, and the amount of crop cover are the factors that govern the daily fluctuations of potato Evapotranspiration (Wright and Stark, 1990). ETc is usually calculated by the product of Kc and ETo (reference evapotranspiration), or as a function of a number of climatic elements to provide the atmospheric potential demand. ETc is an essential agro meteorological index, which can be used to determine both the amount of water to be applied and the irrigation frequency for a particular crop and site. Erdem et al. (2005) reported that in the non-stressed treatments, the amount of total irrigation water applied ETc was 417 and 524 mm, respectively for drip irrigation. Early research reported that seasonal potato ETc ranged from 350 to 800 mm for different climatic and environmental conditions (Onder et al., 2005).

Ideally, a soil should hold enough water to facilitate plant growth, and have good drainage system for excess water. Soils ability to store water varies depending on their texture. Most soil profiles are a mixture of the various textural classes, and the total water storage capacity depends on the cumulative storage capacities of the various layers within the profile. Therefore, water irrigators should consider the water holding capacity of the soil. Soil moisture status is expressed in percent total available soil water (TAW) content. Total available soil water content is the amount of water that plants can extract from a given volume of soil in the crop effective rooting zone. Total available soil water is usually expressed between field capacity and permanent wilting point. Soil water tension can be measured directly using tensiometers or granular matrix sensors (Shock, 2003).

2.5. Nutrient Requirements

Fertilizers are sources of plant nutrients that can be added to the soil to supplement its natural fertility. There is usually a very dramatic improvement in both quality and quantity of plant growth when appropriate fertilizers are added. Organic and mineral fertilizers are both good for plants and for animals or people eating the plant food (Troeh and Thompson, 1993). Primary nutrients (N, P and K) are utilized in the large amounts by crops, and therefore, are applied at higher rates than secondary nutrients and much of the increase in world agriculture production and production per capita is due to expansion in the use of fertilizers (N, P_2O_5 and K_2O) (Stories and Garity,1994). A well-fertilized plant develops a more robust root system and healthier canopy, which allows it to utilize available soil moisture more effectively for photosynthesis and growth, a concept known as Water Use Efficiency (WUE). Researchers consistently affirm that the maximum productivity of crops is achieved when water and nutrient application are optimized together (Li et al., 2019). The imbalance of either resource limits the effectiveness of the other; for instance, over-fertilization under water-scarce conditions can lead to salt buildup in the soil, damaging roots and further reducing the plant's ability to absorb water, thereby severely hampering productivity (Wang et al., 2020).

Potato, as a high yielding crop, consumes more nutrients from the soil at a given time. Tuber yield is a product of three major processes: radiation interception, conversion of the intercepted radiation to dry matter and partitioning of the dry matter between tubers and the rest of the plant. The effect of nutrient supply on radiation use and dry matter partitioning where the nutrient in question is in short supply is a well-proven phenomenon (Gebremedhin et al ., 2008). The maturity class and growing season length are two primary factors determining potato nutrient requirements. Short-season, early maturing (determinate) potatoes generally have a high and intense nutrient demand during the vegetative and tuber initiation stages. Long-season potatoes (indeterminate) have a longer period of nutrient uptake. The specific fertilization strategy must be adjusted for the different varieties and maturity classes (Mikkelsen, 2006). Growing healthy potatoes for maximum yield and quality requires that all the essential nutrients be supplied at the right rate, the right time, and the right place. For potatoes, either deficient or excessive plant nutrition can reduce tuber bulking and quality. Nutrient deficiencies may limit the leaf canopy growth and its duration, resulting in reduced carbohydrate production and tuber growth. Maintaining healthy leaves is a key to producing high yields. However, excessive nutrient applications may cause nutrient imbalances or over-stimulate vegetative growth at the expense of tuber production. Some nutrients, such as S, may also have indirect yield benefits by reducing tuber disease (Mikkelsen, 2006). The total nutrient requirement is determined by a combination of plant, soil, and environmental factors. Many of these factors can be carefully controlled, but other factors (such as rainfall, temperature, and sunlight) cannot be. The main consideration is to manage those factors that can be controlled and keep the plants in the best condition to withstand whatever environmental stresses may occur (Mikkelsen, 2006).

Potassium and nitrogen are found in the largest amounts in a potato plant, followed by calcium (Ca) and magnesium (Mg). Most of the phloem-mobile nutrients will be in the tubers at harvest while the immobile nutrients will be in the residual vegetative portions of the plant. Total uptake amounts are site specific since plants generally take up more nutrients than required if available (Westermann, 2005). Potato crops need full range of plant nutrients for normal growth and development but in intensively managed soils where there is no risk of trace elements deficiency tuber yield is normally dependent up on the supply of nitrogen, potassium and phosphorus. Generally, solanaceous vegetables require large quantity of major nutrients like nitrogen, phosphorus and potassium, in addition to secondary nutrients such as calcium and sulphur for better growth, fruit and seed yield (Jagadeesha, 2008). Assefa et al. (2023)

reported that the use of potassium-rich blended fertilizers, specifically formulated for potatoes, significantly increased both tuber yield and water use efficiency (WUE) compared to the conventional DAP-Urea regime.

2.6 Effects of water stress and irrigation on potato production

Global food production is affected by periodic water stress or drought, characterized by an extended period of abnormally dry conditions in a region due to consistently below-average rainfall (Dai, 2011). A lack of rainfall triggers agricultural and hydrological droughts; but other factors, including high temperature, poor irrigation management, and external factors such as overgrazing and erosion also cause drought. Higher temperatures also increase the crop water requirement, which together with changing rainfall patterns could bring about greater drought stress risks for potato. Crop growth models suggest potato yield decreases in consequence to climate change of up to 32% on a global scale until 2050 (Schafleitner et al ., 2011).

Drought may be the most important abiotic stress factor for future potato production. Although potatoes are an irrigated crop and can use water effectively as reflected by a high harvest index (Vos and Haverkort, 2007), current potato cultivars are extremely sensitive to water stress as well as heat stress (Iwama and Yamaguchi, 2006; Levy and Veilleux, 2007). Studies have investigated the physiological, biochemical and agro-morphological responses of potato to water stress at a specific stage of the growth threatens potato production (Alva et al ., 2012; Shi et al ., 2015). Furthermore, deficit water supply at any growth stage poses detrimental effects on crop growth and development in general but varies depending on the severity of stress and the crop growth stage. Most drought effect studies in the field were conducted on deficient irrigation and supplement irrigation under irrigation and rain fed condition, respectively based on the effects of drought on morphological, and physiological processes in potato crop are as follows.

2.6.1 Growth parameters of potato

The effects of drought range from morphological to molecular levels and are evident at all phonological stages of plant growth whichever stage the water deficit takes place. The permanent or temporary water deficit severely hampers the plant growth and development more than any other environmental factor. The first and foremost effect of drought is impaired germination and poor stand establishment (Harris et al., 2002). According to Jeffery (1993) the first morphological expression of drought effects in the potato is a reduction in leaf size and the individual leaves was reduced by drought and it results in a reduction in the amount of intercepted radiation and leads to a decrease in tuber dry mass accumulation. Drought affects potato canopy architecture through decreasing leaf size and leaf expansion rate while limiting formation of new leaves and increasing the rate of senescence (Fleisher et al . 2008). Potato is very sensitive to water deficit after planting. When the young plant is devoid of leaves and therefore has very low transpiration, it can tap most of its early moisture needs from the ‘mother’ tuber. Moreover, if moisture stress continues, however, tuberization can be delayed, negatively affecting yield (Lebot, 2009). Deblonde and Ledent (2001) investigate that potato stem height was sensitive to drought and the effect was stronger on later cultivars especially when water shortage started early and drought decrease plant growth. They also found that in case of drought tolerant potato cultivar that drought affected more strongly stem height than tuber yield. Besides drought reduced total stem number, total aerial biomass, dry mass of leaves, leaf area index (LAI), leaf area duration (LAD) and the number of green leaves of some cultivars (Deblonde and Ledent, 2001; Lahlou et al ., 2003). According to Kirnak et al. (2002) studies severe water stress reduced by 46%, 51%, and 43% plant height, stem diameter and total dry weight, respectively. In other studies drought stress reduced the total stem number by 28% but when the main-stem number was considered, there was no effect of drought (Alberola et al ., 2008). Lahlou et al. (2003) found that drought stress reduced total aerial biomass, dry mass of leaves, leaf area index and leaf area duration. Other scholars revealed that reduction in expansion of stems and leaves, leading to reduced foliage, reduced canopy, reduced leaf area index, decreased shoot biomass, and finally reduction in dry matter content (Mane et al ., 2008; Albiski et al ., 2012; Anithakumari et al ., 2012). These morphological responses depend on the time of stress (development stage) also whether the stress is short or long term. Water deficit is accountable for reduced number of leaves, low plant water potentials, reduced leaf area, plant dwarfing, limited ground cover, limited stem extension and tuber yield reduction (Hassanpanah, 2010; Schafleitner et al ., 2007). Moreover drought stress affects the development and the growth of shoots, root and tubers, reduced leaf growth and accelerated leaf senescence are common responses to water deficits condition (Lahlou et al ., 2003; Luitel et al ., 2015) . Therefore, depending on the above discussion water stress affects most of potato growth parameters that are responsible for potato yield reduction.

On the other hand, Shrestha et al. (2024) and Yuan et al. (2003) reported that plant height and number of branches per plant-reduced plant as irrigation level reduced. Aytekin and Çaliskan

(2023) also reported these parameters reduced significantly. However, Elhani et al. (2019) did not find significant difference in plant height and stem number per plant among full irrigation and the other reduced irrigation level when potatoes were grown under glasshouse conditions.

2.6.2 Tuber yield, yield component and quality of potato

Water stress induced yield reduction has been reported in many crop species, which depends upon the severity and duration of the stress period. Potato crop may suffer significant yield reduction even under short periods of water depletion because of a relatively shallow root system and low capacity of recuperation after water stress (Iwama, 2008). Several researchers have studied the effect of drought on yield and yield component. Water stress reduced tuber number, fresh and dry tuber yield, total aerial biomass, and the harvest index (HI), while drought increased dry matter concentration of tubers (Deblonde and Ledent, 2001; Lahlou et al ., 2003).

The magnitude of water stress /drought effects on potato production depends on the phonological timing, duration and severity of the stress. Emergence and tuberization (sink strength) are two critical periods where water stress most affects final tuber yield. Drought shortens the growth cycle (Kumar et al., 2007) and reduces the number and size of tubers (Schafleitner et al., 2007). Monneveux et al. (2013) and Okogbenin et al. (2013) reported that tuber crops suffer greater yield loss when drought occurs during tuber initiation and bulking than during vegetative growth. Water stress during tuber bulking also causes potato tuber malformations and reduces their number and size (Monneveux et al., 2013; Luitel et al., 2015). With the imposition of drought stress, accumulation of tuber dry matter and final tuber yield have been shown to decline although the effect may depend on the stage of potato development during the stress period (Schafleitner, 2009). Economic yield depends strongly on tuber quality, and affected by irrigation management. Water deficit in the early part of the tuberization stage increases the occurrence of spindled tubers, which is more noticeable in cultivars of cylindrical tuber compared to those of round tuber. Water deficit during this stage followed by irrigation may result in tuber cracking or tubers with black heart. Water deficit following tuber initiation can reduce the yield of marketable tubers from 90 percent to 70 percent or even 50 percent (FAO, 2012).

The amount and quality of irrigation water are key factors to consider for achieving higher yields. According to the findings of Faberio et al. (2001), 597 mm of irrigation water is required to attain a maximum tuber yield of 45.18 t ha^{-1}. Yuan et al. (2003) reported increased tuber yield with irrigation applications. Onder et al. (2005) found that irrigation levels significantly affected all yield parameters, with yields under 66% and 100% full irrigation regimes being significantly higher than those under 33% irrigation and non-irrigated treatments. In addition, Onder et al. (2005) reported the highest tuber mean weight from irrigation treatment of 66 and 100% of full irrigation. On the other hand, Erdem et al. (2006) reported that irrigation regimes did not significantly affect tuber weight but significantly affected only tuber yield. Nagaz et al. (2007) explained reduction in tuber number and weight because of water supply shortage during tubers initiation and development. Significantly, the highest plant yield for 66 and 100% full irrigation over 33% and non-irrigated treatments was indicated (Onder et al., 2005). Darwish et al. (2006) found out that increased water supply increased the harvest index with the highest amount at 100% of irrigation. Shahnazari et al. (2007) reported similar result.

The yield of tubers, plant dry matter, and leaf area index in potato crops were significantly reduced under water-stressed conditions (Kashyap and Panda, 2003). Yuan et al. (2003) observed that increasing irrigation amounts led to greater plant height, biomass, total yield, and marketable yield; however, specific leaf weight, canopy temperature, and tuber specific gravity decreased significantly with higher irrigation rates**.** In contrast, Erdem et al. (2006) found no significant differences in plant height, tuber size, number of tubers per plant, or tuber yield across various irrigation rates when 30%, 50%, and 70% of available water was utilized under semi-arid conditions in Turkey. Tuber dry matter yield increased with increasing water supply from 60- 100% full irrigation but it decline at 120% of full irrigation (Darwish et al ., 2006**.** On the other hand, Darwish et al. (2006) stated lowering of deficit irrigation the tuber dry matter production and the average weight of the commercial tuber. Increased water stress decreased total dry matter yield (Kashyap and Panda, 2003).

2.7 Water relation of the crop

Water is fast becoming an economically scarce resource in many areas of the world, especially in arid and semiarid regions. The increased competition for water among agricultural, industrial, and urban consumers creates the need for continuous improvement of irrigation practices in commercial crop production. Crop growth in arid and semiarid regions usually depends on irrigation, but inappropriate irrigation practice can result in water stress. The reduction in plant growth and yield caused by water stress has been well documented (Kirnak et al., 2002; Sximsxek et al., 2004).

Drought stress affects the water relations of plants including potato at cellular, tissue and organ levels, causing specific as well as unspecific reactions, damage and adaptation reactions (Beck et al ., 2007). Relative water content (RWC), leaf water potential, stomatal resistance, rate of transpiration, leaf temperature and canopy temperature are important characteristics that influence plant water relations (Farooq et al ., 2009). According to Katerji and Mastrolli (2009) report significant decrease in water use efficiency and reduced water uptake occurs during the active growing phase of the crop. When water is limiting, stomatal conductance decreased at leaf water potentials (Iwama and Yamaguchi, 2006). Since maximum CO_2 fixation is essential to optimal crop production in potato (Blum, 2009). However, reduced transpiration leading to sub-optimal yield at relatively consistent production levels may be acceptable for subsistence farming in drought prone environments (Sinclair, 2011).

2.7.1. Water use efficiency and water productivity of potato

Water use efficiency (WUE) is a broad concept, which has many definitions. In production, WUE is estimated considering harvested crop yield and water supplied. It is calculated as a ratio of tuber yield, biomass dry or fresh weight to water consumed in potato production (Doorenbos and Pruitt, 1977).When referring to a crop, the terms water use efficiency (WUE) can be defined as the amount of crop yield per unit of water used by the crop (Hatfield et al, 2019). According to Djaman et al. (2018) Ati et al (2012), Hatfield (2019) and others commonly used the following equations to calculated Crop water use efficiency, Irrigation use efficiency and Water or irrigation productivity.

Water use efficiency (WUE): $$WUE = \frac{Total\ Yield\ (kg)}{Seasonal\ water\ suppy (m3)} \qquad \text{Eq 2.5}$$

When there is supplement irrigation under rainfed condition

Irrigation water use efficiency: $$IWUE = \frac{(Irrigated\ plot\ yield - Rainfed\ plot\ yild)kg}{Seasonal\ irrigation\ amount\ (m3)} \qquad \text{Eq 2.6}$$

Crop water productivity (WPc): $$WPc = \frac{Marketable\ \ yield (kg)}{Total\ amount\ of\ water\ applied\ (m3)} \qquad \text{Eq 2.7}$$

Improving WUE in crop production requires an increase in water productivity, which in turn increases marketable crop yield while reducing water losses from the plant-rooting zone. Water use efficiencies (WUE) vary with irrigation regimes and planting time (Steyn et al., 2007).

For irrigation specialists, a correct definition of the crop water-use efficiency (WUEc) is the crop evapotranspiration divided by the amount of water supplied by irrigation and precipitation (Fernández, 2023). This ratio has the same units in the numerator and in the denominator, such that WUEc is dimensionless. On the other hand, the crop water productivity (WPc) is defined as the marketable yield produced by a crop along the growing season (kg ha^{-1}) divided by the water consumed by the crop in the same period. Also used is the irrigation water productivity (IWP), calculated as the marketable yield produced by a crop along the growing season (kg ha^{-1}) divided by the irrigation water applied in the same period (m^3 ha^{-1}). (Fernández, 2023)

$$Crop\ water\ use\ efficency(WUEc) = \frac{ETc}{Irrigation\ water + Rainfall} \qquad \text{Eq.2.8}$$

$$Irrigation\ water\ productivity\ (IWP) = \frac{Maretable\ yield(kg)}{Irrigation\ water\ applied\ (m3)} \qquad \text{Eq 2.9}$$

Water use efficiency (WUE) is commonly defined as crop yield over evapotranspiration (ET) (Bouman, 2007), where: Evapotranspiration (ET) is the sum of soil evaporation (E) and crop transpiration (T) (Kang et al., 2002; Siahpoosh and Dehghanian, 2012). Actually, only T is a direct consequence of crop production, while E is ‘unproductive’ water loss/rainfall. Soil evaporation (E) can be large, especially in arid and semi-arid regions with unpredictable rainfall. Hence, the central question for rainfed agriculture is ‘how to transform unproductive water loss (E) into productive water use (T)’. Unfortunately, the partitioning between E and T is often unknown, due to difficulties and high cost in distinguishing E and T. As a result, water use of crops is commonly reported as evapotranspiration (ET), instead of E and T separately (Kang et al., 2002; Zhang et al., 2010).

Potato requires from 0.35 to 0.8 m of water to produce 1 kg of tuber dry matter. Under field conditions, this translates into a water requirement during the growing period of 350 to 650 mm, which is dependent on climate and cultivar (Sood and Singh, 2010). The water productivity for yield of fresh tuber, which contains about 75% moisture, is 4 to 11 kg/m^3. Under conditions of limited water supply, the available supply should preferably be directed towards maximizing yield per hectare rather than spreading the limited water over a larger area.

Savings in water can be made mainly through improved timing and depth of irrigation application (Steduto et al., 2012).

2.8. Nutrient relations of the crop

Decreasing water availability under water stress generally results in limited total nutrient uptake and their diminished tissue concentrations in crop plants including potato. An important effect of water deficit is on the acquisition of nutrients by the root and their transport to shoots. Lowered absorption of the inorganic nutrients can result from interference in nutrient uptake and the unloading mechanism, and reduced transpiration flow (Garg, 2003; McWilliams, Farooq *et al* ., 2009). However, plant species and genotypes of a species may vary in their response to mineral uptake under water stress. Moisture stress induces an increase in N, a definitive decline in P and no ultimate effects on K (Garg, 2003). Water stress conditions also affect nutrient transport to the root surface by inducing root shrinkage and subsequent loss of the soil-root contact (Ahmad *et al*., 2013). Water stress in the plant leads to stomata closure**,** reduction of transpiration and water transport through the plant. Reduced water uptake also decreases the nutrient absorption rate (He and Dijkstra, 2014). These factors have significant effects on physiology, yield and grade of potato crop. Proper nutrition is also crucial in determining potato yield and quality, as well as the potato plant’s ability to withstand pest, environmental, and other stresses. In general, there are many management practices to alleviate negative effects of drought. They include, among others, soil management practices, irrigation, crop residues and mulching, and choice of crops and varieties to be grown.

2.8 .1. Nutrient use efficiency of potato

Water and nutrients are key factors for plant growth and development, as they are involved in many processes, including photosynthesis, respiration, transpiration, plant development, and yield formation (Bernacchi & VanLoocke, 2015). Additionally, interactions between water and nutrient use can affect crop yield. For example, water stress may lead to stomatal closure, which inhibits nutrient uptake (Chaves et al., 2002). Plants with nitrogen (N) deficiency are often small and develop slowly, because of low efficiency in photosynthesis and plant development; consequently, evaporative losses are relatively high and water use efficiency low. Adequate water and nutrient supply contributes to shoot and root growth, which increases plant water and nutrient uptake, and thereby improves yield (Salvagiotti et al., 2008; Setiyono et al., 2010). The crop takes up most of the water and nutrients from the soil, and soil quality or fertility is a major determinant of land productivity (He et al., 2014). The water use efficiency of plants plays an important role in determining the exchange of water between terrestrial ecosystems and the atmosphere, thus affecting the global water cycle. It also shapes the water-energy balance of ecosystem. A decrease in water flux may mean an increase in surface temperature, which is particularly relevant in the context of climate change scenarios Seibt et al. (2008). Fertilization can enhance root growth and early development, which leads to larger and earlier plant canopy and thereby reduces E. Increasing planting density may also increase plant canopy and reduce E. However, there may be also tradeoffs; consuming too much water at the early stage may lead to water stress at the later stage. Minimizing negative tradeoffs requires a quantitative understanding of the water balance of the crop growing seasons.

Nutrient use efficiency (NUE) can be defined as the ratio of yield to total Nutrient (N,P and other nutrients) inputs, also known as partial factor productivity (PFP) (Dobermann, 2005; Cassman et al., 2002):   where NUE is often express as kg kg^{-1}, Y is harvested crop yield (kg ha^{-1}) and N is the sum of the Nitrogen, or other input.

The NUE of fertilizer N applications can be increased through the so-called 4R strategy, i.e., applying the right fertilizer, at the right amount, the right time, and at the right place (IPNI, 2012). Fertigation, i.e., the combined application of water and N through precision drip irrigation is an advanced technology for increasing both WUE and NUE. Due to the relatively high cost of the investment and maintenance, fertigation is mainly used in high-value crops. However, even with fertigation, the optimization of water and N applications remain challenging because of the erratic rainfall and often-unpredictable supply of N from soil (Phogat et al., 2013). In many arid and semi-arid regions of less developed countries, WUE and NUE are often low due to low crop yields, degraded soil fertility and low and erratic water and N inputs (Rockstrom and Falkenmark, 2015; Rockstrom et al., 2010). In many developed and rapidly developing countries, WUE and NUE are also rather low because of over application and poor management (Sutton et al., 2013; Zwart and Bastiaanssen, 2004; Zwart et al., 2010). It has also been documented that increasing water supply may increase NUE, and increasing N may increase WUE, depending on the specific environmental conditions (Gong et al., 2011).

The potato plant presents unique challenges for nutrient and water management due to its relatively shallow and sparse root system, making it sensitive to both drought and nutrient imbalances (Zebarth et al., 2020). Fertigation, the application of fertilizers through irrigation systems, is a highly effective practice for potatoes. It allows for precise "spoon-feeding" of nutrients, synchronizing supply with crop demand, thereby simultaneously increasing NUE and WUE (Badr et al., 2021). However, its adoption can be limited by cost and infrastructure.

Phosphorus (P) and potassium (K) use efficiencies are also critical. Phosphorus use efficiency (PUE) is often low due to the immobility of P in soil and its fixation by soil minerals. In potato, P fertilization is vital for early root and canopy development, which enhances WUE. However, high P application can sometimes slightly reduce calculated PUE while still being agronomically beneficial (Sun et al., 2018). Potassium plays a crucial role in osmoregulation and stomatal control, directly enhancing the plant's tolerance to drought stress (Wang et al., 2014). Ultimately, optimizing NUE in potato requires a systems approach that integrates improved irrigation scheduling, precision fertilizer placement, and variety selection to manage trade-offs and build resilience under increasingly variable climate conditions (Arora, 2019).. It is well known that soil water status is one of the most important factors affecting the plantavailability of P in the soil. According Suna et al. (2015), report P fertilization enhanced potato growth and WUE whilst slightly reduced PUE. Reduced irrigation regimes, could enhance P allocation into the root, and may potentially to increase PUE in place where irrigation water resources are limited in potato (Sun et al., 2014; McBeath et al., 2012). WUE of potato plants was significantly affected by Phosphoruse (P) fertilization and being higher in plants grown under P fertilized than plants grown unfertilized P; whereas it was not affected by the irrigation regime. A number of studies have shown that the addition of P alleviates the negative effect of drought stress on yield (Faye et al., 2006; Jin et al., 2008). Potassium is particularly important in helping plants adapt to environmental stress such as drought, frost, diseases and insect pests (Brady and Weil, 2002)

2.8.2. Effect of micronutrients on potato yield and quality

The application of inorganic fertilizers along with micronutrients is considered essential to produce high tuber yield. To improve productivity, potato plant requires a balanced dose of NPK along with adequate amount of micronutrients like boron, sulphur, zinc and manganese (Singh and Kathayat, 2018). Nutrient elements especially zinc, boron sulphur and magnesium not only increase the yield of potato but also improve the quality of potato tubers (Taya et al., 1994). Sulphur and Zinc some of the forgotten element in the recent past is now receiving attention because of its widespread deficiency in potato growing areas. In potato, sulphur is required for many metabolic activities for plant growth and development and boron play vital role in sprouting, plant growth and tuber enlargement (Ali Muthanna et al ., 2017). Islam et al. (2014) reported that application of Sulphur increases plant height, stems per hill, leaves per hill and total dry mass. Singh et al. (2018) reported in their study that foliar application of sulphur increased dry matter and starch level in potato tubers and improved tuber yield, dry matter content, starch content, economic yield and net income. Zinc is considered as the most important micronutrient for potato and low recovery of applied Zn is the main limitation in enhancing the yield of potato (Singh et al., 2014). Depending upon the duration of variety, potato crop is highly sensitive to Zn application and Zn application increases ascorbic acid content, but reduce the tyrosine and total phenol content in tubers, which are important criteria for the processing quality (Mondal et al ., 2015). Furthermore, Zn application is beneficial for both qualitative as well as quantitative yield of potato tuber (Banerjee et al., 2016). A number of authors have worked on improvement of yield in potato through micronutrient application. Rahman et al. (2011) in their experiment reported that application of Zn 4kg ha $^{-1}$ showed highest number of tubers per hill, maximum weight of tubers per hill and the highest weight of tubers per plot and hectare. El babky et al. (2010) reported that quality characters namely, total sugar, total carbohydrate and crude protein increases by application of Zn.

2.9. References

Ahmad, R. , Waraich, E.A., Ashraf, M .Y., Ahmad, S. and Aziz, T. 2013. Does Nitrogen Fertilization Enhance Drought Tolerance In Sunflower? A review. Journal of Plant

Alberola, C., Lichtfouse, E., Navarrete, M., Debaeke, P. and Souch, V. 2008. Agronomy for sustainable development. *Italian Journal of Agronomy*, *3*(3): 77–78

Albiski, F., Najla, S., Sanoubar, R., Alkabani, N., and Murshed, R. 2012. In vitro screening of potato lines for drought tolerance. Physiol. Mol. Bio. Plants, 18: 315–321.

Ali Muthanna,M., Singh, K.A., Tiwari, A., Jain,V.K. and Padhi,M. 2017. Effect of Boron and Sulphur Application on Plant Growth and YieldAttributes of Potato (Solanum tuberosum L.). Int.J.Curr.Microbiol.App.Sci, 6(10): 399-404

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. and Ab, W. 1998. Crop Evapotranspiration: Guidelines for Computing Reference Crop Evapotranspiration; FAO Irrigation and Drainage Paper, 56: UN-FAO: Rome, Italy.

Alva, A., Moore, A. and Collins, H. 2012. Impact of deficit irrigation on tuber yield and quality of potato cultivars. J. Crop Improv, 26: 211–227

Amtmann, A. and Blatt, M.R. 2009.Regulation of macronutrient transport. New Phytologist, 181:35- 52

Anithakumari, A. M., Nataraja, K. N., Visser, R. G. F. and Van Der Linden, C.G. 2012. Genetic dissection of drought tolerance and recovery potential by quantitative trait locus mapping of a diploid potato population. Mol. Breed, 30: 1413–1429.

Arcus, V.L. and Mulholland, A.J., 2020. Temperature, dynamics, and enzyme-catalyzed reaction rates. Annual review of biophysics, 49(1):163-180.

Arora, V. K. 2019. Climate resilient agriculture for potato. Current Science, 116(1): 42-50.

Assefa, S., Tulema, B., Ayalew, D., and Zewdie, S. 2023. Effect of blended fertilizer types on yield and water use efficiency of potato under supplementary irrigation in Ethiopia. Cogent Food & Agriculture, 9(1): 2229131.

Aytekin, R.I. and Caliskan, S. 2023. Irrigation and potassium fertilization effects on plant growth, tuber yield, quality, and water use efficiency of potato. Irrig. Sci, 42: 367–385

Badr, M. A., El-Tohamy, W. A. and Zaghloul, A. M. 2021. Fertigation strategies for improving water and nitrogen use efficiency in potato under arid regions. Journal of Soil Science and Plant Nutrition, 21(1), 349–362.

Banerjee, H., Sarkar, S., Deb, P., Dutta, S.K., Ray, K., Rana, L. and Majumdar,K. 2016. Impact of Zinc Fertilization on Potato (Solanum tuberosum L.) Yield, Zinc Use Efficiency, Quality and Economics in Entisol of West Bengal. Journal of the Indian Society of Soil Science, 64 (2): 176-182.

Beck, E.H., Fettig, S., Knake, C., Hartig, K. and Bhattarai T. 2007.Specific and unspecific responses of plants to cold and drought stress, J. Biosci, 32: 501–510.

Berga,M.V.D.,Boosman, M. ,Cucco,I., Cuna,L., Jansson,N., Moustier,P., Prota,L., Purcell, T.,Smith,D. and Wijk,S. 1993. Making Value Chain Work Better for the Poor: A tool book for practitioners of value chain analysis.

Bernacchi, C.J. and VanLoocke, A. 2015. Terrestrial Ecosystems in a Changing Environment: A Dominant Role for Water. Annu Rev Plant Biol.

Birch, P.R., Bryan, G., Fenton, B., Gilroy, E.M., Hein, I., Jones, J.T., Prashar, A., Taylor, M.A., Torrance, L and Toth, I.K. 2012. Crops that feed the world 8: Potato: are the trends of increased global production sustainable? Food Security, 4 (4):477-508.

Blum, A. 2009. Effective use of water and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crop Res, 112:119-123.

Bouman, B. 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales. Agricultural Systems, 93: 43-60.

Central Statistical Agency (CSA). 2016. Agricultural Sample Survey 2015/2016. Report on Area and Production of Major Crops. Private Peasant holdings, Meher Season, Vol I:14-18. Addis Abeba, Ethiopia.

Central Statistical Agency (CSA).2017. Agricultural Sample Survey 2016/2017. Report on Area and Production of Major Crops. Private Peasant holdings, Meher Season, Volume I: 12-18. Addis Abeba, Ethiopia.

Centeral Statistics Agency. (2022).Agricultural Sample Survey 2021/22 (2014 E.C.) Volume V: Report on Area, Production and Farm Management Practice of Belg Season Crops for Private Peasant Holdings. Statistical Bulletin 578. Addis Ababa.

Central Statistical Agency (CSA). (2021). The Federal Democratic Republic of Ethiopia Central Statistical Agency Agricultural Sample Survey 2020/21 (2013 E.C.), Volume I, Report on Area and Production of Major Crops. Addis Ababa, Ethiopia.

Cassman, K. G., Dobermann, A. and Walters, D. T. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. AMBIO: A Journal of the Human Environment, 31(2), 132-140.

Chaves, M.M., Pereira, J.S., Maroco, J., Rodrigues, M.L., Ricardo, C.P.P., Osorio, M.L., Carvalho, I., Faria, T. and Pinheiro, C. 2002. How plants cope with water stress in the field. Photosynthesis and growth. Annals of Botany, 89: 907-916.

Clinton,S. 2010. Water Requirements and Irrigation. In: William H. B. and Steven .B. J. (eds.).Commercial Potato Production in North America. Second Revision of American Potato Journal Supplement Volume 57 and USDA Handbook 267by the Extension Section of The Potato Association of America. , Idaho, Maine, Pp 54-56.

Dai, A. 2011. Drought under global warming: a review. WIREs Climate Change, pp45–65

Darwish, T.M., Atallah, T.W., Hajhasan, S. and Haidar, A. 2006. Nitrogen and water use efficiency of fertigated processing potato. Agriculture Water Management, 85(1-2): 95-104.

Deblonde, P. M. K. and Ledent, J. F. 2001. Effects of moderate drought conditions on green leaf number, stem height, leaf length and tuber yield of potato cultivars. European Journal of Agronomy, 14(1): 31–41.

Djaman, K., O'Neill, M., Owen, C.K., Smeal, D., Koudahe, K., West, M., Allen, S., Lombard, K. and Irmak, S. 2018. Crop evapotranspiration, irrigation water requirement and water productivity of maize from meteorological data under semiarid climate. Water, 10:405.

Doorenbos, J. and Pruitt, W.O. 1977. Crop water requirements, irrigation and drainage paper 24. Food and Agricultural Organization of the United Nations Rome, Italy.

Dzwonkowski, W., Szczepaniak, J., Zalewski, A., Chotkowski, J., Rembeza, J. and Mieczkowski, M. 2010. Rynek ziemniaka stani perspektywy. Wyd. IERiGŻ, ARR, MRiRW Warszawa.

Deblonde, P. M. K. and Ledent, J. F. 2001. Effects of moderate drought conditions on green leaf number, stem height, leaf length and tuber yield of potato cultivars. *European Journal of Agronomy*, *14*(1): 31–41.

Elhani, S., Haddadi, M., Csákvári, E., Zantar, S., Hamim, A., Villányi, V., Douaik, A. and Bánfalvi, Z. 2019. Effects of partial root-zone drying and deficit irrigation on yield, irrigation water-use efficiency and some potato (Solanum tuberosum L.) quality traits under glasshouse conditions. Agric. Water Manag, 224: 105745.

El-Baky, A., Ahmed, A.A. and El-Nemr, M.A., 2010. Effect of potassium fertilizer and foliar zinc application on yield and quality of sweet potato. Research Journal of Agriculture and Biological Sciences.

Ethiopian Institute of Agricultural Research (EIAR).2016. National Potato Research Program. Research Project for the Period 2017-2019.

Erdem, T., Orta, A.H., Erdem, Y. and Okorsoy, H. 2005. Crop water stress index for potato under furrow and drip irrigation systems. Potato Research, 48:49-58.

Erdem, T., Erdem, Y., Orta, H. and Okursoy, H. 2006. Water-yield relationships of potato under different irrigation methods and regimens. Sci. Agric, 63: 226–231.

Evers, D., Lefevre, I., Legay, S., Lamoureux, D., Hausman, J.F. and Rosales, R. O. G. 2010. Identification of drought-responsive compounds in potato through a combined ` transcriptomic and targeted metabolite approach. J. Exp. Bot, 61: 2327–2343.

Fabeiro, C., Martin de Santa Olalla, F,. and de Juan, J.A. 2001. Yield and size of deficit irrigatedpotatoes.AgriculturalWaterManagement,48(3):255-266.

Food and Agriculture Organization of the United Nations (FAO). (2021). FAOSTAT: Crops and livestock products. Retrieved from https://www.fao.org/faostat/en/#data/QCL

FAO. 2012. FAOSTAT. FAO Statistics Division. On line at http://faostat.fao.org/

FAO. 2011. Food and Agricultural Organization of the United Nations Database. Rome.

FAO). 2008. The International Year of the Potato 2008: New Light on a Hidden Treasure. Rome: FAO.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D. and Basra. S. M. A.2009. Review article

Plant drought stress : effects , mechanisms and management. *Agronomy for Sustainable Development*, *29*(1): 185–212.

Faye, I., Diouf, O. and Guisse, A., Sene, M., Diallo, N. 2006. Characterizing root responses to low phosphorus in pearl millet (Pennisetum glaucum (L.) R. Br.]. Agron J, 98:1187–1194.

Fernández, E., 2023. Editorial note on terms for crop evapotranspiration, water use efficiency and water productivity. Agricultural Water Management, 289:108548.

Fixen,P.E. and Bruulsema,T.W. 2014.Potato management challenges created by phosphorus chemistry and plant roots. Am.J. Potato Res,.91:121–131.

Fixen, P., BrentruP,F., Bruulsema,T.,Garcia,F.,Norton,R. and Zingore,S .2014 . Nutrient/fertilizer use efficiency (N/FUE); Measurement, Current Situation and Trends.', Managing Water and Fertilizer for Sustainable Agricultural Intensification, 3400: 1-29.

Fleisher, D.H., Timlin, D.J. and Reddy, V.R. 2008. Interactive effects of carbon dioxide and water stress on potato canopy growth and development. Agron J, 100: 711-719

Garg, B.K. 2003.Nutrient uptake and management under drought: nutrient-moisture interaction, Current .Agric culture, 27: 1–8.

Gastelo, M., Kleinwechter, U. and Bonierbale, M. 2014. Global Potato Research for a Changing World. Working Paper. Available online at: http://cipotato.org

Gebremedhin, W. G., Bekele, A., Tessema, B., Tadele, E., Tsegaye, D., and Mulat, Y. 2023. Impact of climate change on potato yield in Ethiopia: A review. Cogent Food & Agriculture, 9(1): 2210489.

Gebremedhin, W., Endale, K., and Lemaga, B. 2020. Potato yield gaps and determinants of attainable yield in the central highlands of Ethiopia. Journal of Agriculture and Rural Development in the Tropics and Subtropics, 121(1): 1-12.

Gebremedhin, W., G. Endale and B. Lemaga.2008. Potato variety development. pp. 326. *In*: Root and tuber crops: The untapped resources W. Gebremedhin, G. Endale, and B. Lemaga ed. Addis Abeba, Ethiopian

Gong, X.Y., Chen, Q., Lin, S., Brueck, H., Dittert, K., Taube, F. and Schnyder, H. 2011. Tradeoffs between nitrogen and water use efficiency in dominant species of the semiarid steppe of Inner Mongolia. Plant and Soil, 340: 227-238.

Govindakrishan, P.M. and Haverkort, A.J. 2006. Eco physiology and agronomic management. In: Gopal J, Khurana, S.M.P. (eds.) Handbook of potato production, improvement, and post-harvest management. Food Products Press, New York, NY, pp. 179–229.

Harris, D., Tripathi, R.S. and Joshi A. 2002. On-farm seed priming to improve crop establishment and yield in dry direct-seeded rice, in: Pandey S., Mortimer M., Wade L., Tuong T.P., Lopes K.,Hardy B. (Eds.), Direct seeding: Research Strategies and Opportunities, International Research Institute, Manila, Philippines,. 231–240.

Hassanpanah, D. 2010. Evaluation of potato cultivars for resistance against water deficit stress under in vivo conditions. Potato Research, 53: 383–392.

Hatfield, J.L. and Dold, C. 2019. Water-use efficiency: Advances and challenges in a changing climate. Front. Plant Sci. 10, 103.

Haverkort, A.J. and Struik, P.C. 2015.Yield levels of potato crops: Recent achievements and future prospects. Field Crops Research, 182:76-85.

He, M. and Dijkstra, F.A. 2014. Drought effect on plant nitrogen and phosphorus: a meta-analysis. New Phytologist, 204: 924–931.

He, Y., Hou, L.L., Wang, H., Hu, K. and McConkey, B. 2014. A modelling approach to evaluate the long-term effect of soil texture on spring wheat productivity under a rain-fed condition. Scientific reports 4.

Hijmans, R.J. and Spooner, D.M. 2001. Geographic distribution of wild potato species. American Journal of Botany, 88: 2101–2112.

International Plant Nutrition Institute (IPNI). 2012. Plant Nutrition: A Manual for Improving the Management of Plant Nutrition. International Plant Nutrition Institute. Norcross, Georgia, USA. ISBN 978-0-9834988-1-0.

International Potato Center. 2024. World potato production and consumption statistics. CIP. https://cipotato.org

International Potato Center (CIP). 2019. Unlocking the potential of potato: Results from on-farm trials and capacity building in Ethiopia (2016-2019). Lima, Peru. Retrieved from

International Union for Conservation of Nature and Natural Resource (IUCN). 2006. Water requirements of major crops for different agro-climatic zones of Balochistan, Water Programme, Balochistan Programme Office, pp139.

Islam, M. R., Roy, T.S., Rahman, M. M., Pulok, M. A. I. and Hussain, M. A. 2014. Influence of potassium and sulfur on growth and yield of potato crop derived from TPS seedling tuber. Int. J.Sustain. Agril. Tech, 10(8): 15-21.

Iwama, K. 2008. Physiology of the potato: new insights into root system and repercussions for crop management. Potato Res, 51: 333-353.

Iwama, K. and Yamaguchi, J. 2006. Abiotic Stresses. In Handbook of potato production, improvement, and postharvest management, ed. J. Gopal and S.M.P. Khurana, 231–278. New York: The Haworth Press.

Jagadeesha, V.2008. Effect of organic manures and bio fertilizers on growth, seed yield and quality in tomato in Dharwad. M.Sc thesis, University of agricultural sciences, Dharwad, Karnataka, India.

Jacobs, M.M.J., Smulders, M.J.M., van den Berg, R.G. and Vosman, B. 2011.what in a name; Genetic structure in Solanum section Petota studied using population-genetic tools. BMC Evol. Biol, 11, 42.

Jeffery, R.A. 1993.Responses of potato genotypes to drought. I. Expansion of individual leaves and osmotic adjustment. Ann. Appl. Biol, 122:93-104.

Jin, J., Wang, G., Liu, X., Pan, X., Herbert, S. and Tang, C. 2008. Interaction between phosphorus nutrition and drought on grain yield, and assimilation of phosphorus and nitrogen in two soybean cultivars differing in protein concentration in grains. Journal of Plant Nutrition, 29:1433-1449.

Kashyap, P.S. and Panda, R.K. 2003. Effect of irrigation scheduling on potato crop parameters under water stressed conditions. Agric. Water Manag, 59: 49-66.

Katerji, N. and Mastrorilli, M. 2009. The effect of soil texture on the water use efficiency of irrigated crops: results of a multi-year experiment carried out in the Mediterranean region. Eur. J. Agron, 30: 95–100.

Khavse, R., Singh, R., Manikandan, N., Chandrawanshi, S.K. and Chaudhary, J.L. 2014. Crop water requirement and irrigation water requirement of mustard crop at selected locations of Chhattisgarh State, India. Eco. Env. & Cons, 209-211

Kidane-Mariam, H.M. 1980. Project Proposal for the Development of an Ethiopian Potato Program. Addis Ababa. Manuscript

Kirkman, M.A. 2007.Global markets for processed potato products. In: Vreugdenhil, D. , (ed.).Potato biology and biotechnology advances and perspectives. Elsevier, Oxford, 27-44.

Kirnak, H., Tas,I., Kaya,C. and Higgs,D. 2002. Effects of deficit irrigation on growth, yield, and fruit quality of eggplant under semiarid conditions. Aust. J. Agr. Res, 53:1367–1373.

Kumar, P., Pandey, S.K., Singh, B.P., Singh, S.V. and Kumar, D. 2007. Effect of nitrogen rate on growth, yield, economics and crisps quality of Indian potato processing cultivars. Potato Res, 50: 143-155.

Lahlou, O., Ouattar, S. and Ledent, J.F. 2003.The effect of drought and cultivar on growth parameters, yield and yield components of potato. Agronomie, 23: 257-268.

Lebot, V. 2009. Tropical root and tuber crops: Cassava, sweet potato, yams and aroids, CABI, Cambridge, UK.

Levy, D., Coleman, W.K. and Veilleux, R.E. 2013. Adaptation of potato to water shortage: irrigation management and enhancement of tolerance to drought and salinity. *American Journal of Potato Research, 90*: 186-206.

Levy, D. and Veilleux, R.E. 2007. Adaptation of potato to high temperatures and salinity: A review. American Journal of Potato Research, 84: 487–506.

Li, Y., Li, J., Gao, L., and Tian, Y. 2019. The interactive effects of water and fertilizer on crop yield and water use efficiency: A meta-analysis. Field Crops Research, 241: 107569.

Luitel, B. P., Khatri, B. B., Choudhary, D., Paudel, B. P., Jung-Sook, S., Hur, O.S. and Yul, R. K. 2015. Growth and Yield Characters of Potato Genotypes Grown in Drought and Irrigated Conditions of Nepal. *International Journal of Applied Sciences and Biotechnology, 3*(3):513.

Lutaladio, N. and Castaldi, L. 2009. Potato: The hidden treasure. Journal of Food Composition and Analysis, 22(6): 491-493.

Machida-hirano, R. and Niino, T. 2017. Potato Genetic Resources, PP.11-13

Mane,S., Vazquez,R.C. and Ulanov,.A.2008.Molecular and physiological adaptation to prolonged drought stress in the leaves of two Andean potato genotypes. Functional Plant Biology, 35: 669-688.

McBeath,T.M., McLaughlin,M.J., Kirby,J.K. and Armstrong, R.D. 2012. Dry soil reduces .Fertilizer phosphorus and zinc diffusion but not bioavailability. Soil Sci. Soc. Am.J, 76: 1301–1310.

Mikkelsen, R. 2006. Best management practices for profitable fertilization of potatoes. *Magnesium (Mg)*, *25*(15): 40.

Ministry of Agriculture (MoA). (2019). Ethiopia National Crop Production Strategy. Federal Democratic Republic of Ethiopia.

Mondal, S.S., Patra, B.C. and Banerjee, H. 2015. Micronutrient management. In Advances in Potato Cultivation Technology. Kalyani Publishers, New Delhi. pp. 115-121.

Monneveux, P., Ramírez, D. A. and Pino, M. T. 2013 .Drought tolerance in potato (S. tuberosum L.). Can we learn from drought tolerance research in cereals?. Plant Science. Elsevier Ireland Ltd,205–206.

Mouillé, B., Charrondière, U.R., Burlingame, B. and Lutaladio, N. 2008. Nutrient composition of the potato. *Interesting varieties from human nutrition perspective*.

Nagaz, K., Masmoudi, M.M. and Mechlia, N.B. 2007. Soil salinity and yield of drip irrigated potato under different irrigation regimes with saline water in arid conditions of southern Tunisia. Journal of Agronomy, 6:324-330,

Okogbenin, E., Setter, T.L., Ferguson, M., Mutegi, R., Ceballos, H., Olasanmi, B. and Fregene, M. 2013. Phenotypic approaches to drought in cassava. *Frontiers in physiology*, *4*: 93.

Osman, K.T. 2018. Management of soil problems (Vol. 448). Cham, Switzerland: Springer International Publishing.

Onder, S., Caliskan, M.E., Onder, D. and Caliskan, S. 2005. Different irrigation methods and water stress effects on potato yield and yield components. Agriculture Water Management, 73(1): 73-86.

Pęksa, A., Kita, A., Kułakowska, K., Aniołowska, M., Hamouz, K. and Nemś, A. 2013 .The quality of protein of colored fleshed potatoes. Food Chemistry, 141 (3):2960-2966

Phogat, V., Skewes, M.A., Cox, J.W., Alam, J., Grigson, G. and Šimůnek, J. 2013. Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. Agricultural Water Management, 127: 74-84.

Rahman, M. H., Halder, B. C. and Khan, M. A. 2011. Effects of zinc and manganese on growth and yield of potato. J. Bangladesh Soc. Agric. Sci. Technol. 1&2: 17-22

Reta, B.G., Hatiye, S.D. and Finsa, M.M., 2024. Crop water requirement and irrigation scheduling under climate change scenario, and optimal cropland allocation in lower kulfo catchment. *Heliyon*, *10*(10).

Rockstrom, J. and Falkenmark, M. 2015. Increase water harvesting in Africa. Nature, 519: 283-285.

Rockstrom, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J. and Qiang, Z. 2010. Managing water in rainfed agriculture-The need for a paradigm shift. Agricultural Water Management, 97: 543-550.

Rosen, C.J., Gupta, S.K. and Souza, E.F., 2020. Potato1. The Physiology of Vegetable Crops, p.209.

Sahil, M., Chen, A., and Volkov, J. 2025. Global trends in root and tuber crop production from 2018to2022.Journal ofAgricultural Science, 12(3):45–58.

Salvagiotti, F., Cassman, K.G., Specht, J.E., Walters, D.T., Weiss, A. and Dobermann, A. 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Research, 108, 1-13.

Schafleitner, Gutierrez, R, Espino, R., Gaudin, A., Perez, J., Martinez, M., Dominguez, A., Tincopa, L., Alvarado, C., Numberto, G. and Bonierbale, M. 2007. Field screening for variation of drought tolerance in Solanum tuberosum L. by agronomical, physiological and genetic Schafleitner R (2009) growing more potatoes with less water. Trop Plant Biol2: 111-121analysis. Potato Research, 50: 71–85.

Schafleitner, R., Ramirez, J., Jarvis, A., Evers, D., Gutierrez, R. and Scurrah, M. 2011. Adaptation of the potato crop to changing climates. Crop adaptation to climate change, pp.287-297.

Scott, G. J., and Ambler, K. D. 2023. Roots, Tubers and Bananas: Contributions to Food Security. In M. J. Sadras and D. F. Calderini (Eds.), Crop Physiology Case Histories for Major Crops. Academic Press.

Scurrah, M, Celis-Gamboa, C. and Chumbiauca, S. 2008. Hybridization between wild and cultivated potato species in the Peruvian Andes and biosafety implications for deployment of GM potatoes. Euphytica, 164: 881–892.

Seibt, U., Rajabi, A., Griffiths, H. and Berry, A.J. 2008. Carbon isotopes and water use efficiency .Oecologia, 155:441-454

Setiyono, T.D., Walters, D.T., Cassman, K.G., Witt, C. and Dobermann, A. 2010. Estimating maize nutrient uptake requirements. Field Crops Research, 118: 158-168.

Shahnazari, A., Liu, F., Anderson, M.N., Jacobsen, S.E. and Jensen, C.R. 2007. Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under field conditions.Field Crop Research,100(1):117-124.

Sharma, P.K. and Kumar, S., 2023. Soil Water and Plant Growth. In Soil Physical Environment and Plant Growth: Evaluation and Management (pp. 33-71). Cham: Springer International Publishin

Shi, S., Fan, M., Iwama, K., Li, F., Zhang, Z. and Jia, L. 2015. Physiological basis of drought tolerance in potato grown under long-term water deficiency. International Journal of Plant Production, 9(2): 305–320.

Shock, C.C. 2003. Soil water potential measurement by granular matrix sensors. In Stewart, B.A. and Howell, T.A. (eds.) The Encyclopedia of Water Science. Marcel Dekker, pp. 899-903.

Shrestha, B., Stringam, B.L., Darapuneni, M.K., Lombard, K.A., Sanogo, S., Higgins, C. and Djaman, K. 2024. Effect of Irrigation and Nitrogen Management on Potato Growth, Yield, and Water and Nitrogen Use Efficiencies. Agronomy, 14:560.

Siahpoosh, M.R. and Dehghanian, E. 2012. Water Use Efficiency, Transpiration Efficiency, and Uptake Efficiency of Wheat during Drought. Agronomy Journal, 104: 1238-1243.

Sieczka, J. B. and Thornton, R.E.1993. Commercial Potato Production in North America. Revision of American Potato Journal Supplement Vol. 57 and USDA Handbook 267 by the Extension Section of the Potato Association of America. Orono, Maine.

Sinclair, T.R.2011.Challenges in breeding for yield increase for drought. Trends in Plant Science, 16; 289-293.

Singh, N. and Kathayat, K. 2018. Integrated Application of Micronutrients to Improve Growth, Yield, Quality and Economic Yield in Potato A Review. Int.J.Curr.Microbiol.App.Sci, 7(08):29302935.

Singh, S.K., Sharma, M., Reddy, K.R. and Venkatesh, T. 2018. Integrated application of boron and sulphur to improve quality and economic yield in potato. Journal of Environmental Biology, 39: 204-210.

Singh, S., Kumar, D., Chandel, B.S. and Singh, V. 2014. Effect of balanced fertilization on yield, nutrients uptake and economics of potato (Solanum tuberosum) in alluvial soil. Indian Journal of Agronomy, 59: 451-454.

Sood, M.C. and Singh, S.P. 2010. Yield and economics of potato (Solanum tuberosum L.) influenced by raised bed planting patterns and drip layout systems. *Progressive Agriculture*, *10*(1): 29-34.

Spooner, D. M., Maria, G,R., Simon, S.H. and Tatjana,. G. 2014. Systematics, Diversity, Genetics, and Evolution of Wild and Cultivated Potatoes. The Botanical Review 80 (4): 283–383.

Steduto, P., Hsiao, T.C., Fereres, E. and Raes, D. 2012 .Crop yield response to water, FAO, Irrigation and Drainage Paper 66.

Steyn, J.M., Kagabo D.M. and Annandale, J.G. 2007. Potato growth and yield responses to irrigation regimes in contrasting season of a subtropical region. African Crop Science Conference Proceedings, 8: 1647-1651.

Storrier, R.R. and Garity, J.W. 1994. Soils for crop production. In: Partely, J. (Ed).Principles of Field Crop Production. Oxford University, New York. pp. 200-201.

Sun, Y., Zhang, J., Wang, H., Wang, L., and Li, H. 2018. Effect of P availability on potato growth, yield, and quality under different irrigation regimes. Journal of Plant Nutrition and Soil Science, 181(5): 747-756.

Suna, Y., Cui, X. and Liu, F. 2015. Effect of irrigation regimes and phosphorus rates on water and phosphorus use efficiencies in potato. Scientia Horticulturae, Amsterdam, 190(4); .64-69.

Suna, Y.Q., Yan, F., Cui,X.Y. and Liu,F.L.2014. Plasticity in stomatal size and density of Potato leaves under different irrigation and phosphorus regimes.J. Plant Physiol, 171: 1248–1255.

Soussa, H.K., 2010. Effects of drip irrigation water amount on crop yield, productivity and efficiency of water use in desert regions in Egypt. Nile Basin Water Science& Engineering Journal, 3(2): 96-109.

Sutton, M.A., Bleeker, A., Howard, C.M., Erisman, J.W., Abrol, Y.P., Bekunda, M., Datta, A., Davidson, E., De Vries, W., Oenema, O. and Zhang, F.S. 2013. Our nutrient world. The challenge to produce more food & energy with less pollution. Centre for Ecology & Hydrology.

Sximsxek, M., Kacxura,M. and Tonkaz,T. 2004. Theeffects of different irrigation regimes on watermelon. yield and yield components under semi-arid climaticconditions. Aust. J. Agr. Res, 55:1149–1157

Taya, J. S., Malak, Y. S. M. L., Pandila, S. C. and Khurana, S. E. 1994. Fertilizers management in potato based cropping system: Growth and yield of potato. J. Indian Potato Assoc, 21(3-

4): 164-188.

Tesfaye, A. 2016. Assessment of Potato (Solanum Tuberosum L.) Production Systems and Constraints in Ethiopia. Master's thesis, Haramaya University.

Tewodros, A., Paul, C. Struik and Adane, H. 2014. Characterization of seed potato (Solanum tuberosum l.) Storage, pre-planting treatment and marketing systems in Ethiopia: the case of west-arizona. African journal of agricultural research, 9(15): 1218-1226.

Thiele, G., Theisen, K., Bonierbale, M. and Walker, T. 2010 .Targeting the poor and hungry with potato science, Potato J, 37: 75–86.

Tolessa, E.S. 2019. A review on water and nitrogen use efficiency of potato (Solanum tuberosum L.) in relation to its yield and yield components. Archives of Agriculture and Environmental Science, 4(2): 119-132,

Troeh, F.R. and Thomposon, L. M. 1993. Soils and soil fertility: fertilizers. (Ed). Oxford university press. New York

Volkov R.A., Komarova N.Y., Panchuk I.I. and Hemleben, V. 2003. Molecular evolution of rDNA external transcribed spacer and phylogeny of sect. Potato (genus Solanum). Molecular Phylogenetics and Evolution, 29: 187–202.

Vos, J. and Haverkort, A.J. 2007. Water availability and potato crop performance. In Potato biology and biotechnology: Advances and perspectives, ed. Vreugdenhil,, D., Bradshaw,J. Gebhardt, C., Govers, F., Taylor, M.A., MacKerron, D.K.L., and Ross, H.A., 333– 351. : Elsevier.

Waglay, A., Karboune, S. and Alli, I. 2014 .Potato protein isolates: recovery and characterization of their properties. Food Chemistry, 142:373-382

Wang, Z., Li, J., and Li, Y. 2020. Effects of nitrogen application on soil salinity and crop yield under drip irrigation. Agricultural Water Management, 234:106123.

Westermann, D. T.2005.Nutritional Requirements of Potatoes. American Journal of Potato Research, 82:301-307

William, H. B. and Steven B. J. 2010. Commercial Potato Production in North America. Second Revision of American Potato Journal Supplement Volume 57 and USDA Handbook 267 by the Extension Section of the Potato Association of America. , Idaho, Maine.

Wright, J. L. and Stark, J.C. 1990. Potato. IN B.A. Stewart and D.R. Nielson (eds.) Irrigation of agricultural crops. ASA CSSA SSSA, 859-888.

World Food Program (WFP). 2009. Food security and vulnerability in selected towns of Tigray region, Ethiopia. WFP-Ethiopia, Vulnerability assessment and mapping (VAM), Addis Ababa, Ethiopia.

Yuan, B.Z., Nishiyama, S. and Kang, Y. 2003.Effects of different irrigation regimes on the growth and yield of drip-irrigated potato. Agriculture and Water Management, 63:153-167.

Zhang, X.Y., Chen, S.Y., Sun, H.Y., Wang, Y.M. and Shao, L.W. 2010. Water use efficiency and associatedtraits in winter wheat cultivars in the North China Plain. Agricultural Water Management, 97: 1117-1125.

Zwart, S.J., Bastiaanssen, W.G.M., de Fraiture, C. and Molden, D.J. 2010. A global benchmark map of water productivity for rainfed and irrigated wheat. Agricultural Water Management, 97: 1617-1627.

Zwart, S.J. and Bastiaanssen, W.G.M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management, 69: 115-133.

Zebarth, B. J., Karemangingo, C., Scott, P., Savoie, D., and Moreau, G. 2020. The perspective of potato yield and nitrogen use efficiency: A review of current knowledge. Agronomy, 10(8): 1151.

CHAPTER 3

3. Assessment of Potato Production Practice, Opportunities, and Constraints, in Semi-arid areas of Tigray, Northern Ethiopia

Abstract:

Potato is widely grown in mid and highland areas of Tigray. However, the productivity is below the national average due to many factors. To understand the reasons of this issue, a survey was conducted in Tigray's major potato production districts to assess potato production practice and identify key constraints, and opportunities related to potato production. A purposive sampling technique was used to select Zone, Wereda, and kebeles. Accordingly, three zones, eight weredas, and 386 farmers were selected. Structured questionnaires were employed to gather data on potato production practices, constraints, and opportunities. The collected data were analyzed using descriptive statistics and index ranking. The result of the survey indicated that 83.4% of interviewed farmers produce potatoes under irrigation and rainfed condition. Potato planting occurs between December 15 and January 15, as well as May 15 and June 30, depending on the irrigation and rainfall conditions, respectively. Among the interviewed farmers, 98.9% use inorganic fertilizers, while 82.2% use organic fertilizers for potato production. 72.3% of the interviewed farmers used the Shashemene cultivar as planting material and obtained it from the local market, while 36.01% use improved variety Gudanie. The study showed that under irrigation and rainfed conditions, farmers achieved an average potato tuber yield of 13.9 t/ha and 13.4 t/ha, respectively, with variability among individual farmers. The key opportunities in the study areas, as ranked by the index, include favorable agroecology, good soil type, access to irrigation water source, and available labor. On the other hand, the most significant constraints in potato production are diseases and pests, drought, lack of improved varieties, and market demand. Therefore, it is recommended that research centers, and higher institutions should focus on development of improved varieties.

Keywords*:* Assessement , Interview, Purposive, Sample, Survey

3.1. Introduction

Potato is an important crop that contributes to food security, poverty alleviation, and income generation ((Nyunza and Mwakije 2012). Potato production provides food, employment, and income as a cash crop and helps in increasing food availability while contributing to a better land use ratio by raising the aggregate efficiency of agricultural production systems (Gastelo et al ., 2014). It is rich in easily digestible carbohydrates, essential vitamins, and high-quality plant proteins, including lysine, which is often lacking in other crops (Pęksa et al., 2013; Waglay et al., 2014). It has a short growing period, high yield potential, and nutritious tubers with high edible dry matter content. Additionally, potatoes are used in various food-processing industries and can supplement diets when other grains are less available or unaffordable (Camire et al, 2009). They are affordable to buy, easy to grow, and can thrive in challenging conditions where other crops may fail (Lutaladio et al., 2009). Factors affecting potato yields include water and soil management, seed quality, fertilization, soil moisture, elevation, slope, and irrigation (Maqsood et al., 2020.). Potatoes require 400 to 800 mm of rainfall or water, depending on meteorological variables, and suitable temperatures ranging from 14-23°C with a suitable daytime temperature of 23–24 ^{0}C (Xu N, et al., 2020).

Potato is the fourth most important food crop worldwide in terms of the volume of production after rice, wheat, and maize (Kennedy et al., 2019). It is also the most important tuber crop, ranking first in volume produced among root and tuber crops (Getachew et al., 2023; Komlaga et al., 2021). Ethiopia has the largest potential for potato production, with approximately 70% of its arable land deemed suitable for cultivation (Shamil & Dereje, 2021). This high potential is attributed to the country's favorable climatic and soil conditions, which enhance both productivity and yield (Chen, 2023). In addition, the Ethiopian government and research institutions have invested a significant amount of money and time in upgrading potato technology and quality in order to enhance smallholder production (Basha et al., 2017).

In recent years, Ethiopia has experienced a substantial rise in potato exports, both in volume and value. The country exported around 71,000 tons of potatoes to regional markets, with Djibouti being the primary destination, accounting for 80–90% of total exports (Brasesco et al., 2019). Ethiopia's annual potato production has also increased from 0.97 million tons in 2017 to 1.14 milion tons in 2022 (Yimam et al., 2024). Despite this growth, Ethiopia's average yield of 13.31 tons per hectare (CSA, 2022) remains low compared to average yield of 35 and 45 tons per hectare in Europe and North America, respectively .

Potato is a high-potential food security and cash crop in the Tigray region of Ethiopia (FAO, 2018). Before the devastating war that started in November 2020, production was steadily increasing due to improved seed availability and extension services (Gebre and Schulz, 2021). However, the currentstatus is catastrophic. The conflict has decimated agricultural infrastructure, displaced farmers, destroyed seed and input stocks, and led to a severe blockade (Mekelle University, 2022), resulting in a near-total collapse of potato production and contributing to a man-made famine (IPC, 2022).In Tigray, potato is cultivated on nearly 604.48 hectares of land byapproximately 12,156 small-scale farmers, with an average yield of 7.85 tons per hectare (CSA, 2019). The productivity of potato in the region is very low compared to the national average yield of 14.18 tons per hectare (CSA, 2019), as well as the yields obtained under experimental conditions, which can reach up to 40 tons per hectare (Amare et al., 2022). Despite suitable agro ecological conditions and available labor, potato yields remain low in the region, hindering its potential benefits. The potato sector faces various challenges, including a lack of improved tuber seeds, disease and pest issues, water stress, and market limitations (Meresa et al., 2024: Merga and Haji, 2019). Moreover, there is a lack of area-specific information on potato production practices, potentials, and constraints in the study areas. In addition, preliminary studies and observations suggest the area is suitable for potato production, though this has not been conclusively proven.

Therefore, assessing potato production potentials, major constraints and practices is important to identify the major constraints and tackle the problems in the future. The objective of this survey was to assess the production practices of potato by smallholder farmers in the study areas and identify the major opportunities and constraints associated with the potato crop production.

3. 2. Materials and Methods

3.2.1. Survey Sites and Descriptions

The assessment was conducted in eight districts across three major potato producing zones of Tigray namely, East, South-East and South zones of Tigray Regional State between Feb-May 2020, which is located in the northern escarpment of Ethiopia between 360 -400E longitude and 12^0 – 15^0 N latitude (Fig 3.1) and an elevation of 2004-2275masl. Annual rainfall ranges from 506.9 mm to 734.4 mm, and the mean annual temperature ranges from 10.0 °C to 27.7 °C. . It borders with Amhara Regional State in the southwest, Afar Regional State in the east, Eretria in the north, and Sudan in the west. The zones were selected purposively based on the Regional Bureau of Agriculture expertise perception and ranked potato as their most important crop in the areas. It has diversified agro ecological districts with varying soil, vegetation, and natural resources. The climate is mainly semi-arid, with the main rainy season (kiremt) from June-mid September (Araya et al., 2010; Gebrehiwot and van der Veen, 2013). According to CSA (2018/19), in Tigray 12,156 households cultivated potato on 604.48 hectares. In addition to potato, wheat and barley are the dominant crops grown in the study

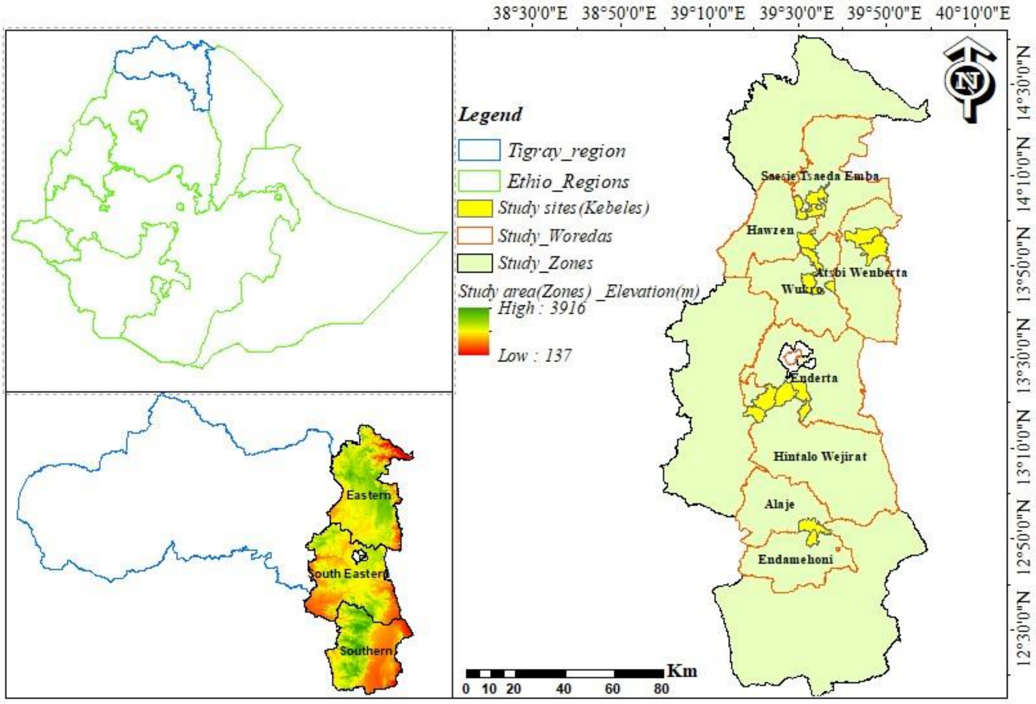


Figure 3.1 Study areas

3.2.2. Sampling procedures and sample size

To study the survey work, permission letters were taken from Tigray Agricultural Research Institute and from Tigray Agricultural Bureau to districts and kebeles. Prepared questionnaires were discussed with experts, and engaged farmers and development agents. The assessment covered eight districts within the three zones such as Saesi-Tsadaemba, Hawzen, Kilte Awlaelo, Atsbi, Enderta, Hintalo-Wejerat, Enba-Alage, and Endamehoni Districts (Woreda).Two kebeles were chosen from each district for the study. The population for the study consisted of the household heads, especially men and women. A purpusive sampling technique had been adopted to select Zone, Wereda and kebeles. A total sample size of 386 farm households were drawn from a population of 11,595 potato-producing households, which represents 70% of the total 16,564-potato producer households identified in the Tigray (CSA report for 2016/17) by employing equation 3.1.

The distribution of the population size to each district had been obtained from the total potato producers in Tigray by using proportional sampling. The number of farmers (n) selected from the potato-producing farmers was calculated as sample size by using a simplified formula of Yamane (1967).

$$n = \frac{N}{1+N(e)^2} \qquad \text{Eq 3.1}$$

Where n = sample size, N = population size, and e = level of precision (0.05).

The interview was conducted randomly from a list of farmers who produce potato in the kebele. Focal group discussions was also carried in 16 kebeles comprising a diverse group of 8-10 members, including model farmers representing various demographics such as men, women, youth, and individuals at different administration responsibilities in the kebele.

3.3.3. Survey data collection procedures

The primary data was collected by using a structured questionnaire. During the preliminary survey, a list of relevant guidelines and questions had been used to guide the discussions with the focal groups. The main reason of pretesting was to identify any shortcomings and assist in making modifications in some questions before the actual data collection. The second stage was the basic data collection. These data included information of households on demographic characteristics, production experience, production and productivity, use of potato production inputs (improved varieties, recommended spacing, fertilizer, soil fertility management), opportunities, constraints and variability. The survey was carried through face-to-face interviews in individual households and focus group discussion (FGD) in each Kebelle.

Interviews conducted carried out in the local language Tigrigna. Open-ended questions added to investigate deeply for additional insights into the information collected. The focus group discussion had used to get more insight in certain topics and to check whether the group validates patterns found in the surveys. FGDs are very suitable to analyze a certain situation or problem in more detail and to identify and evaluate potential solutions to these problems. Specific topics discussed under my guidance. The observed data on what was happening in the field and general appearance of the area were noted in a notebook. Secondary data were obtained from CSA, Bureau of Regional Agriculture and Natural resources and Research reports and other documents from various offices of bureaus of agriculture at different levels. Family size categories and age group was grouped according to Jirčíková et al.(2013 and Butani(2006)

3.2.4. Data Analysis and Interpretation

Data analyzed using the Statistical Package for the Social Science (SPSS, version 20). The important descriptive statistical measures such as percentage, frequency, and mean used to summarize and categorize the research data. In addition, chi square test was used to assess the association between potato production variables. Potato production opportunities and constraints had been ranked by using index ranking based on the respondents' rankings of variables that was calculated using the formula adopted from Kosgey (2004) ranking technique. According this method, farmers were asked to specify the rank of all factors of potato production constraints and opportunity and the results of such ranking have been converted into index value with the help of the following formula:

Index = sum of the number respondents rank of the variable in each rank divided to the sum of all variables ranked in each rank that is the weighted sum formula as indicated in equation 3.2

$$Index = Sum\frac{\{(w * Nrank1^{st}) + (w - 1 * Nrank2^{nd}) + \cdots + (w - n * Nrankn^{th})\}}{over\ all\ sum\ (Sum1 + \cdots + Sumn)} \qquad Eq\ 3.2$$

The weighted sum formula allowed to assign greater importance to certain variables by giving them higher weights. In this method, *N* represents the number of respondents in each specified rank, while $w_1...wn$ denote the weights assigned to each variable (number of variables in the computation). The rankings provided by respondents for each variable are represented as $rank_1...rank\ n$, and $Sum_1...Sumn$ refers to the subtotal of each individual variable under computation. This technique is also applied to determine the major horticultural crops by calculating the (sum) of all individual variables. In the study, there are 8 variables, ranked from 1st to 8th, with N representing the number of responses. The Index is calculated as follows:

Numerator: Sum of weighted scores for an individual variable across all rankings:

- 8 × (Number of times the variable was ranked 1st, i.e., N_1)
- 7 × (N_2 for 2nd)
- 6 × (N_3 for 3rd)
- 5 × (N_4 for 4th)
- 4 × (N_5 for 5th)
- 3 × (N_6 for 6th)
- 2 × (N_7 for 7th)
- 1 × (N_8 for 8th).

Denominator: Total possible weighted sum across *all* variables (calculated the same way as the numerator but summed over all 8 variables).

3.3. Results and discussion

3.3.1. Demographic characteristics of households

The result revealed that the majority (87.3%) of respondents were male household heads, while the remaining (13.7%) were female household heads (Table 3. 1). This significant disparity suggests that farming is predominantly a male-led activity in these regions. However, without productivity data, we cannot conclude that male-headed households are more productive; we can only observe they are far more common.Similar results had been reported in previous studies by Muthoni et al. (2013), and Gebru et al. (2017), where a majority of farmers interviewed in Kenya and Welayta Zone, Ethiopia, were male. Additionally, in the study area, men typically handle land preparation, plowing, planting and harvesting while women are involved in cultivation, weeding, marketing of farm products, and purchasing food and non-food items for consumption, indicating women's involvement in potato production. Furthermore, the survey revealed that the majority of farmers (97.5%) were married, while a small percentage were unmarried (2%) and divorced (0.5%). Given the labor-intensive nature of potato crop farming, the involvement of multiple individuals is necessary, and this could be facilitated by the participation of the wife, husband, and children.

The data shows that the potato farming community is dominated by middle-aged household heads, with a significant majority (81.61%) falling in the 25-54 years age bracket (Table 3.1). The age group data implies that potato production is currently reliant on a stable, experienced, and physically capable core of middle-aged farmers. This result is consistent with global agricultural patterns. This profile indicates a current reliance on a stable and experienced core of middle-aged farmers, who are at the peak of their physical capacity and human capital accumulation (FAO, 2018; Benjamin & Kimhi, 2006). However, this distribution also underscores the common challenge of an aging agricultural workforce and the critical need for policies that facilitate generational renewal to ensure the long-term sustainability of potato production.

About 55.18% of interviewed farmers had family sizes >7, regardless of their active participation in the labor force. Whereas, 31.87 and 12.95% had family sizes ranging from 4-6 and 1-3, respectively (Table 3.1). In the same way, Simonyan and Obiakor (2012) reported that majority of the rural residents had family size of more than five. According to FGD, the labor available for work per household had influenced by family size and relies on the participation of household members in agricultural activities. As the number of household members' increases, tasks related to agriculture, including potato production, could be completed in short timedue to shared responsibilities.

Table 3.1. Demographic characteristic of the respondents

Variable	Zones			Total (Frequency)	Percent (%)
	East	South east	South		
Sex of HH head :-					
• Male	159	91	87	337	87.3
• Female	28	11	10	49	12.7
Total	187	102	97	386	--
Percent (%)	48.6	26.3	25.1	--	100
Age of HH head					
• 18-24	2	0	0	2	0.52
• 25-54	152	95	68	315	81.61
• 55-65	16	7	26	49	12.69
• >65	17	0	3	20	5.18
Total	187	102	97	386	
Family Size					
○ 1-3 (small)	37	12	1	50	12.95
○ 4-6 (medium)	60	27	36	123	31.87
○ >7 (large)	90	63	60	213	55.18
Total	187	102	97	386	100

Educational level of HH head					
▪ No education	65	25	33	123	31.9
▪ 1-5	62	34	27	123	31.9
▪ 6-8	39	23	23	85	22.0
▪ 9-10	17	9	6	32	8.3
▪ 11-12	1	7	0	8	2.1
▪ Diploma and above	3	4	8	15	3.9
Total	187	102	97	386	100

The amount of labor available for agricultural activities also determined by factors such as family size, age, and gender. This suggests that farmers with a higher labor equivalent are more likely to engage in agricultural and potato production activities, leading to increased income, regardless of having a large family size. Similar to the findings of this study, Simonyan and Obiakor (2012) observed that a large household size does not necessarily guarantee increased labor efficiency, as the family members may have different ages, sexes, and labor capacities. However, Okoye et al. (2008) and Udensi et al. (2011) reported that relatively larger household sizes are more likely to provide the necessary labor for farm operations, such as weed control and fertilizer application

About 31.9% of household heads lacked formal education, while the majority (68.10%) had received formal education at various levels ranging from Grade 1 to BSc. The very small proportion with education beyond 12th grade (3.9%) suggests that higher education is not common among farmers in this survey. This could imply a potential barrier to adopting new technologies or practices that might boost productivity and income.This proportion (68.1%) is notably higher than the national adult literacy rate of 46.7% (Doss, 2003). Education and training contribute to increased productivity among farmers and facilitate the adoption of new production technologies. Similar to this Kateta et al. (2015) reported that high literacy level, improved potato production practices of farmers through reading materials such as pamphlets, leaflets, and other aids. Additionally, literacy enables farmers to access reading materials such as pamphlets and leaflets, facilitating the dissemination of improved potato production practices. Fikadu and Gebre (2021) reported that farmers with higher levels of education and skills in farm organization tend to achieve better productivity. In addition, they reported that literacy levels positively affect the adoption of agricultural technologies.

Land scarcity is a significant constraint on agricultural production in Ethiopia, particularly in the study area. The average land holdings of farmers in the eastern and southeastern zones of

Tigray had found to be 0.83 to 1.54 hectares, respectively (Fig 3.2). When it came to potato production, farmers allocated 0.4 to 0.46 hectares of land for rainfed cultivation and 0.14 to 0.17 hectares for irrigation. These findings indicate that the majority of farmers in the region operate on smallholdings of less than 2 hectares, likely due to the prevailing land tenure system. Furthermore, there were variations in land size between zones, with farmers in the southeastern zone owning larger plots, averaging 1.54 hectares (Fig 3. 2). In contrast, those in the eastern zone owned less than one hectare and allocated smaller areas for potato cultivation, whether under irrigation or rainfed conditions. This discrepancy could attributed to water scarcity for irrigation and farmers prioritizing other crops with lower water requirements, such as barley and chickpea. In agreement to this result, Girma and Ayalew (2024) reported that Ethiopian farmers manage small plots of land, often less than 2 hectares, due to historical land tenure systems and population pressures. They also reported that smallholder farmers often operate below their potential due to limited land availability, which affects their efficiency and productivity. The allocation of land for potato cultivation was consistent with the study (Senbeta and Worku, 2023) who reported that farmers allocate limited resources like land based on water availability and market demand.

In most rural areas, a family receives a larger farm only if it has members who were old enough to claim land during the government's land distribution. This typically means members who were over the age of 18 at that time.This implies that large family size is not guarantee to have large land. In General, the present study implies that land size is one factor for potato production in the region either under irrigation or under rainfed condition. Therefore, it is important to introduce high yielding, disease and pest tolerance variety with appropriate agronomic practice to increase productivity in small land. In addition, there are mountain-terraced areas in the study areas as a potential, this could be important to allocate the mountain-terraced areas for youths to produce potato.

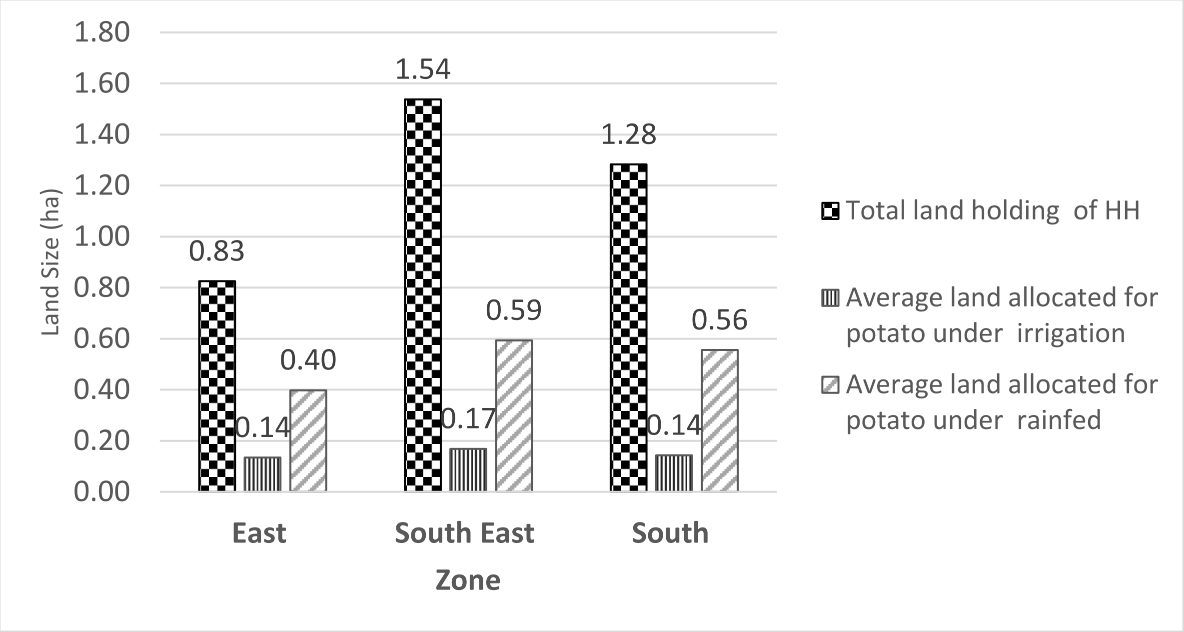


Figure 3.2. Land holding of the household

3.3.2. Potato production condition and practice

More than 80% of the farmers in each Zone grow potatoes under both rainfall and irrigation conditions. Specifically, 83.4% of the interviewed farmers cultivate potatoes using both irrigation and rainfall, while 14.5% rely solely on rainfed conditions and 2.1% solely on irrigation (Fig 3.3). About 81.7, 86.3 and 83.5% of the interviewed farmers in East, Southeast and South zone produce potato under both rainfed and irrigation condition, respectively and less than 10% of the interviewed farmers produce only under irrigation condition (Fig 3). This suggests that only a small number of farmers exclusively use irrigation for potato production. According to farmers' perception and focal group discussions, the agroecology of the study area is suitable for cultivating potatoes under both irrigation and rainfall conditions. The majority of farmers plant potatoes between May 15 and June 30 in rainfed conditions, although some wait until June 30 to July 15, depending on the onset or expected onset of rainfall. A few farmers plant potatoes on the start of rainfall. In the highlands, especially in the South zone, farmers plant potatoes earlier compared to farmers in the South East and East zone mid-highlands. Furthermore, most interviewed farmers' plant potatoes from December 15 to January 15 under irrigation conditions. Some farmers also plant potatoes between September and October when the land becomes flooded during the main season, and they supplement irrigation. Therefore, adjusting the planting time of potatoes to coincide with the low temperatures required for tuber formation is critical for potato production.

All interviewed farmers used the furrow irrigation method for irrigating potato crops. The exclusive use of furrow irrigation in a drought or water-stressed area is an alarming finding. It signifies that the agricultural sector in that region is operating with a high degree of vulnerability, wasting a scarce resource, and is unprepared for increasing water scarcity due to climate change. This result should be a catalyst for immediate action to promote and support the adoption of more efficient, water-saving irrigation technologies.The main sources of water in the study area were streams (through diversion and water pumps), dams, groundwater (shallow well/borehole), and ponds. Most farmers obtained their irrigation water from diversion, while a smaller percentage relied on dams and shallow well/boreholes. A few farmers in the eastern zone (2.14%) depended on rivers through water pumps. Some farmers (7.81%) used multiple water sources. To increase potato productivity, it is recommended improving streams, implementing water, and soil conservation measures. The predominant planting methods for potato among the farmers in the study area were flat and ridge planting. Ridge planting commonly practiced under both rain-fed and irrigation conditions, while some farmers used flat planting and later created ridges during cultivation during the rain. The spacing between potato plants ranged from 30 - 40 cm, while the spacing between rows varied from 50-75 cm. Focal group discussions revealed that the recommended spacing for potato was 30 cm between plants and 80 cm between rows in the study area. Therefore, it is important to provide training and advice to farmers on the significance of spacing and ridge creation.

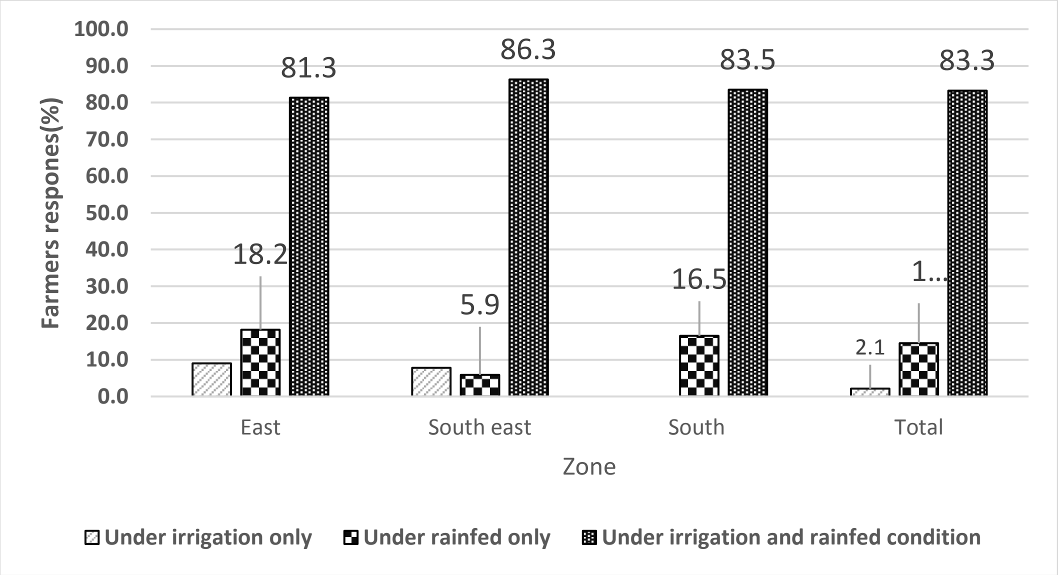


Figure 3.3. Farmers produce potato under irrigation and rain-fed condition in each zone

3.3.3. Potato production inputs and management practices in the study areas

Most farmers' response indicated that inorganic fertilizers, organic fertilizers, agro-chemicals and improved seed are the major inputs used to increase potato production in the study areas (Table 3.2). According to the focal group discussion on inputs for potato crop production, organic and inorganic fertilizers, chemicals and improved seed had a significant effect on potato production. Table 2 indicates that 98.9, 100 and 97.94 % of the interviewed farmers in East, Southeast and South Zone used inorganic fertilizer for potato production. According the chi-square (χ2) result, there is no statistically significant difference in the use of inorganic fertilizer among the zones. The variation in the use of inorganic fertilizer across the zones is not statistically significant, indicating that the differences in usage are likely due to random variation rather than a systematic difference between the zones. 82.1% of the farmers in the study areas used organic fertilizer for potato production. There is a statistically significant difference in the use of organic fertilizers across the zones. This suggests that different zones may have varying practices or preferences regarding organic fertilizer application. This study is in agreement with the findings of Gebru et al. (2017) who reported that most of farmers (88.5%) in Wolaita zone, southern Ethiopia used fertilizers for potato production. In addition, Nyamwamu et al. (2014) in Kenya who reported that farmers using recommended types of fertilizers were 96 % and farmers using recommended fertilizer rates were 58 % for potato production.

Table 3.2. Assesment of used for Potato production by the farmers in the study areas (%)

Potato production inputs	Zones				
	East	South east	South	Total	χ^2
Inorganic fertilizer	98.93	100.0	97.94	98.96	2.06^{ns}
Organic fertilizer	82.35	74.5	89.69	82.12	7.82*
Improved tuber seed	48.66	18.6	42.27	39.12	25.54***
Agro-Chemicals	67.91	78.4	35.05	62.44	44.54***
χ^2		79.96***			

Source: Compiled by the author

Note: χ^2 is Chi-Square, ns is Not significant association between categorical variables at 5% probability level (P > 0.05) * is a significant association between categorical variables at 5% probability level (P ≤ 0.05), ** is highly significant association between categorical variables at $0.01 \leq P > 0.001$ and highly significant association between categorical variables (***) $P \leq 0.001$.

About 48.7%, 18.6%, and 42.3% of the interviewed farmers in the East, Southeast, and South zones, respectively, used improved potato seed varities. This indicates that most farmers in all zones, especially in the Southeast, did not use improved tuber seed in potato production. Additionally, there is a highly significant difference in the use of improved seeds among the zones, suggesting that the availability and adoption of improved seeds vary greatly by zones. In the Eastern and Southern zones, there are some seed tuber multiplier cooperatives and individuals. The use of improved tuber seeds shows a highly significant difference across the zones. This significant difference in seed use acts as a diagnostic tool, revealing that zonal gaps are not random but stem from a complex mix of market, agro-ecological, and socio-economic barriers. This indicates that some zones may be more effective or willing to use improved seeds than others may, which could affect overall potato production. Regarding the agro-chemicals, there is a highly significant difference in the use of agro-chemicals across the zones, indicating that some zones rely more heavily on these inputs than others. Ridomil and Mancozeb were the common chemicals used by the farmers in all the study areas. Moreover, over 60% of farmers used chemicals to protect their potato crops from diseases and pests (Table 3.2). There is a highly significant difference in the use of agro-chemicals among the zones. This discrepancy could reflect varying agricultural practices, pest pressures, or economic factors influencing the use of these chemicals. Gebru et al. (2017) reported that 43.05% of the respondents applied chemicals (Ridomil and Mancozeb) to control late blight in potato farm. The overall chi-square indicates that the inputs for potato production differ significantly across the zones. This suggests that factors such as geography, local agricultural practice, and farmer preferences affect how inputs are utilized in potato production.

In general, the data suggest that while the use of inorganic fertilizers is consistent across zones, organic fertilizers, improved seeds, and agro-chemicals show significant variation. This could be due to local agricultural practices, preferences, or availability of resources. The highly significant differences in improved seeds and agro-chemicals confirm that these Zonal differences are not due to random chance but reflect real, systematic disparities.

3.3.3.1. Potato varieties in the study areas

The majority of farmers interviewed, commonly used cultivar Shashemene (72.28%), which is introduced from Shashemene, Oromia Region, Ethiopia, followed by local (55.70%). Gudanie (36%) and Belete (20.5%) have moderate usage, while Jaleni (8.8 %) and Gera (5.96%) is the least used. The Chi-square values indicate the statistical significance of the differences in variety usage across Zones (Table 3.3). All varieties show a highly significant difference (indicated by ***), meaning the distribution of potato varieties used is not uniform across the Zones. The highest number of farmers in Southeast and East Zone used Shashemene.\, is notably favored, especially in the East and South East. This is related to lack of access to improved varieties seeds in the study areas. Farmers selected and used the Shashemene cultivar based on criteria such as high yield, market demand, early maturity, low seed cost, access to seeds in the market, but its drawback is susceptibility to diseases and pests which was not consider by farmers. On the other hand, the criteria for selecting and using improved varieties were high yield, quality, market demand, and tolerance to water stress, disease and pest resistance. However, the drawbacks of improved varieties were limited access to seed tubers and high seed costs, which led to a majority of farmers not using them. Gudanie also has strong usage, particularly in the East, but shows less preference in the South East. Belete and Jalene used less frequently, indicating they may not be as popular or well adapted in these regions. Gera is rarely used, which could suggest poor performance or lack of awareness among farmers. The significant Chi-square values reveal that the choice of potato variety is influenced by Zonal factors, emphasizing the need for targeted agricultural strategies that consider local preferences and conditions. In other studies (Gebru et al., 2017) reported that Gudanie (32.2%) and Jalene (31.0%) were cultivated more by smallholder farmers in Welayta Zone, Ethiopia.

Table 3.3. Potato varieties used by the farmers (%) in the study areas

Potato varieties and cultvaries	East	South east	South	Total	χ^2
Gudanie	47.06	16.67	35.05	36.01	26.508***
Belete	24.60	4.90	28.87	20.47	21.346***
Jalene	14.97	0.00	6.19	8.81	19.531***
Gera	12.30	0.00	0.00	5.96	26.027***
Shashemene	73.26	92.16	49.48	72.28	45.360***
Local	59.89	31.37	73.20	55.70	39.799**
χ^2	169 .943***				

Source: Compiled by the author

Note: χ^2 is Chi-Square, ns is not significant association between categorical variables at 5% probability level ($P > 0.05$) * is a significant association between categorical variables at 5% probability level ($P \leq 0.05$), ** is highly significant association between categorical variables at $0.01 \leq P > 0.001$ and highly significant association between categorical variables (***) $P \leq 0.001$,

The data suggests a clear Zonal preference for specific potato varieties, primarily influenced by factors such as suitability to the environment, farmer experience, and market dynamics. This information is crucial for agricultural development programs focusing on improving potato cultivation and ensuring food security.The overall chi-square indicates that the varieties or cultivars used for potato production differ significantly across the zones. This suggests that factors such as seed availability, market, cost of seed, and farmer preferences affect the variety /cultivar used for potato production

3.3.3.2. Seed source of potato

Local market, farmers' seed multiplier associations, non-governmental organizations (NGOs), and research centers are the main sources of seed potatoes in the study areas (Table 3.4). The local market is the predominant source across all zones, with a perfect response rate in the Southeast and South. A high chi-square value indicates a significant association between the source and the zones, as 100% of interviewed farmers in the Southeast and South zones obtained their seed from the local market. In the East zone, 87.7% of farmers relied on the local market, while 30.6% obtained their seeds from farmers' seed multiplier associations. The latter source is less utilized, particularly in the Southeast zone, where no respondents reported using it; however, 33.7% of farmers in the East zone did use it. NGOs have moderate usage, especially in the Southeast, with significant differences among zones, albeit less pronounced than the previous sources. Research centers were minimally utilized, with no responses from the Southeast or South zones, indicating that this source is not favored in these areas (Table 4). In general, the majority of farmers in the study area acquired their seed potatoes from the local market, while small amount of farmers received them as gifts from NGOs. A small portion of farmers obtained their seed from research centers, particularly in the East zone's Atsbi district, where a seed multiplier association exists. Research institutions played a minor role, representing only 8.6% as a source of potato seed (min-tuber). Farmers primarily purchased seed potatoes with cash from the local market and seed multipliers, whereas NGOs and research institutes provided seed potatoes as gifts. Most respondents purchase potato seed every year instead of keeping seed from their harvest. Some farmers interviewed, however, do keep their potato seed from their harvest and use it for 2nd and 3rd seasons, renewing their seed every two to three years. Farmers perceive that changing the soil texture for potato crops, such as planting potatoes in different types of soil each year; can also renew the potato seed tuber.

Table 3.4. Seed source of potato

Source of potato seed tuber	Zone						
	East		South east		South		
	N	%	N	%	N	%	χ^2
Local market	164	87.7	102	100	97	100	26.027***
Potato seed tuber multiplier	63	33.7	0.0	0.0	8.0	8.2	58.791***
Non-government organization	20	10.7	28	27.5	20	20.6	13.572**
Research centers	16	8.6	0.0	0.0	0.0	0.0	16.977***
χ^2	116.153***						

Source: Compiled by the author

Note: χ^2 is chi-square, N is number of respondents, % is respondents in percent, ns is not significant association between categorical variables at 5% probability level ($P > 0.05$), * is a significant association between categorical variables at 5% probability level ($P \leq 0.05$), ** is highly significant association between categorical variables at probability $0.01 \leq P > 0.001$ and *** is highly significant association between categorical variables at $P \leq 0.001$,

The data indicates substantial variation in the sources of potato seed tubers across different zones. The local market is the most common source, particularly in the South East and South zones. There is a marked preference sources in specific zones of the regions, highlighting the importance of geographical context in agricultural practices. The high chi-square values across categories suggest that interventions or policies could tailored based on these regional preferences. This implies that the crtical problems related to access and affordability ,creating awareness on avalable that ensure increased production and profitblity. This study reveals that most farmers in the area do not have access to clean and healthy improved seed in local market, which negatively affects potato crop production and productivity. The study recommends that research centers, seed producer associations, agro-industrial organizations, and other non-governmental organizations collaborate to improve the production of quality seed tubers. This result is supported by the result (Forbes et al., 2020) they reported that in many low-income countries, farmers often rely on informal seed systems, which include local markets and farmer-to-farmer exchanges. These informal systems are crucial for providing access to planting material, especially in regions where formal seed systems are underdeveloped or inaccessible. In addition, they indicated that in some areas, farmers might prefer local markets due to familiarity and immediate access, despite the potential benefits of organized seed multiplication. Furthermore, Forbes et al.,(2020) reported that in many agricultural systems where formal research does not adequately address the realities faced by smallholder farmers. These informal networks become the primary, and often only, source of viable and context-appropriate planting material.

3.3.3.3. Inorganic and organic fertilizer use and management in the study areas

Farmers use chemical fertilizer, such as NPS and Urea, along with animal manure and compost to improve soil fertility and increase crop production. The use of manure and compost had found to enhance crop productivity in the study areas. The majority of farmers in all zones use this combination Urea and NPS, with the highest usage in the East (94.7%) and Southeast (91.2%). This suggests that farmers prefer combining these fertilizers for better yield. A small percentage of farmers do not use inorganic fertilizers, notably higher in the South (4.2%). The Chi-square statistic (105.549, $p < 0.01$) indicates a significant association between the type of inorganic fertilizer used and the zone, suggesting that the choice of inorganic fertilizer varies significantly by zone (Table 3.5). According to the discussions with farmers and interviews conducted; both inorganic and organic fertilizers have a significant impact on improving potato crop production. Most farmers interviewed use both types of fertilizers, some are unable to afford inorganic fertilizer due to financial constraints. Additionally, a few farmers do not use organic fertilizer because they have a limited number of animals and lack the necessary materials to make compost. Although farmers in the three zones apply similar rates of inorganic fertilizers, they have different soil types and fertility levels.

Table 3.5. Type of Inorganic and organic fertilizer used by the farmers in each Zone (%)

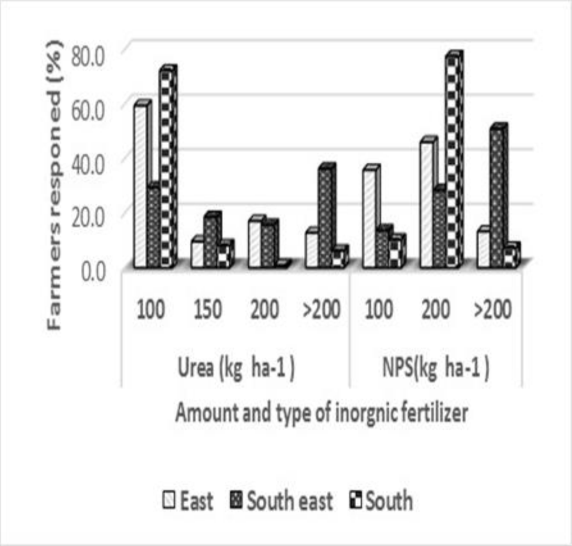
Fertilizer		Zone		
		East	South east	South
inorganic	Urea only	3.73	7.8	1.0
	NPS only	0.54	1.0	22.9
	Both urea and NPS	94.7	91.2	71.9
	Not used inorganic	1.1	0.0	4.2

χ^2		105.549**		
Organic	Manure only	43.0	63.7	78.4
	Compost only	4.8	2.9	1.0
	Both compost &manure	32.8	7.8	8.2
	Not used	19.9	25.5	12.4
χ^2		80.068***		

Source: Compiled by the author

Note: χ^2 is Chi-square, ** is highly significant association between categorical variables at probability level $0.01 \leq P > 0.001$ *** is highly significant association between categorical variables at probability level ($P \leq 0.001$)

Most interviewed farmers in in East and South zones apply (100 kg ha^{-1}) uUrea and 200 kg ha^{-1}of NPS for potato production, while in South east 36.3 and 50.9% of the interviewed farmers apply >200 kg ha^{-1} Urea and NPS, respectively. Conversely, some farmers exceed the recommendation by applying higher amounts Urea greater than 165 kg ha^{-1} and 200 kg ha^{-1} NPS. Regarding NPS, a majority of respondents (200 kg ha^{-1}) follow the recommended regional and national dosage for potato production. However, a significant portion applies a lower amount NPS kg ha^{-1}, and only a few farmers exceed the recommended dosage (Fig 3.4). According to FGD, all farmers apply a full NPS rate and half Urea rate at planting, with the remaining Urea applied at early flowering. Most farmers use the drill application method at planting, while a smaller percentage employ spot application. Some farmers also use spot and broadcast methods for applying inorganic fertilizers. These findings suggest that farmers possess awareness of the importance of fertilizers, but economic constraints limit their usage among some individuals



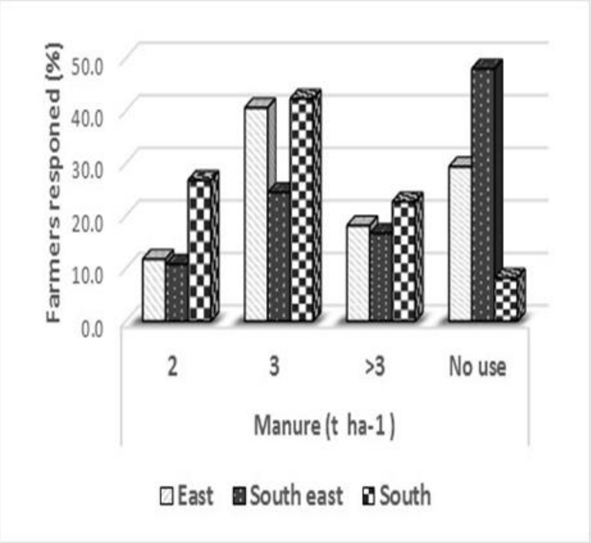


Figure 3.4. Amount and type of inorganic and organic fertilizers

Farmers in the study area utilize both inorganic and organic fertilizers, including manure and compost, for their potato farms. Among the farmers surveyed, most of them apply manure only while small percentage of farmers apply or use both manure and compost and compost alone (Table 3.5). The Chi-square statistic (80.068, $p < 0.001$) indicates a significant association between the type of organic fertilizer used and the zone, highlighting regional differences in organic fertilizer practices. In general both inorganic and organic fertilizer usage varies significantly by zone, with distinct preferences observed. Farmers in the East and Southeast predominantly use both Urea and NPS, while manure is the favored organic option, especially in the South. These findings can inform targeted agricultural intrventions and support programs to enhance fertilizer use efficiency in the respective zones. Similar to this result Gebru et al. (2017) reported that most farmers in Welayta Zone use fertilizer for potato production and most of the respondents were aware on the method and time of application. Furthermore, Nyamwamu et al.(2014) reported that most farmers using recommended fertilizer type for potato production. The resulting implication is a powerful call for targeted, location-specific, and integrated agricultural policies that respect and build upon existing farmer knowledge and practices.

The quantity of manure applied to potato fields varies greatly, ranging from 2 to 3 t ha^{-1} depending on factors such as the availability of resources like animals and the distance of the farm from home. The majority of farmers apply manure at a rate of 2-3 t ha^{-1} 40.6, 24.5 and 42.3 % of the interviewed persons in East, Southeast and South zone, respectively apply 3 t ha^{-1} of manure for potato production (Fig 3.4). Small percentage of the farmers apply greater than 3 qt ha^{-1}. According to the farmers, response there was no difference in the amount of manure and compost applied to potato field. In agreement to this, Gebru et al.(2017) reported that farmers in Welayta Zone, Ethiopia apply 2.1 t ha^{-1} compost to potato farm but small amount farmyard manure of 1.1 t ha^{-1}. In addition, Negasi et al (2013) reported that farmers in the central rift valley of Ethiopia applied 1.71 and 1.56 t ha^{-1} of FYM and compost, respectively, to their onion farms. In general, most farmers use inorganic and manure fertilizers, which contribute to increased potato yield and quality, as well as the improvement of soil organic carbon levels. However, the majority of farmers do not utilize compost fertilizer. Therefore, further research is necessary to determine the optimal rates, types, and timing of organic fertilizer application to fully maximize potato productivity.

3.3.4. Potato productivity in the study areas

Timely harvesting and careful handling are crucial for the perishable potato crop. In this study, most potato varieties reached maturity between 90 and 120 days after planting, regardless of the season. Under rainfall conditions, tuber yields ranged from 12.4 to 14.6 t ha^{-1} in the South zone and the Eastern zone, respectively, and from 12.6 to 15.0 t ha^{-1} in the South zone and the Eastern zone, respectively (Fig 3.5). The average yield of potato under irrigation was 13.9 t ha^{-1}, while under rainfall conditions it was 13.4 t ha^{-1}. The highest average tuber yields of 15.0 t ha^{-1} and 14.6 t ha^{-1} were recorded in the East zone under irrigation and rainfed conditions, respectively. The lowest yields were observed in the South zone, with average tuber yields of 12.4 t ha^{-1} and 12.6 t ha^{-1} under rainfed and irrigation conditions, respectively (Fig 3.5). The narrow yield gap does not mean irrigation is unimportant. Instead, it reveals that for the season studied, may be the natural rainfall was sufficient to bring rain-fed yields close to the potential currently limited by other factors.Farmers achieved higher average yields under irrigation due to sufficient water, fewer disease and pest issues, and better management practices.

In agreement to this, Gebru et al.(2017) reported that the majority of the farmers obtained 11.5 to 17.2 t ha^{-1} yield of potato in Welayta Zone, South Ethiopia. Furthermore, Bezabih and Mengistu (2011) reported that yield of 14.2 t ha^{-1} in Southern Nations, Nationalities and People Region, but lower yield of 9.3 t ha^{-1} in Tigray Regions of Ethiopia. In another study conducted in southern Ethiopia, Mitiku et al.(2015) reported average tuber yields of 16.6 t ha^{-1}.

.

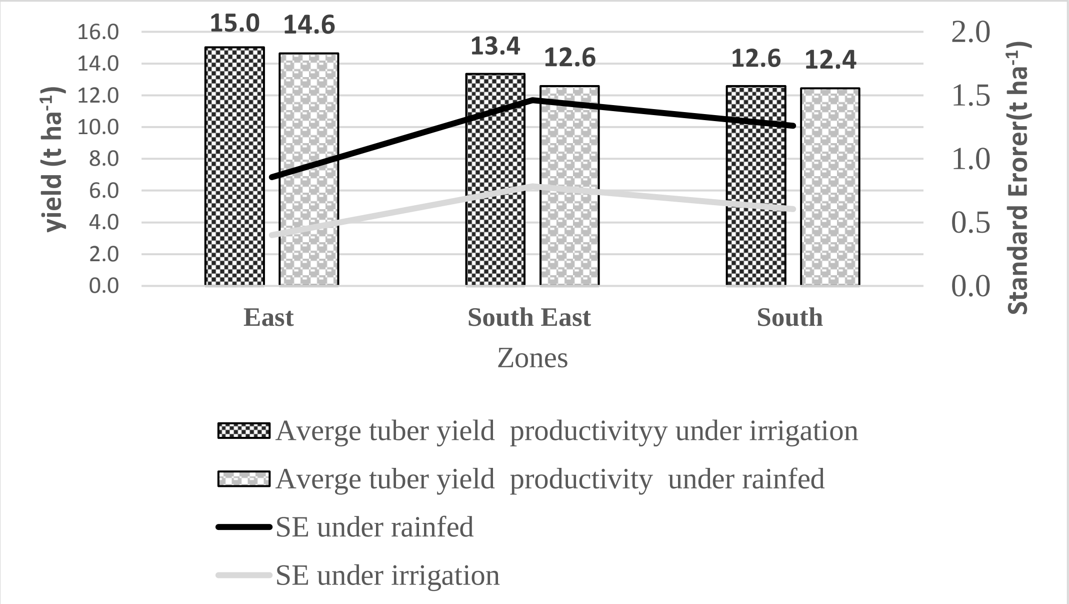


Figure 3.5 Average productivity of potato in the study areas under rain-fed and irrigation condition

According to a survey, farmers agree that there is variability in potato production. Factors contributing to this variability include management practices, input quantities and types, soil fertility, access to water and improved seed, knowledge, and income. To enhance productivity among all farmers, the study suggests promoting experience sharing on potato crop management and protection measures, improving technical knowledge and skills through training on agronomic practices, water and fertilizer management, and providing effective extension services to increase potato yield.

3.3.5. Potato production opportunities in the study area

The study findings highlight key opportunities for potato production in the study areas (Table 3.6). These opportunities include suitable agro-ecology, good soil type, access to irrigation and labor, availability of improved seed, rainfall, access to local markets, and transportation. The most commonly mentioned opportunities by farmers is related to suitable agro-ecology, good soil type, access to irrigation water, and labor across all study areas. However, certain opportunities, such as access to improved seeds, market and transport and rainfall are ranked lower and may pose challenges for potato production. It is important to note that opportunities identified by farmers in one area may not necessarily apply to other areas within the same zone. For example, an available improved variety may be an opportunity in one Wereda but a constraint in another. Overall, the analysis indicates that suitable agro ecology, good soil type and access to irrigation are the most significant factors for enhancing potato production in the semi-arid regions of Tigray. While access to improved seeds, market, and transport are less favorable, improving these issues could potentially enhance overall production opportunities. Addressing these key factors can facilitate better agricultural practices and increase potato yields in the region. Furthermore, developing and promoting potato production will require research and development on improved varieties adapted to different stresses and enhanced management practices. Similar to this study, previous research has shown that certain regions in Ethiopia, such as west and southwest Shewa zones of Oromia, have favorable conditions for potato production, including suitable agro-ecology, soil types, water sources, and fertile lands (Alemayehu , 2016). Ethiopia also has opportunities for various vegetable commodities due to favorable climate, proximity to markets, government policies, and cheap labor, as reported by Hunde (2017. In summary, identifying and capitalizing on the specific opportunities in each region, such as agro-ecology, soil quality, and access to resources, will play a crucial role in advancing potato production and productivity in Ethiopia.

Table 3.6. Potato production opportunities in Semi-Arid Areas of Tigray

List of production opportunities	East Zone			South east Zone			South Zone			Over all in the study area		
	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank
Suitable agro ecology	1478	0.220	1	802	0.217	1	772	0.221	1	3052	0.219	1
Good soil type	1303	0.194	2	728	0.197	2	683	0.195	2	2714	0.195	2
Availability to improved seed	633	0.094	6	236	0.064	7	166	0.047	8	1035	0.074	7
Access to irrigation	981	0.146	3	561	0.152	3	564	0.161	3	2106	0.151	3
Enough rainfall	820	0.122	4	419	0.114	5	417	0.119	4	1656	0.119	5
Access to labour	749	0.111	5	467	0.127	4	462	0.132	5	1678	0.121	4
Access to market	511	0.076	7	300	0.081	6	257	0.073	6	1068	0.077	6
Access to transport	256	0.038	8	178	0.048	8	176	0.050	7	610	0.044	8

Source: Compiled by the author

3.3.6. Production constraints in the study area

Potato production faces numerous constraints, including biotic and abiotic factors as well as institutional issues. In the study area, all farmers (100%) identified drought, disease, pests, lack of improved seed varieties, market challenges, soil fertility, frost, input availability, and lack of extension services (training, advice and access to credit) as major constrains in producing potato production despite their rank difference (Table 3. 7). Regardless of the high merits of potato to farmers, their production has been constrained by a numerous factors. According to the index ranking among the different production constraints the farmers identified diseases and pest, water stress (drought), lack of improved variety seed tuber and market as the most important (1st–4th rank) constraints for the production of potato in the study areas in general and in eastern zone in particular (Table 3.7)

Farmers in the South and East Zone face disease and pests, water stress, improved variety, and market as their main challenges. In the South East Zone, the major constraints are disease and pest, improved variety, water stress, and market. This indicates that the primary issues in one area may not be the same in another, requiring location-specific solutions. However, regardless of location, disease and pest, water stress (drought), improved variety seed, and market consistently emerged as the four major constraints across all districts and zones. The study highlights that diseases and pests, water stress, and insufficient quality seed tubers hinder potato production in semi-arid areas of Tigray. Some farmers also struggle with water scarcity during dry seasons, leading to reduced potato production. The analysis indicates that disease and pests, along with water stress, are critical challenges facing potato production in Tigray. Addressing these issues may significantly improve agricultural productivity in the region. To address these challenges, there is a need to strengthen the research-extension linkage and develop improved varieties and management practices that can withstand various stresses affecting potato production. In general, the study highlights the constraints faced by potato farmers, the ranking of these constraints, the location-specific nature of the challenges, the common constraints across different areas, and the need for tailored solutions and recommendations to improve potato production. Gebru et al.(2017) identified key constraints in potato production in Welayta Zone, south Ethiopia, including diseases, storage problems, low market prices, and insufficient seed tubers. Another study by Emana B. and Gebremedhin H.(2007) highlighted major constraints in horticulture production in Ethiopia, such as pests, drought, limited seed variety, high fuel prices for irrigation, and fertilizer limitations. Muzari et al .(2012) attributed the low national mean yield of potatoes to various factors, including low adoption of improved agricultural technologies, drought, and lack of improved varieties, poor cultural practices, diseases, and environmental degradation. Insufficient or irregular rainfall and limited irrigation water also led to moisture stress and reduced yields. Alemayehu (2016) reported that major challenges in fruit and vegetable production in West and Southwest Shewa Zones of Oromia Region, Ethiopia included the unavailability of improved varieties, price fluctuations, and diseases and pests.

Table3.7. Potato production constraints in Semi -Arid Areas of Tigray

List of production constraints	East Zone			South east Zone			South Zone			Over all in the study area		
	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank
lack of improved seed	1068	0.159	3	700	0.194	2	576	0.166	3	2344	0.170	3
Disease and pest	1380	0.206	1	704	0.195	1	696	0.200	1	2780	0.202	1
Market	998	0.149	4	538	0.149	4	550	0.158	4	2086	0.151	4
Water stress	1290	0.192	2	558	0.155	3	582	0.168	2	2430	0.176	2
Frost	710	0.106	5	420	0.116	5	438	0.126	5	1568	0.114	5
Input (other than seed)	703	0.105	6	383	0.106	6	340	0.098	6	1426	0.103	6
Poor soil fertility	302	0.045	7	165	0.046	7	179	0.052	7	646	0.047	7
lack of extension service	259	0.039	8	141	0.039	8	112	0.032	8	512	0.037	8

Source: Compiled by the author

3.4. Conclusions and recommendations

The assessment confirms that potato is the main horticultural crop in the study areas, serving as cash, food, and seed purposes under both irrigation and rainfall conditions. All farmers in the study have experience with potato production. In Tigray, potatoes had typically planted between Dec 15 and Jan 15, as well as May 15 and Jun 30, under irrigation and rainfall conditions, respectively. Most farmers use both inorganic and organic fertilizers for potato production, regardless of the amount and application method. The average land holdings allocated for potato was 0.83 to 1.54 ha, which is very small. The average tuber yield under irrigation ranges from 15.0 to 12.6 t ha^{-1}, while it ranges from 14.6 to 12.4 t ha^{-1} under rainfall condition. The study findings reveal that the availability of suitable agroecology, good soil type, access to irrigation water, and labor as the major opportunities for potato production in eastern, southeastern, and southern zones of Tigray. However, farmers face several challenges, including diseases and pests, lack of improved varieties, drought, and limited access to markets (low crop prices at harvest but high seed tuber prices at planting) in the semi-arid areas of Tigray, Northern Ethiopia. Moreover, the amount, type, and timing of fertilizer application, land size and fertility, access to improved varieties seed, and water availability (irrigation and rainfall) are the key factors influencing potato production and productivity variability among farmers in the study areas.

The agricultural bureau and research centers should support farmer-based seed tuber production in the region. Cooperation with nearby stakeholders such as higher education institutions and research centers is important for area-specific fertilizer use programs and appropriate land-use systems. This will help maintain soil fertility and ensure the availability of clean seed. Training should be provided to farmers and development agents to improve their technical knowledge and skills in potato crop production, disease and pest protection measures, and agronomic practices. Collaboration between the International Potato Center (CIP), research centers, seed producer associations, agro-industrial organizations, and non-governmental organizations focusing on quality seed production and overall potato productivity in Tigray, Ethiopia is recommended.

3.5. References

Alemayehu, H.W. 2016. Assessment of Horticultural Crops (Vegetables, Tubers & Fruits) Production Constraints and Opportunities in West and Southwest Shewa Zones of Oromia Region, Ethiopia. International Journal of Agricultural Economics, 1(3): 84-90.

Amare, T., Bazie, Z., Alemu, E., Alemayehu, B., Tenagne, A., Kerebh, B., Taye, Y., Awoke, A., Feyisa, T., and Kidanu, S. 2022. Yield of potato (Solanum tuberosum L.) increased by more than two-folds through nitrogen and phosphorus fertilizers in the highlands of North-Western Ethiopia .Heliyon 8(10): e10941

Araya, A., Keesstra, S.D., and Stroosnijder, L. 2010. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia. Agricultural and Forest Meteorology, 151: 1047–1064.

Basha, K., Peter, N.E., and Eric, N.O. 2017. Factors Affecting Productivity of Smallholder Potato Growers in Bore District, Guji Zone, Oromia Regional State, Ethiopia. Developing Country Studies, 7(9): 18-26 .

Benjamin, C., and Kimhi, A. 2006. Farm Work, Off-Farm Work, and Hired Farm Labor: Estimating a Discrete-Choice Model of French Farm Couples' Labor Decisions. European Review of Agricultural Economics.

Bezabih, E., and Mengistu, N. 2011. Potato Value Chain Analysis and Development in Ethiopia: Case of Tigray and SNNP Regions. International Potato Center (CIP-Ethiopia), Addis Ababa, Ethiopia.

Brasesco, F., Asgedom, D., and Casari, G. 2019. Strategic analysis and intervention plan for fresh and industrial tomato in the Agro-Commodities Procurement Zone of the pilot Integrated Agro-Industrial Park in Central Eastern Oromia, Ethiopia. Food and Agriculture Organization of the United Nations (FAO).

Butani, S.J. 2006. Business employment dynamics: tabulations by employer size. *Monthly Lab. Rev.*, *129*, 3.

Camire, M.E., Kubow, S. and Donnelly, D.J. 2009. Potatoes and human health. Critical Rev Food Sci Nutr, 49:82340.

Chen, P. 2023. Increasing potato productivity and nutrition to improve smallholder farmer's food security. Global Journal of Plant breeding and Genetics, 9(3): 10.

CSA (Central Statistical Agency). 2017. The Federal Democratic Republic of Ethiopia. Agricultural Sample Survey 2016/17 (2009 E.C.) Volume I Report on Area and

Production of Major Crops (Private Peasant Holdings, Meher Season). Pp.18-20 .Addis Abeba, Ethiopia.

Daccache, A., Weatherhead, E.K., Stalham, M.A. and Knox, J.W. 2011, Impacts of Climate Change on Irrigated Potato Production in a Humid Climate. Agric. For. Meteorol, 151: 1641–1653.

Dhami, J., Roy, S., Nain, A.S. and Panwar, R. 2012.Suitability analysis of apple and pear using remote sensing and GIS in Uttarakhand. Journal of Agrometeorology, 464– 474.

Emana, B. and Gebremedhin, H. 2007. Constraints and opportunities of horticulture production and marketing in eastern Ethiopia. Dry land coordination group (DCG) *report*, (46). http://www.drylands-group.org

FAO (Food and Agriculture Organization of United Nations). 2010. Strengthening potato value chains: Technical and policy options for developing countries. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2018. The Future of Food and Agriculture – Alternative Pathways to 2050. Rome.

Fikadu, A.A. and Gebre, G.G. 2021. Evidence from Fogera district in Ethiopia on configuration of farmer's information literacy conditions that explain better productivity performance of the horticultural crops. *Agriculture & Food Security, 10*:1-13.

Forbes, G.A., Charkowski, A., Andrade-Piedra, J., Parker, M.L. and Schulte-Geldermann, E. 2020. Potato Seed Systems. In: The potato crop: Its agricultural, nutritional and social contribution to humankind, (pp. 431-447). Cham: Springer International Publishing.

Gebrehiwot, T. A. and van der Veen. 2013. Assessing the evidence of climate variability in the northern part of Ethiopia. Journal of Development and Agricultural Economics, 5(3): 104-119.

Gebre, E. and Schulz, S. 2021. Economic and Environmental Analysis of Potato Production in Tigray, Ethiopia. Journal of Agriculture and Rural Development in the Tropics and Subtropics

Gebru, H., Mohammed, A., Dechassa, N. and Belew, D. 2017. Assessment of production practices of smallholder potato (Solanum tuberosum L.) farmers in Wolaita zone, southern Ethiopia. *Agriculture & Food Security*, *6*: 1-11.

Girma Asefa, Y. and Ayalew Muluken, A. 2024. Land size and efficiency in agriculture: the case of Ethiopian smallholder farmers. A meta-analysis. *Frontiers in Sustainable Food Systems*, *8*: 1447186.

Grewal, J., Sharma, R. and Saini, S. 1992. Agrotechniques for intensive potato cultivation in India. Tms bulletin on the agro techniques tor intensive potato cultivation in ‘India. Indian Council of Agricultural Research. New Delhi, India, 132.

Hailu, G., Ali M., Nigussie, D. and Derbew, B. 2017. Assessment of production practices of smallholder potato (Solanum tuberosum L.)Farmers in Wolaita zone, southern Ethiopia. Agriculture & Food Security, 6:31

Handayani, T., Gilani, S.A. and Watanabe, K.N. 2019.Climatic Changes and Potatoes: How Can We Cope with the Abiotic Stresses? Breed Sci, 69: 545.

Hunde, N.F., 2017. Opportunity, Problems and Production Status of Vegetables in Ethiopia: A Review. J Plant Sci Res, 4(2): 172.

Integrated Food Security Phase Classification (IPC). 2022. Acute Food Insecurity Analysis: Tigray Region.

Jirčíková, E., Pavelková, D., Bialic-Davendra, M. and Homolka, L. 2013. The age of clusters and its influence on their activity preferences. *Technological and Economic Development of Economy*, *19*(4): .621-637.

Kateta, S.Y., Kabambe, V., Lowole, M.W. and Nalivata, P.C. 2015. Production practices of potato (Solanum tuberosum L.) by farmers in Mzimba District, Northern Malawi. Afr J Agric Res, 10:797–802.

Kennedy, G., Raneri, J. E., Stoian, D., Attwood, S., Burgos, G., Ceballos, H., Ekesa, B., Johnson, V., Low, J. W., and Talsma, E. F. 2019. Roots, tubers and bananas: Contributions to food security. In Encyclopedia of Food Security and Sustainability, 231–256.

Kosgey, I.S., Van Arendonk, J.A. and Baker, R.L. 2004. Economic values for traits in breeding objectives for sheep in the tropics: impact of tangible and intangible benefits. Livestock Production Science, 88(1-2):143-160.

Lutaladio, N. and Castaldi, L. 2009. Potato: The hidden treasure. Journal of food composition and analysis, 22(6): 491-493.

Maqsood, J., Farooque, A.A., Wang, X., Abbas, F., Acharya, B. and Afzaal, H. 2020. Contribution of Climate Extremes to Variation in Potato Tuber Yield in Prince Edward Island. Sustainability, 12(12): 4937.

Mekelle University & Regional Bureau of Agriculture. 2022. Rapid Assessment of Agricultural Damage in Tigray. (Various internal and shared reports).

Merga, B., and Haji, J.2019.Factores impeding effective crop production in Ethiopia .J.Agric.sci, 11(10): 1-14.

Meresa, E., Hadgu, F., G/yowhans, S., G/medhin, T., and Abebe, N. 2024. Identification of Potentials, Constraints and Possible Intervention Areas to Improve Agricultural and Natural Resources Productivity at Illala Sub-watershed, Tigray, Ethiopia. Asian Journal of Research and Review in Agriculture, 6(1): 185–198.

Mitiku, M., Shiferaw, W. and Tadesse, A. 2015. Adaptability study of improved Irish potato (*Solanum tuberosum L.*) varieties at South Ari Wereda, Ethiopia. Am Sci Res J Eng Technol Sci, 7:26-30.

Muthoni, J.J., Shimelis, H., and Melis, R. 2013.Potato production in Kenya: farming systems and production constraints. J Agric Sci, 5(5):182–97.

Muzari, W., Gatsi, W., and Muvhunzi, S. 2012. The impacts of technology adoption on smallholder agricultural productivity in sub-Saharan Africa: a review. J Sustain Dev., 5:69.

Negasi, T.A., Nigussie, D.R., Kebede, W., Lemma, D., and Abuhay, T. 2013. Characterization of soil nutrient management and post-harvest handling practices for onion production in the central rift valley region of Ethiopia. Agric For Fish, 2 (5):184–95.

Nyamwamu, R.O., Ombati, J.M. and Mwangi, J.G. 2014. Effectiveness of agricultural training centers' curriculum in promoting adoption of agricultural technologies: evidence from small-scale potato farmers in Nyandarua County, Kenya. Int J Agric Manag Dev, 4 (2):133- 145.

Nyunza, G., and Mwakije, A .2012. Analysis of round potato marketing in Tanzania: the case of Rungwe district. Tanzania, International Journal of Business and Social Sciences 3(23):86–96.

Okoye, B.C., Onyenweaku, C.E., and Agwu, A.E. 2008.Technical efficiency of smallholder cocoyam farmers in Anambra State, Nigeria: implications for agricultural extension policy. J Agric Ext, 12(1).

Pęksa, A., Kita, A., Kułakowska, K., Aniołowska, M., Hamouz, K. and Nemś, A. 2013.The quality of protein of colored fleshed potatoes. Food Chemistry, 141 (3):2960-2966.

Senbeta, A. F., and Worku, W. 2023. Ethiopia's wheat production pathways to self-sufficiency through land area expansion, irrigation advance, and yield gap closure. *Heliyon*, 9(10).

Shamil, A., and Dereje, G. 2021. Adaptability of Released Potato (Solanum tuberosum L.) Varieties at Masha and Chena, Southwestern Ethiopia. World J Agri & Soil Sci, 6(5).

Simonyan, J.B., and Obiakor, C.T. 2016. Analysis of household labour use in yam production in Anambra West Local Government Area of Anambra State, Nigeria. Prod Agric Technol, 8:1–16.

Taye, B., Tsigereda, A. and Woldemariam, W. 2021. Effect of Plant Spacing on Yield and Yield Components of Potato (Solanum tuberosum L.) Cultivars at Wolaita Sodo University, Ethiopia. Inc. Curr.Res.Aca.Rev, 9(01): 103-125.

Waglay, A., Karboune, S. and Alli, I. 2014 .Potato protein isolates recovery and characterization of their properties. Food Chemistry 142:373-382.

Udensi, E., Gbassey, T., Ebere, U.F.G., Asumugha, C.E., Okoye, B.C., Okarter, C., PaulI, Richardson, O., and Alfred, D. 2011.Adoption of selected improved cassava varieties among smallholder farmers in South-Eastern Nigeria. Int J Food Agric Environ, 9(1):329–35.

Yemane, T. 1967. Elementary Sampling Theory, New Jersey: Prantice –Hall, Inc.

Yimam, M. A, Andreini, M., Carnevale, S., and Muscaritoli, M.2024. Perspective: could Ethiopian potatoes contribute to environmental sustainability, the Ethiopian economy, and human health? Front. Sustain. Food Syst. 8:1371741.

Xu, N., Meng, F., Zhou, G., Li, Y., Wang, B., and Lu, H. 2020. Assessing the suitable cultivation areas for Scutellaria baicalensis in China using the Maxent model and multiple linear regression. Biochemical Systematics and Ecology, 90: 104052.

CHAPTER 4

4. Analysis of Farmers' Perception and Observed Climate Variability: Implication for Potato Production in Semi-Arid Areas of Tigray, Northern Ethiopia

Abstract:

In Tigray*, most potato-producing areas are vulnerable to climate change. Any change in climate leads to potato yield and quality decline. Analysis of farmers' perceptions and observed climate data is crucial in understanding the implication of climate change on potato. This study was conducted to analyze climate variability and its implications on potato production, as well as to assess the relationship between historical climate data and farmers' perception of climate variability in Tigray, northern Ethiopia. Long-term daily rainfall and temperature data (1975-2019) were obtained from* meteorological *stations in potato-producing districts. Additionally, 293 farmer close to the stations were interviewed to investigate their perceptions of rainfall trend. Mann–Kendall test and Sen's slope estimator statistical trend analysis techniques were used to analyze the annual and seasonal rainfall and temperature. The study revealed a decline in annual rainfall across most stations, accompanied by a rise in both annual and seasonal temperatures. The highest annual rainfall at Edagahamus decreased by 3.73 mm per decade, while Mekelle station recorded the lowest decrease at 0.895 mm per decade. The highest decline in Kiremt rainfall, at 2.09 mm per decade, was observed at Adigudom. Notably, the maximum annual temperature at Maychew station showed a significant increase of 0.052°C per year. Moreover, Adigrat and Mekelle stations experienced noteworthy upward trends in Kiremt maximum temperature, with rates of 0.034°C and 0.037°C per year, respectively. Most farmers perceived a decrease in rainfall and an increase in temperature each year. They also experienced shorter rainy seasons due to delayed onset and early cessation of rainfall, matching climate data. These changes negatively affected potato productivity. To address this, it is recommended to develop drought-tolerant potato varieties and implement suitable agronomic and water management practices.*

Keywords*:* Climate variability, Mann-Kendal's test, Perception, Rainfall, Temperature

4.1. Introduction

Globally, the earth has experienced rising temperatures and reduced rainfall, leading to climate change and variability in various sectors (Fancheren et al., 2003; Khanal 2009; Rosegrant et al., 2008). Agriculture, particularly in sub-Saharan African countries (SSA), where rainfed farming is crucial for 90% of the population, is highly susceptible to these changes (Falloon and Betts, 2010). Studies have shown that climate change has caused a 22% reduction in crop yields in this region (Spore, 2015), and Ethiopia, which heavily relies on rain-fed agriculture, is similarly affected (Deressa, 2006).

Ethiopia's agriculture is vital to its economy, contributing significantly to Gross Domestic Product GDP, exports, and employment. However, the sector is heavily dependent on rainfall and consists mostly of subsistence and small-scale farmers (Deressa et al., 2009). Climate change has disrupted rainfall patterns, leading to food insecurity and economic hardship. A study revealed a significant decrease in production and an increase in poverty due to rainfall variability (Hagos et al., 2009). These consequences have hindered the country's economic growth (Hagos et al., 2009; (Zenebe et al., 2011). Ethiopia, especially the Tigray region, is highly vulnerable to climate change impacts, with recurring challenges of drought and flooding exacerbating the region's limited resources.

Potatoes have high nutritional value with easily digestible carbohydrates, essential vitamins, and a notable plant protein (Pęksa et al., 2013). According to CSA (2016/17), potato yields in Tigray are low compared to the national average (13.5 t ha-1). Conversely, Haverkot et al. (2012) noted the highest recorded yield of potato (64 t ha^{-1}) around Shashemene in Ethiopia's rift valley, highlighting the variability in potato productivity across the country due to various biotic and abiotic factors. However, potato production in Tigray faces challenges such as disease, pests, and water stress. Climate variability exacerbates these challenges, making potato cultivation in the region difficult. Potatoes are susceptible to drought and high temperatures, which result in reduced yields and quality (Foti et al., 1995; Haverkort et al., 1990). Farmers in various countries use indigenous coping methods to tackle climate change, but these strategies vary by context and location. Ahmed et al. (2024) conducted a study on the influence of climate change on agricultural productivity and food security in Ethiopia, focusing on four major seasonal crops: barley, wheat, maize, and sorghum. In contrast, Eshetu et al. (2020) specifically examined sorghum. Additionally, many other researchers, such as Abraham et al.

(2021), Chala et al. (2020), and Gebre et al. (2013), have investigated climate change trends in various regions of Ethiopia related to agriculture. The specific impact of climate change on potato production remains unexplored in the study area. To develop effective adaptation measures, it is crucial to comprehend climate trends and their effects on potato farming. This study aims to analyze climate patterns, evaluate their influence on potato production, and explore how historical climate factors relate to farmers' perceptions of climate change.

4.2. Materials and Methods

4.2.1. Description of the study area

The study was conducted in Tigray Regional State, situated in northern Ethiopia between 36^{0}-40^{0}E longitude and 12 ^{0} –15^{0} N latitude. It boarders Amhara Regional State in the south, Afar Regional State in the east, Eretria in the north, and Sudan in the west (Fig 4.1). The study areas have diverse high and midlands suitable for potato production. The region has varied agro-ecological zones with distinct soil, geology, vegetation cover, and natural resources. The climate is mainly semi-arid, with a rainy season (kiremt) from June to mid-September and a small rain shower (Belg) from February to May (Araya et al., 2010). The dry season, known as Bega, occurs from October to January. According to CSA (2016/17) cropping season the total population of households who produce potato was 16,564 with an area of 622.22 ha .The most dominant crops in the study areas are wheat, barley and potato.

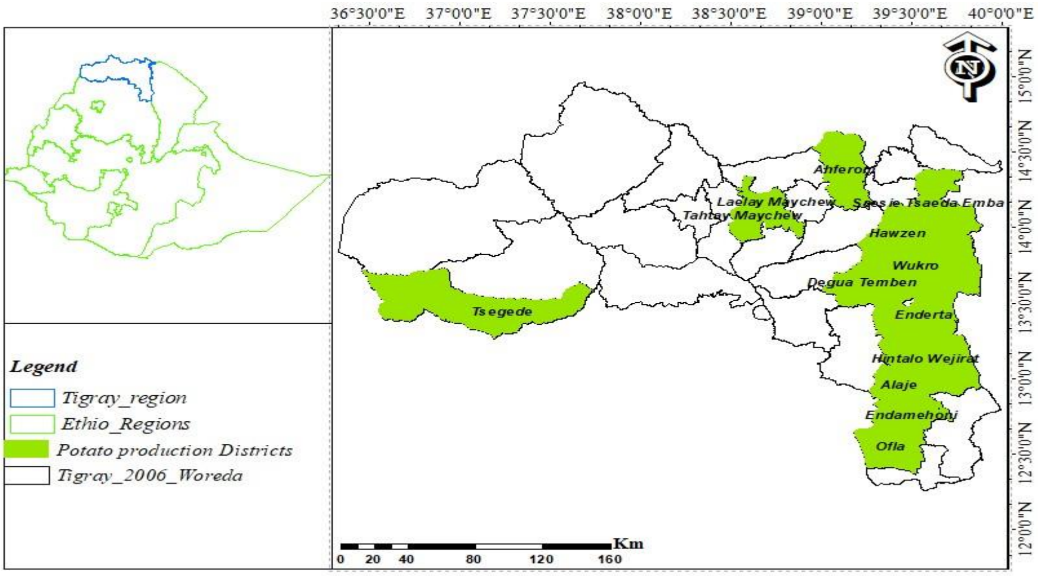


Figure 4.1 Potato Production areas of Tigray

4.2.2. Data collection and analysis

Daily rainfall (mm) from 1975-2019 and maximum and minimum temperature (^{0}C) data from 1992-2019 were obtained from the Ethiopian National Meteorological Service. Seven (Adigrat, Edagahamus, Hawzen, Wukro, Mekelle, Adigudom, and Maychew) meteorological stations lying within the potato producing areas of the region (Fig 4.1.) used as source of data for this study. Missing values estimated and filled following the first-order Markov chain model (Stern et al., 2006).

4.2.2.1. Data quality control

Data quality control involved assessing the accuracy, completeness, consistency, and reliability of data (Jaafar, and Al-Lami, 2019) .Tukey's fence method was used to identify and remove outliers (Ngongondo et al., 2011). Trimming outliers helps reduce the influence of extreme values and facilitates the use of subsequent data analysis techniques. Acceptable data ranges within the lower and upper fence, as shown below.

$$Q_1\text{-}1.5*IQR \leq, \text{Acceptable range} \leq Q3+1.5*IQR, \qquad \text{Eq 4.1}$$

Where Q_1 and Q_3 are the lower and upper quartile points respectively, 1.5 is the standard deviation from the mean, and IQR is the interquartile range. This study set such outliers to a limit value corresponding to ±1.5*IQR.

Homogeneity test:

To address this issue, this study employed the cumulative deviation test for detecting inhomogeneities in meteorological time series. This method offers advantages in terms of ease of application and interpretation, low inter-station correlation, and reduced data interpretation requirements (Kang and Yusuf 2012; Ngongondo et al . 2011; Sahin and Kerem, 2010). Buishand (1982) proposed tests for homogeneity based on adjusted partial sums formulated as follows:

$$S_0^* = 0 \text{ and } S_k^* = \sum_{i=1}^{k}(y_i - \bar{y}), \quad k= 1,\ldots,n$$

Eq 4.2

The term S^*_K is the partial sum of the given series. If there is no significant change in the mean, the difference between Y_i and ȳ will fluctuate around zero. The significance of the change in the mean calculated with ‘rescaled adjusted range’ R, which is the difference between the maximum and the minimum of the S^*_K values scaled by the sample standard deviation as:

$$R = (maxS^*_{K-}\, minS^*_K)/SD \qquad \text{Eq 4.3}$$

$$0 \leq K \leq n$$

$R/\sqrt{n}$ Value compared with the critical values of Buishand (1982) to test for significance.

Test of randomness:

Positive serial correlation can lead to misleading results in non-parametric tests. To address these issues, the time series data was tested for randomness and independence using the autocorrelation function (r1) described in Box and Jenkins (1976) as follows.

$$r_1 = \frac{\sum_{i=1}^{n-1}(x_i - \bar{x})(x_{i+1} - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Eq 4.4

Where x_i is an observation, xi+1 is the following observation, $\bar{x}$ is the mean of the time series, and n is the number of data. Dahmen and Hall (1989) defined the critical region at 5% probability as follows;

$$\left[\left(-1-1.96\sqrt{(n-2)}\right)/(n-1), \left(-1+1.96\sqrt{(n-2)}\right)/(n-1)\right]$$

Eq 4.5

Serial correlation of lag^{-1} (the correlation of two consecutive observations in the time series data) was engaged in this study. Whenever a significant correlation appeared in the data series, the data series was 'pre-whitened' following the procedure described in Partal and Kahya (2006). The pre-whitened data series may be obtained as (X_2-r_1X_1, X_3-r_1X_2… X_n-r1X_{n-1})

4.2.2.2 Trend analysis

Nonparametric Mann-Kendall and Sen's slope tests was used to examine long-term rainfall and temperature trends in rainfall and temperature. The Mann-Kendall trend test determined the statistical significance of increasing or decreasing trends. Equation 6 represented the test statistic (S) of the series (x).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$$

Eq 4.6

Where S is the Mann-Kendal’s test statistics; xk and xj are the sequential data values of the time series in the years k and j (j > k), and n is the length of the time series. k and j are the later and early measured values of the year, respectively. A positive S value indicates an increasing trend, and a negative value indicates a decreasing trend in the data series. Sgn (xj−xk) calculated as follows (Eq 4.7)

$$sgn(x_j - x_k) = \begin{cases} +1 \; if \;\; x_j - x_k > 0 \\ 0 \; if \;\; x_j - x_k = 0 \\ -1 \; if \;\; x_j - x_k < 0 \end{cases}$$

Eq 4.7

The variance computed as

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18}$$

Eq 4.8

Where n is the number of data points, m is the number of tied groups, and ti denotes the number of ties of extent i. A tied group is a set of sample data having the same value. In cases where the sample size n>10, the standard normal test statistic ZS computed using Equation. (4.8):

The Sen’s estimator of slope:

Sen's estimator is a non-parametric test that measures the trend's strength. It calculates the slope and intercepts (Sen, 1968). A positive slope indicates an upward trend, while a negative slope indicates a downward trend in the time series.

Onset and cessation date: - Rain onset was determined using Tesfaye and Walker's (2004) method, which requires 20 mm of rainfall over three consecutive days and no dry period exceeding seven days in the next 30 days. The end of the season is the date when the available soil water content reaches 10 mm m^{-2}. The length of the growing period is calculated as the difference between the onset and end dates of the season.

4.2.2.3 Variability analysis

Rainfall and temperature variability were analyzed using three descriptors: standardized anomaly index, precipitation concentration index, and coefficient of variation (Bewket and Conway 2007; Hara, 1983).

The standardized Anomaly Index (SAI):-This index is used to examine inter-annual rainfall fluctuations and determine the record's dry and wet years. Its formula is:

$$Z = \frac{(x-\mu)}{\delta},$$

Eq 4.9

Where Z is the standardized rainfall anomaly, x is the annual rainfall total of a particular year, μ is the mean annual rainfall over a period of observation, and δ is the standard deviation of annual rainfall over the period of observation.

Precipitation Concentration Index (PCI) was analyzed using De Luı's et al. (1999). It computed both annual and seasonal rainfall concentrations (Equation 4.10)

$$PCI = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100$$

Eq 4.10

Where, Pi is the rainfall amount of the i^{th} month. PCI values below 10 indicate uniform monthly rainfall distribution; values 10-15 indicate moderate rainfall distribution 16-20 Irregular rainfall distribution; and above 20 indicate strong irregular rainfall distribution.

The coefficient of variation (CV) was calculated to evaluate the variability of the rainfall and its characteristics by dividing the standard deviation of the event by its mean. Hare (1983) used a scale to classify CV into less, moderate, and high rainfall variability. Accordingly, CV value < 20 % indicates less variable, 20 % to 30 % is moderately variable, and > 30 % is highly variable, areas with CV > 30 % are said to be vulnerable to drought.

4.2.2.4 Socioeconomic data collection and analysis

Survey: before the formal survey, an initial exploratory study was conducted to gain clear insight and prioritize key issues within the community. Through this survey, data on agro ecological conditions, potato-producing farmers, and socioeconomic characteristics of the study area were collected. To enhance the formal survey, a checklist was prepared and distributed to various social groups within the communities. The formal survey was then designed based on the insights obtained during the exploratory phase. Accordingly, based on the potential and suitability for potato production, seven districts were purposively selected. From each district, two peasant association near to metrological stations were randomly chosen. Finally, 293 farm households were sampled randomly using probability proportional to the size (PPS) of the population of the district and peasant association from which sample households drawn. To select sample households from the chosen peasant associations, a list of potato-producing household heads was utilized. The distribution of sample households in the study area is presented in Table 4.1.

Table 4.1. Distribution of sample households (HH) in the study area

District	Total No of HH	No of HH of sampled peasant associations	No of sample HH	%
Kilte Awlaelo	27704	2025	19	6.5
Saesi Tsaedaemba	19702	4645	44	15.0
AtsbiWenberta	22009	4230	40	13.7
Hawzen	33608	4517	44	14.7
Enderta	31713	3882	37	12.6
H/wejerat	19054	3946	37	12.6
EnbaAlage	23117	3657	34	11.6
Endamehoni	24867	4146	39	13.3
Total	201774	31048	293	

Source: Office of agriculture of the respective woreda

Qualitative data obtained from interviews and document reviews were compiled, organized, and interpreted based on concepts and opinions. Descriptive statistics, such as the mean and percentage, along with quantitative statistics like the chi-square test, were computed to summarize the perception farmers' on rainfall and temperature changes. Analytical tools such as the statistical packages for social sciences (SPSS) Version 20 was used to summarize data.

4.3. Results and Discussion

4.3.1 Annual and seasonal rainfall total

Table 4.2 presents the annual and seasonal rainfall data of the studied station. The findings revealed that mean annual rainfall varied from 506.9mm at Adigudom to 734.4mm at Machew. Stations in the southern zone generally had higher annual rainfall compared to those in the southeastern and eastern parts. The coefficient of variation in annual rainfall ranged from moderately variable to extremely variable, indicating a moderate to high degree of variability in rainfall across the tested stations. This means there is a low probability of receiving the mean annual rainfall in any given year at most stations.The Kiremt season contributed the largest share (56 - 90%) to the annual total, followed by the Belg season depending on the station. This suggests that the Kiremt season is crucial for meeting crop water requirements for rainfed potato production. The coefficient of variation for seasonal rainfall in the Kiremt season also showed moderate to extreme variability. In line with this, Bewket and Conway (2007), Krauer (1988), and Gebre et al. (2014) found that Kiremt rainfall contributes significantly to annual rainfall in Tigray and Ethiopia as a whole. Additionally, Getachew (2018) and Bewket and Conway (2007) observed variability in Kiremt rainfall in the Amhara regional state of Ethiopia. Considering the importance of potato and relevance of the crop water requirement, this study emphasizes the need for proper agronomic practices, water management, and the development of drought-tolerant cultivars to maximize potato yield in the study area. Therefore, Hawzen, Wukro, Mekelle, and Adigudom are the areas that would benefit most from the introduction and promotion of drought-tolerant potato varieties

Table 4.2. Long-term mean annual and Seasonal rainfall (1975-2019)

Location	Season rainfall (mm) and its contribution to annual totals (%)						Annual total rainfall (mm)
	Bega (Oct to Jan)		Belg (Feb to May)		Kiremt (Jun to Sep)		
	mm	%	mm	%	mm	%	
Adigrat	61.9	10	186.4	32.6	323.5	56.6	571.7
Eidaga hamus	66.3	8.7	197.3	30.0	417.7	61.3	681.3
Hawzen	29.9	5.6	77.3	14.4	429.0	80.0	536.2
Wukro	10.3	1.7	84.2	13.7	518.1	84.6	612.7
Mekelle	14.5	2.5	101.8	17.5	465.1	80.0	581.3
Adigudom	7.0	1.4	46.4	9.2	453.4	89.5	506.9
Maychew	103.9	14.4	216.3	29.5	414.3	56.4	734.4

Source: Compiled by the author.

Note: mm and % is the amount of rainfall each month contributed to annual rainfall in millimeter and percentage respectively.

Precipitation Concentration Index (PCI)

Table 4.3 shows the Precipitation Concentration Index analysis for six stations. Most stations had PCI values ranging from 13% to 29%, indicating high monthly concentrations according to De Luı's et al. (1999) classification. This study emphasizes the need for informed planning to improve the monthly distribution of precipitation for potato production. Similarly, Bewket and Conway (2007), Ayalew et al. (2012), and Gebre et al. (2014) reported that rainfall in

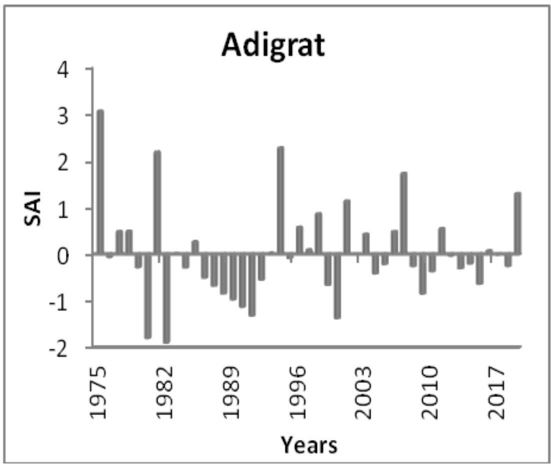
Tigray and the Amhara region of Ethiopia is characterized by high to very high monthly concentrations.

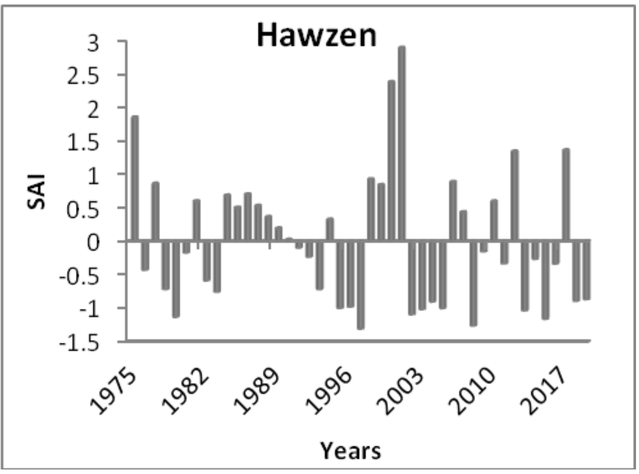
Table 4.3. Coefficient of variation and PCI values (1975-2019)

Location	Coefficient of variation (CV %)				PCI (%)	SAI:
	Annual	Kiremt	Belg	Bega		(%)
Adigrat	25.3	39.9	40.7	93.8	15.7	55.6
Hawzen	21.7	24.9	58.4	89.1	25.2	55.6
Edagahamus	67.8	67.2	97.4	191.9	16.1	66.7
Mekelle	23.6	28.8	63.2	119.4	24.8	53.3
Adigudom	39.0	43.6	68.4	171.7	29.0	53.3
Maychew	22.3	29.9	50.0	66.6	13.7	51.1
Mean	33.3	39.1	63.0	122.1	20.8	

Source: Compiled by the author.

Standardized anomaly index (SAI): The analysis of the anomaly index (Fig 4.3) showed that over 50% of the recorded years at all stations had below average Kiremt rainfall. This indicates a high variability in yearly rainfall, leading to moisture deficit and highlighting the need for careful planning in potato production in the study areas. Similarly, Getachew (2018) observed alternating dry and wet years in three stations of the south Gonder Zone. Bewket and Conway (2007) and Ayalew et al. (2012) used the SAI to demonstrate drought intensity and frequency at different time scales, confirming its usefulness in identifying drought characteristics





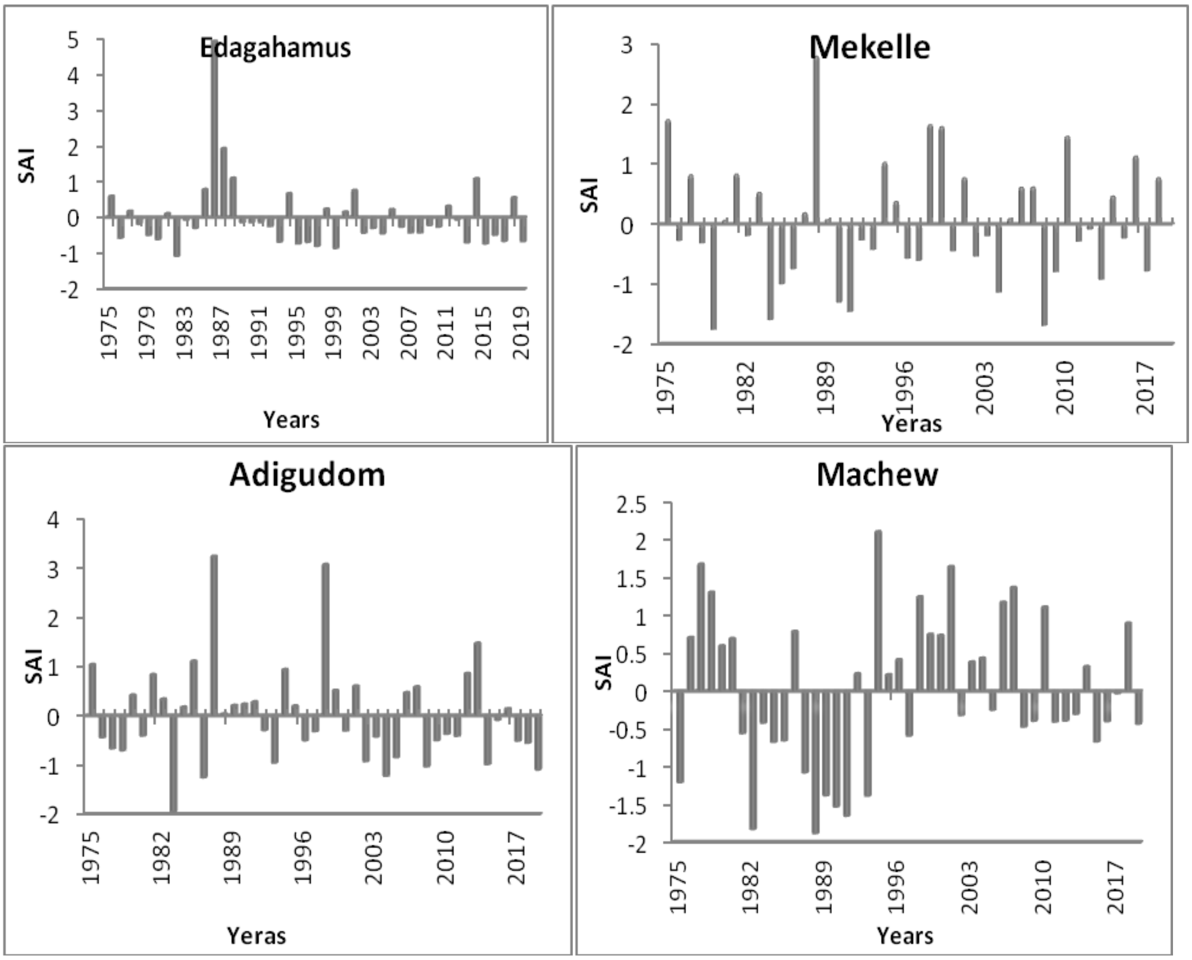


Figure 4.2. Standardized time series plot of Kiremt rainfall (1975-2019)

4.3.2. Trend analysis

4.3.2.1 Annual and seasonal rainfall

Table 4.4 shows the rainfall trends in seven stations in the potato-producing areas of Tigray, Ethiopia. All stations experienced a decrease in annual rainfall except Wukro. Similarly, Edagahamus, Hawzen, and Adigudom had a decrease in Kiremt rainfall. However, these trends were not statistically significant in any of the stations, possibly because of alternating wet and dry years observed in most stations (Fig 4.2). Fluctuations in rainfall, as shown in Fig 4.2, can have a negative impact on potato production, necessitating planning based on weather forecasting. In terms of Belg season rainfall, all stations, except Hawzen, saw a decrease, but only Maychew station had a statistically significant trend. Particularly, Adigudom had a significantly increasing trend, while Hawzen showed a significant decrease of rainfall in Belg season. In line with this, Conway (2000), Seleshi and Zanke (2004), Cheung et al. (2008), Viste et al. (2013), and Gebre et al . (2013) reported a non-significant trend of annual and seasonal rainfall totals in northern Ethiopia. Furthermore, Bewket and Conway (2007) and Ayalew et al. (2012) reported that the direction and magnitude of the trend in seasonal rainfall in the Amhara regional state of Ethiopia varied from station to station.

Table 4.4. Trends of annual and seasonal rainfall totals (1975-2019)

Stations	Annual		Kiremt Season		Belgi Season	
	Z_{MK}	Slope	Z_{MK}	Slope	Z_{MK}	Slope
Adigrat	-0.54^{ns}	-1.273	0.34^{ns}	0.317	-1.07^{ns}	-1.086
Edagahamus	-1.50^{ns}	-3.725	-0.77^{ns}	-1.793	-1.25^{ns}	-1.416
Hawzen	-1.18^{ns}	-1.642	-1.23^{ns}	-1.358	0.41^{ns}	0.277
Wukro	0.69^{ns}	1.730	0.57^{ns}	2.467	-0.73^{ns}	-1.092
Mekelle	-0.51^{ns}	-.895	0.16^{ns}	0.242	-1.00^{ns}	-0.640
Adigudom	-1.03^{ns}	-2.341	-1.16^{ns}	-2.096	-0.80^{ns}	-0.303
Maychew	-1.42^{ns}	-3.290	0.52^{ns}	0.786	-2.14^{*}	-2.697

Source: Compiled by the author.

Z_{MK} is the Mann–Kendall trend test, Slope (Sen's slope) is the change (mm)/annual and seasonal; ns is a non-significant trend, and * indicates a significant trend at 0.05 significant level When /Z_{MK}/ > /1.96/ it indicates significant at 5%, When /Z_{MK}/ > /2.576/ it indicates significant at 1%

4.3.2.2. Trend of long-term characteristics of Kiremt rainfall

Table 4.5 shows the rainfall characteristics of the studied station, including the onset date, cessation date, and length of growing period (LGP). The onset of the kiremt season was similar across all stations, occurring between late June and early July. Most stations did not show a significant trend in the onset date, except for Adigrat and Adigudom, where it increased by 3 and 6 days per decade, respectively. The variability in the onset date was high, making it difficult to predict Kiremt rainfall and requiring careful decision making for potato planting. However, the inter annual variability in the onset date was generally low (CV < 12%) across most stations. Overall, the study highlighted the inconsistency in the trend of the onset date and emphasized the need for considering site-specific factors for potato production, such as planting dates and varieties. In line with this Araya and Stroosnijder (2011) reported similar results where the onset of Kiremt rainfall at Adigudom, Maychew, and Mekelle was the first decade of July.

The kiremt rainfall stops in the frist week of September in all stations except Maychew, where it extends into the second week. The cessation date is decreasing in all stations, with statistically significant trends in Adigrat and Edagahamus. The cessation date is stable and predictable in all stations, making it easy to plan agricultural activities. There was a decreasing trend in length of growing period (LGP) across all stations, with Adigrat and Adigudom showing a statistically significant decrease. The coefficient of variation was high (>20%), indicating variability between years in LGP. In general, the study suggested that the need for early maturing varieties and supplementary irrigation for optimal potato crop production in the area. This finding is consistent with previous studies by Araya and Stroosnijder (2011) on rainfall patterns in Tigray.

Table 4.5. Long term Kiremt rainfall characteristic (1975-2019)

Rainfall characteristic	Statistics	Stations						
		Adigrat	Edagamus	Hawzen	Wukro	Mekelle	Adigudom	Maychew
Onset date	Mean	July -6	June -30	July -3	July-1	July -3	July -7	July-8
	Z_{KM}	3.30**	1.66^{ns}	-0.01^{ns}	-0.02ns	1.73^{ns}	3.13**	0.19^{ns}
	Slop	0.319	0.339	0.000	.000	0.286	0.594	0.014
	SD	11.88	15.87	8.635	16.875	11.29	20.66	17.80
	CV (%)	6.4	8.8	4.7	9.3	7.8	11.0	9.4
Cessation date	Mean	Sep-9	Sep-9	Sep-10	Sep-8	Sep -10	Sep-9	Sep-19
	Z_{KM}	-2.89**	-2.15*	-1.94^{ns}	-0.96ns	-1.04^{ns}	-0.39^{ns}	-0.35^{ns}
	Slop	-0.218	-0.155	0.148	0.000	-0.092	0.00	0.00
	SD	7.64	8.525	8.64	6.17	7.37	6.34	18.25
	CV (%)	3.0	3.4	3.4	2.5	2.9	2.5	7.00
LGP	Mean	65	71	70	67	67	64	77.0
	Z_{KM}	-2.18^{*}	-1.65ns	-1.72^{ns}	-0.53ns	-1.53^{ns}	-3.59**	-0.56^{ns}
	Slop	-0.333	-0.369	-0.220	-0.264	-0.222	-0.687	-0.119
	SD	12.80	20.04	12.69	17.60	15.33	18.44	15.58
	CV (%)	19.3	28.2	18.2	26.4	22.9	28.8	20.3

Source: Compiled by the author.

Note: LGP is the length of the growing period, SD->Standard Deviation, Z_{MK} is the Mann–Kendall trend test, Slope (Sen's slope) is the change (mm)/annual and seasonal, CV is Coefficient of variation

4.3.3. Mean Annual and seasonal Temperature trends

Trends of the studied stations' maximum and minimum temperatures is showen in Table 4.6. The results reveal differences in the direction of change for the average annual maximum and minimum temperatures. Maychew had a significant annual maximum temperature increase of 0.052°C per year. The coefficient of variation and standard deviation for most stations were below 10% and 20, respectively, indicating relatively low variability in temperature changes from year to year. Most stations experienced increasing trends in seasonal mean maximum and minimum temperatures. Adigrat and Mekelle stations showed a significant increase in Kiremt maximum temperature, with a yearly rate of 0.034°C and 0.037°C, respectively. The variation and standard deviation of Kiremt season temperatures had generally low; indicating the increase of maximum temperature is predictable. This predictability can aid in planning potato production activities. Generally, the result showed a rising trend in maximum and minimum temperatures across most stations, which could affect potato yield and tuber intuition growth. Consequently, location specific planting dates and the development of heat tolerant potato varieties are necessary. Similar to this , the region's mean minimum and maximum temperatures for 1954-2008 have increased by 0.72 ^{0}C and 0.36 ^{0}C per decade, respectively, faster than the national average of 0.25 ^{0}C (Gebrehiwot and van der Veen, 2013). Getachew (2018) also noted a similar situation in the neighboring Amhara region. Likewise, Joshua et al. (2011) have reported increasing trends of temperature at regional and global earth levels over the past years.

Table 4.6. Trends of annual and seasonal maximum (max) and minimum (min) (1992-2019)

			Stations											
			Adigrat		Sinkata		Hawzen		Wukro		Mekelle		Maychew	
Temperature (^{O}C)			Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
		Test												
Season	Kiremt	Mean	23.28	9.97	23.46	12.32	26.10	12.56	27.72	12.68	24.37	12.70	23.23	6.77
		Z_{MK}	2.93^{*}	1.50^{ns}	1.87^{ns}	-1.44^{ns}	-0.08^{ns}	2.20*	1.75^{ns}	2.07^{*}	2.33*	0.13^{ns}	1.48^{ns}	0.18^{ns}
		Slop	0.034	0.053	0.050	-0.036	-0.002	0.133	0.023	0.055	0.037	0.13	0.024	0.002
		SD	0.53	1.64	0.608	1.628	0.80	1.11	1.32	1.36	0.64	0.69	0.91	2.68
		CV (%)	2.3	16.4	2.6	13.2	3.1	9.0	4.2	10.7	2.6	5.4	3.9	39.7
Annual		Mean	23.56	7.94	24.2	11.17	27.25	10.56	27.7	11.17	24.23	11.66	21.98	10.01
		Z_{MK}	-0.96^{ns}	0.29^{ns}	1.76^{ns}	-1.44^{ns}	-0.68^{ns}	1.09^{ns}	1.33^{ns}	1.5^{ns}	-0.26^{ns}	-1.16^{ns}	4.29^{**}	0.42^{ns}
		Slop	0.015	0.038	0.033	-0.058	-0.032	0.051	0.022	0.030	-0.002	0.001	0.052	0.004
		SD	0.97	1.58	0.460	1.427	0.71	0.78	0.94	0.93	0.61	0.34	0.71	2.34
		CV (%)	4.5	19.9	1.9	12.8	2.6	7.4	3.4	8.4	2.5	2.9	3.2	61.4

Source: Compiled by the author.

Note: -ns is negative non-significant trend, +ns is positive non-significant trend

4.3.4. Farmers’ perception of climate variability

The perception of farmers on trends and variability of annual and seasonal rainfall is indicated in Table 4.7. The study found that farmer’s perception in different locations significantly varied on the directions of climate variability. Most farmers situated in the southern and southeastern zones perceived a decreasing trend in annual, kiremt, and belg rainfall compared to the eastern zone. This suggests that farmers' perceptions about rainfall changes differ meaningfully across the locations, indicating varying experiences or observations regarding annual kiremt and belg rainfall patterns. This might be resulted due to variations on delivery of climate information by respective administrations and/or localized difference of the areas. The metrological evidence also revealed similarity with the perception of the farmers’ that there was an overall decline in the annual and seasonal rainfall amounts in the potato producing areas while its magnitude varies with station. This information can guide policymakers and agricultural extension services to tailor their interventions based on the specific needs and perceptions of farmers in each location. In line with present findings, Deressa et al. (2009) and Mengistu (2011) reported that farmers in Tigray perceived a decrease in the amount and timing of precipitation. Similarly, Gebre et al. (2014) reported that most of the interviewed farmers at Mekelle and Alamata had perceived a decreasing trend of Annual, and Kiremt rainfall totals.

The study also found that most farmers in the area experienced late onset, early cessation, and a shorter growing period of Kiremt rainfall. Farmers in all locations observed delayed rainfall, earlier termination of the season, and a reduced length of the crops growing period. The study found that farmers generally agreed with the observed data on late onset of kiremt rainfall, except in K/Awlaelo and Hawzen. Overall, farmers' perceptions aligned with the observed data, which can aid in confident planning of agronomic and water management activities (not shown data). In Agreement with this, Nyanga et al. (2011) reported that farmers in Ghana and Zambia, respectively, perceived rainfall timing had changed, resulting in increased frequency of drought.

In addition, most farmers in the study area perceived increasing trends in annual and seasonal temperatures (Table 4.8). However, there was a significant difference in farmers' perceptions across different woredas regarding both annual and seasonal temperature changes. Most importantly, farmers living in the highland areas perceived changes in annual and seasonal temperatures compared to those in the midland. Furthermore, meteorological records from each station support the farmers’ perceptions on temperature changes. The study suggests that farmers in different locations have varying experiences or observations regarding temperature patterns. This could imply that local factors, such as topography, climate, or agricultural practices, may influence how farmers perceive temperature changes. This rise in temperatures has affected potato growth, particularly during the tuber initiation stage. Therefore, it is essential to design location-specific crop management practices that account for these temperature changes. In line with this, Mengistu (2011) and Deressa et al.(2011) revealed that most of the farmers in Ethiopia are aware of the fact that the temperature is increasing.

Table 4.7. Percepation of farmers via observed metrological data

Location /District		Annual rainfall (%)				Kiremt rainfall (%)				Belg Rainfall			
		Increase	Decrease	No change	Metrological trend	Increase	Decrease	No change	Metrological trend	Increase	Decrease	No change	Metrological trend
East Zone	Kilte Awlaelo	44.8	24.1	31.0.	+NS	44.8	24.1	31.0	+NS	75.9	20.7	3.4	-NS
	Saesi Tsaedaemba	24.4	44.4	31.1	-NS	35.6	40.8	24.4	-NS	22.2	53.3	22.4	-NS
	Atsbi Wenberta	22.0	48.0	32.0	-NS	22.0	34.8	44.0	-NS	18.0	48.0	34.0	-NS
	Hawzen	29.0	64.5	6.5	-NS	16.1	77.4	6.5	-NS	51.6	32.3	16.1	+NS
South east Zone	Enderta	13.9	41.7	44.4	-NS	13.9	66.7	19.4	+NS	13.9	55.6	30.6	-NS
	H/wejerat	5.7	65.7	28.6	-NS	5.7	65.7	28.6	-NS	5.7	65.7	28.6	-NS
South Zone	Enba Alage	40.7	59.3	0.0	-NS	40.7	48.1	11.1	+NS	40.7	59.3	0.0	-ST*
	Endamehoni	12.5	72.5	15.0	-NS	12.5	72.5	15.0	+NS	12.5	72.5	15.0	-ST*
	Chi-Square (X^2)		50.212***				56.08***					77.87***	

Source: Compiled by the author

Note: -NS is negative non-significant trend, +NS is positive non-significant trend, ST* negative significant trend at 5%; ***highly significant at 5%

Table 4.8. Perception of farmers (%) on mean annual and seasonal temperature trends

District	Annual Temperature				Kiremt Temperature				Belg Temperature			
	Increase	Decrease	No change	Metrological trend	Increase	Decrease	No change	Metrological trend	Increase	Decrease	No change	Metrological trend
Kilte Awlaelo	79.3	20.7	0.0	+NS	58.6	41.4	0.0	+ST*	48.3	51.7	0.0	+ST*
Saesi Tsaedaemba	70.7	9.8	19.5	-NS	68.3	12.2	19.5	-NS	75.6	7.3	17.1	-NS
AtsbiWenberta	79.5	0.0	20.5	+NS	65.9	9.1	25.0	+NS	84.1	6.8	9.1	+NS
Hawzen	50.0	16.7	33.3	+NS	30.0	40.0	30.0	+NS	73.3	10.0	16.7	+ST*
Enderta	61.1	11.1	27.8	-NS	27.8	19.4	52.8	+NS	47.2	13.9	38.9	+NS
H/wejerat	60.0	28.6	11.4	-NS	17.1	65.7	17.1	+NS	65.7	28.6	5.7	+NS
EnbaAlage	100.0	0.0	0.0	+NS	88.9	0.0	11.1	+NS	81.5	0.0	18.5	+ST**
Endamehoni	85.0	5.0	10.0	+NS	77.5	7.5	15.0	+NS	57.5	0.0	42.5	+ST**
Chi-Square (X^2)	52.13***				80.89**				74.90***			

Source: Compiled by the author
Note: -NS is negative non-significant trend, +NS positive non-significant trend, +ST* positive significant trend at 5%, +ST** positive significant trend at 1%

4.3.5. Farmers’ perceived impact of climate change on potato production

The study revealed that farmers in the study area, identified water shortage, higher temperatures, and increased disease and pests as the main impacts of climate change (Table 4. 9). These changes had a negative effect on potato crop production, leading to lower yields and poorer quality, as well as overall food insecurity. To ensure future food security, it is crucial to develop effective adaptation strategies that can mitigate the effects of climate change on potato production. Given that most farmers in the area are smallholders with limited options, the adaptation measures should be simple, affordable, and accessible. Some of the commonly used measures include using different potato varieties, implementing soil and water conservation techniques, adjusting planting dates, providing supplementary irrigation, and adopting ridge planting methods.

Table 4.9. Percepation of Farmers on the impact of climate change

	Respondent	
Perceived impacts	N	%
Shortage of water/occurrence of drought	282	100
Prevalence of disease and pest	206	73.0
Decrease tuber yield	262	96.7
Decrease tuber quality	235	86.7
Decrease potato growth	233	86.0

Source: Compiled by the author.
Note: The result of the impact of climate change and its effect on potato production based on multiple responses from respondents

Most interviewed households used soil and water conservation and changed planting dates to adapt to climate change in potato production. However, a small percentage employed ridge planting, changed varieties, used supplemental irrigation, and diversified crops. These findings suggest that farmers' adaptation measures were limited. Breeding drought, disease, and pest-tolerant potato varieties could help mitigate climate change threats. Additionally, improving irrigation methods and water capture is crucial due to decreasing water availability. Farmers emphasized the responsibility of government, non-governmental organizations, and individuals in addressing the problem.

In agreement with this result, Gebre et al. (2014) and Mengistu (2011) identified common climate change and adaptation methods in Tigray, Ethiopia, including changing crop type/varieties, soil and water conservation practices, and irrigation. Generally, farmers in these regions rely on a combination of practices to adapt to climate change, including changes in crops, soil and water management, planting dates, and irrigation.

4.4. Conclusions and Recommendations

In the southern zone, rainfall is higher compared to the southeastern and eastern parts of the study area. Most stations show-decreasing trends in annual and seasonal rainfall, while mean maximum and minimum temperatures are increasing. These trends however, vary across locations. Year-to-year variability in rainfall is significant, indicating poor monthly distribution during the kiremt season. Late-onset and early cessation of kiremt rainfall are observed, resulting in a shorter growing period in most stations. These observations align with farmers' perceptions of decreased rainfall and increased temperatures. Farmers also report more frequent late onset and early cessation of rainfall, corresponding to the observed data. Given these climate patterns, it is crucial for potato breeders to explore additional germplasm and use modern breeding techniques to develop drought-tolerant varieties. Therefore, implementing appropriate agronomic and water management practices is recommended to mitigate the impact of climate variability.

4.5 .References

Ahmed, B., Taimur, S., Faruk, B. and Mohammad, Z.A. 2024. Impacts of the changing climate on agricultural productivity and food security: Evidence from Ethiopia. Journal of Cleaner Production, 449: 141993.

Araya, A. and Stroosnijder L .2011. Assessing drought risk and irrigation need in northern Ethiopia. Agricultural and Forest meteorology, 151(4): 425–436.

Araya. A., Keesstra, S.D. and Stroosnijder L .2010. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia. Agricultural and forest meteorology, 150(7-8): 1057–1064.

Bewket, W. and Conway, D. 2007. A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. Int. J. Climatol, 27:1467-477.

Box, G.P. and Jenkins, G.M. 1976. Time-series analysis, forecasting and control. Rev. Ed.Oakland, California: Holden-Day.

Buishand, T.A., 1982 .Some methods for testing the homogeneity of rainfall records. Journal of Hydrology, 58: 11-27.

Chala, D., Belay, S. and Bamlaku, A. 2020.Analysis of farmers' perceived and observed climate variability and change in Didessa sub-basin, Blue Nile .River, Ethiopia. African Journal of Agricultural Research, 15(2): 149-164.

Central Statistics Authority (CSA). 2017. Agricultural Sample Survey 2016/2017. Report on Area and Production of Major Crops. Private Peasant holdings, Meher Season; Volume I: 12-18. Addis Abeba, Ethiopia.

Cheung, W.H., Senay, G.B. and Singh, A. 2008. Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. International Journal of Climatology: A Journal of the Royal Meteorological Society, 28(13):1723-1734. http://dx.doi.org/10.1002/joc.1623

Conway, D. 2000. Some aspects of climate variability in the northeast Ethiopian highlands-Wollo and Tigray. SINET: Ethiopian J. Sci, 23 (2):139-161

Deressa, T., Hassan, R.M., Alemu, T., Yesuf, M. and Ringler, C. 2008. Analyzing the determinants of farmers' choice of adaptation methods and perceptions of climate change in the Nile Basin of Ethiopia. Intl Food Policy Res Inst.

Deressa, T.T., Hassan, R.M., Ringler, C., Alemu, T. and Yesuf, M. 2009. Determinants of farmers'hoice of adaptation methods to climate change in the Nile Basin of Ethiopia. Global Environmental Change, 19 (2): 248-255.

Deressa, T.T., Hassan, R.M. and Ringler, C. 2011. Perception of and adaptation to climate change by farmers in the Nile basin of Ethiopia. The Journal of Agricultural Science, 149(1), 23-31.

Deressa, T.T. 2007. Measuring the economic impact of climate change on Ethiopian agriculture (Vol. 4342). World Bank Publications.

De Luı´s, M., Gonza´lez-Hidalgo, J.C., Raventos, J., Sanchez, J.R. and Cortina, J. 1999.Spatial analysis of rainfall trends in the region of Valencia (East Spain). International Journal of Climatology, 20: 1451–1469.

Devaux, A., Ordinola, M.E., Hibon, A. and Flores, F.A. eds. 2010. El sector papa en la region andina: Diagnóstico y elementos para una visión estratégica (Bolivia, Ecuador y Perú). International Potato Center.

Eshetu, Z., Gebre, H. and Lisanework, N. 2020. Impacts of climate change on sorghum production in North Eastern Ethiopia. African Journal of Environmental Science and Technology, 14(2): 49-63.

Fallon, P. and Betts, R. 2010. Climate impacts on European agriculture and water management in the context of adaptation and mitigation. The importance of an integrated approach. Science of the Total Environment, 408 (23):5667-5787.

Food and Agriculture Organization of the United Nations (FAO), 2010. Agricultural based livelihood systems in dry lands in the context of climate change: Inventory of adaptation practices and technologies of Ethiopia. FAO, Rome.

Fancherean, N., Trzaska, M., Rouault, M. and Richard, Y. 2003.Rainfall variability and changes in Southern Africa during the 20th Century in the Global Warming Context. Natural Hazards, 29:139-154.

Foti, S., Mauromicale, G. and Lerna, A. 1995. Influence of irrigation regimes on growth and yield of potato cultivar Spunta, Potato Research, 38:307–318.

Gebrehiwot, T. and Veen.van der, A. 2013. Assessing the evidence of climate variability in the northern part of Ethiopia. Journal of Development and Agricultural Economics, 5(3): 104-119.

Gebre, H., Kindie, T., Girma, M. and Belay, K. 2013. Trend and variability of rainfall in Tigray, Northern Ethiopia: Analysis of meteorological data and farmers' perception. Academia Journal of Agricultural Research, 1(6): 088-100.

Gebre, H., Kindie, T., Girma, M. and Belay, K. 2014. Analysis of farmers' perception, and adaptation methods to climate variability/change in Tigray region, northern Ethiopia .Research Journal of Agricultural and Environmental Sciences, 1(1): 15-24.

Getachew, B. 2018. Trend analysis of temperature and rainfall in south Gonder zone, Ethiopia. J.Degrade.Min. Land Manage, 5(2): 1111-1125.

Gonzalez-Hidalgo, J.C., Lopez-Bustins, J., Stepanek, P., Martin-Vide, J., and De Luis, M. 2009. Monthly precipitation trends on the Mediterranean fringe of the Iberian Peninsula during the second half of the twentieth century (1951–2000). Int. J. Climatol, 29:1415–1429.

Gonzalez-Rouco, J.F., Luis, J.J., Quesada, V. and Valero, F. 2001. Quality control and homogeneity of precipitation data in the southwest of Europe. Journal of Climate, 14: 964-978.

Grewal, J. S., Sharma, R. C. and Saini, S.S. 1992. Agro-techniques for intensive potato cultivation in India. New Delhi: Indian Council of Agriculture Research

Hagos, F., Makombe, G., Namara, R.E. and Awulachew, S.B. 2009. Importance of irrigated agriculture to the Ethiopian economy: Capturing the direct net benefits of irrigation (Vol. 128). IWMI.

Haverkort, A.J., van de Waart, M. and Bodlaender, K.B.A. 1990. The effect of early drought stress on numbers of tubers and stolons of potato in controlled and field conditions, Potato Research, 33:89–96.

Haverkort, A.J., Van Koesveld, M.J., Schepers, H.A.M., Wijnands, J.H.M., Wustman, R. and Zhang X.X. 2012. Potato prospects for Ethiopia: on the road to value addition (No. 528). Praktijkonderzoek Plant & Omgeving.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate change: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. In: Pachauri RK, Meyer LA (Eds.), Geneva: IPCC, p.151.

Jaafar, A.J. and Al-Lami, A.M. 2019. Quality control of annual precipitation measurement for selected stations in Iraq. Al-Mustansiriyah J. Sci, 30, 9–17.

Kang, H.M. and Yusof, F. 2012. Homogeneity tests on daily rainfall series in Peninsular Malaysia. International Journal of Contemporary Mathematical Sciences, 7 (1):9 – 22.

Khanal, R.C. 2009. Climate change and organic agriculture. The Journal of Agriculture and Environment, 10:100-109. Review Paper.

Krauer, J. 1988. Rainfall erosivity and isorodent map of Ethiopia. Soil Conservation Research Project Report 15.

Kulkarni, A. and Von Storch, H. 1995. Monte-Carlo experiments on the effect of serial correlation on the Mann–Kendall test of trend. Meteorologische Zeitschrift, 4(2): 82–85.

Kumar, V. 2014. Role of indigenous knowledge in climate change adaptation strategies: A study with special reference to North-Western India. J Geogr Nat Disast, 5(131): 2167-0587.

Mengistu, D.K. 2011. Farmers' perception and knowledge of climate change and their coping strategies to the related hazards: Case study from Adiha, central Tigray, Ethiopia. Agricultural Sciences, 2 (2): 138-145.

Minhas, J.S., Kumar, D., Joseph, T. A., Raj, B. T., Khurana, S. M .P, Pandey, S. K. and Naik, P.S. 2006. Kufri Surya: A new heat-tolerant potato variety suitable for early planting in Northwestern plains, peninsular India and processing into frenchfries and chips, Potato Journal, 33: 35-43.

Mohammed, R. and Scholz, M. 2023. Quality control and homogeneity analysis of precipitation time series in the climatic region of Iraq. Atmosphere, 14(2): 197.

Ngongondo, C., Yu-Xu, C., Gottschalk, L. and Alemaw, B. 2011. Evaluation of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region. Theoretical and Applied Climatology, 106: 79-93.

Nyssen, J., Munro, N., Haile, M., Poesen, J., Descheemaeker, K., Haregeweyn, N., Moeyersons, J., Govers, G. and Deckers, J. 2007. Understanding the environmental changes in Tigray: a photographic record over 30 years. Tigray Livelihood Papers, 3: 82.

Okonya, J.S., Syndikus, K. and Kroschel, J.J. 2013. Farmers’ Percepation and Coping Strategies to Climate Change: Evidence from Six Agro-Ecological Zons of Uganda. Journal of Agricultural Science, 5(8):252-263.

Pęksa, A., Kita, A., Kułakowska, K., Aniołowska, M., Hamouz, K. and Nemś, A. 2013.The quality of Protein of colored fleshed potatoes. *Food Chemistry,* 141 (3):2960-2966

Rosegrant, M.W., Ewing, M., Yohe, G., Burton, I., Huq, S. and Valmonte-Santos, R. 2008. Climate change and agriculture: threats and opportunities.

Sahin, S. and Cigizoglu, H.K. 2010. Homogeneity analysis of Turkish meteorological data set. Hydrological Processes: An International Journal, 24(8): 981-992.

Sen, P.K. 1968. Estimates of the regression coefficient based on Kendallstau. J. Am. Stat. Assoc, 39:1379–1389

Simelton, E., Quinn, C.H., Batisani, N., Dougill, A.J., Dyer, J.C., Fraser, E.D., Mkwambisi, D., Sallu, S. and Stringer, L.C. 2013. Is rainfall really changing? Farmers’ perceptions, meteorological data, and policy implications. *Climate and development*, *5*(2), pp.123-138.

Spore. 2015. Climate change challenges and opportunities, Spore special issue, October 2015, 4-7

Stern, R., Rijks, D., Dale, I. and Knock, J. 2006. INSTAT (interactive statistics) climate guide, 330.

Taddesse, T. 2011. Farmers' perception and adaptation mechanisms to climate change and variability: the case of La’ilay Maichew woreda, central Tigray, Ethiopia. An MSc Thesis Presented to the School of Graduate Studies of Haramaya University.

Tesfaye, K. and Walker, S. 2004. Matching of crop and environment for optimal water use: the case of Ethiopia. Physics and Chemistry of the Earth, Parts a/b/c, 29(15-18): 1061-1067.

Viste, E., Korecha, D. and Sorteberg, A. 2013. Recent drought and precipitation tendencies in Ethiopia. Theoretical and Applied Climatology, 112: 535-551.

Zenebe Gebreegziabher, Z.G., Stage, J., Alemu Mekonnen, A.M. and Atlaw Alemu, A.A. 2011. Climate change and the Ethiopian economy: a computable general equilibrium analysis.

CHAPTER 5

5. Growth, Yield, and Water use Efficiency of Potato Genotypes under Supplemental and Non-supplemental irrigation Conditions of Semi-Arid areas of Northern Ethiopia

Abstract

Potato is the dominant tuber and root crops grown in Tigray. However, the productivity is very low due to moisture stress, traditional production techniques and low-yielding varieties. Hence, this study aimed at determining potato yield of genotypes under supplemental and non-supplemental irrigation conditions. The study involved five potato genotypes and two irrigation levels used as treatments arranged in split plot using randomized complete block design with three replication. Results revealed a significant difference in days to flowering and maturity, marketable and total tuber yield and water productivity due to the main and interaction effect of genotype and irrigation. Among gontype tested, CIP-390478.90 produced significantly higher marketable yield (27.13 t ha^{-1}*), total tuber yield (28.71 t ha*$^{-1}$*) and water productivity of 7.59 kg m*$^{-3}$* under supplemental irrigation. Genotype CIP-394611.112 had produced high marketable yield (24.45 t ha*$^{-1}$*), total yield (25.60 t ha*$^{-1}$*) and total water productivity (8.51 kg m*$^{-3}$*) under non-irrigated treatment. Additionally, potato water requirements in September and October exceeded rainfall amounts, suggesting that supplemental irrigation is necessary during this period for optimal yields. Likewise, genotypes CIP-394611.112 and CIP-390478.90 are recommended for semi-arid areas to enhance tuber yield with or without irrigation.*

Keywords: Genotype; interaction, Irrigation; Potato; Quality; Water productivity; Tuber Yield

5.1. Introduction

Potato (*Solanum tuberosum* L.) is among the most productive food crops in terms of yields of edible energy and good quality protein per unit area per unit time (Górska-Warsewicz et al., 2021**).** Potato is a staple food consumed worldwide and categorized as a dietary vegetable containing many minerals and vitamins (Beals, 2019; Górska-Warsewicz et al., 2021). Potato is a high potential food security crop due to its ability to its high productivity, adaptation to diversified cropping systems and producuction of quality product per unit input with a shorter crop cycle (Devaux et al., 2021). In addition, it provides income and employment (Devaux et al., 2019). Exploring these merits seems to be the right way to secure food in developing countries like Ethiopia.

Potato is one of the most vulnerable crops to changing climates, with events such as long-lasting droughts, extreme heat, and unanticipated frosts (Jennings et al., 2020; Quiroz et al., 2018).Potato yields depend on water and soil management practices, seed quality, chemical and bio-fertilization, soil moisture contents, elevation, slope, and supplemental irrigation (Maqsood et al .,2020). Potato requires 400 to 800 mm of rain/water, which invariably depends on meteorological variables and other factors (Handayani et al., 2019: Daccache et al., 2011). Water shortage beyond 60% to 65% causes drought that reduces the growth rate (Handayani et al., 2019: Geddes, 2022). Water stress conditions can likewise affect optimal potato yields (Handayani et al., 2019: Srivastava et al., 2019). Potato is generally considered to be sensitive to drought. Short root length in the soil profile results in a limited ability of potato roots to absorb water and has been suggested as the basis for potato's drought sensitivity (Iwama and Yamaguchi, 2006). Water stress at any growth stage leads to a considerable negative impact on potato tuber yield and quality (Ahmadi et al., 2010; Shayannejad, 2009). The impacts of water restriction on potato production will also likely increase over the next decades, due to climate change and the extension of potato cultivation in drought prone areas (Monneveux et al ., 2013)

Crop production in the semi-arid area is highly influenced not only by the amount of rainfall but also by its extreme variability, with high intensities, and poor spatial and temporal distribution (Johan et al., 2010; Theib and Ahmed, 2006). Similarly, Tigray is located in northern Ethiopia, which is characterized by a semi-arid climate where crop production is highly influenced by rainfall distribution. In Tigray, rainfall is a key source of agricultural water for crop production but it is erratic, torrential, highly variable, and poorly distributed over the growing season. More than 70% of annual rainfall in the region is received in July and August (Gebrehiwot T and Veen.van der, 2011). In addition, the rainfall is either too much at one time or no rain at another time (Araya and Stroosnijder, 2011). Thus, frequent dry spells and shorter growing periods due to the late-onset and early cessation of rainfall and dry spell in between is the major causes of crop failures in Tigray (Araya and Stroosnijder, 2011). These imply that there is a pressing need for supplying water to the crops as rainfall is inadequate to fulfil the crop water requirement.

Potato is one of the staple tuber crops growing in Tigray in both the middle and highland areas under rainfed and irrigation condition. It contains an important essential amino acid, which is often lacking in other crops like cereals and other vegetables (Waglay et al., 2014). However, the average yield of potato in Tigray is (8.1t ha^{-1}), which is far below the national average of 13.5 t ha^{-1} (CSA, 2017) and other countries like New Zealand (50.2 t ha^{-1}) and North America (41.2 t ha^{-1}). Even the yield potential of potato had reported to reach about 100 t ha^{-1} (Grewal et al., 1992), which indicates the prospect of crop to feed the rising population.

Despite its importance, potato production in Tigray is plagued by numerous problems, such as water stress, lack of drought tolerant genotypes, uneven distribution of rainfall and disease and pests. In addition, potato yield, potato is affected by fertilizer type and method (Niguse et al, 2016). Until this period , no varieties are released for drought tolerance particularly in Ethiopia. The existing varieties are not evaluated for their relative tolerance to drought stress conditions. The requirements of the potato crop for supplemental irrigation in the study areas had not been well investigated. Supplemental irrigation (SI) is the addition of limited amounts of water to rainfed crops to improve and stabilize yields during a shortage of rainfall by providing sufficient moisture for normal plant growth (Oweis and Hachum, 2009). Supplemental irrigation can improve crop yield and water productivity, especially during critical crop growth stages. Moreover, supplemental irrigation can play an important role in the adaptation efforts to climate change in rainfed agro-ecosystems (Nangia et al., 2018). The hypothesis is that potato genotypes have the plasticity to grow in water-limited areas with a small amount of supplemental irrigation to complement the natural short rainy seasons. Therefore, the objective of this study was evaluation of growth performance, physiology and yield as well as water productivity of potato genotpes under supplemental and non-supplemental irrigation conditions. This helps to identify drought-tolerant genotypes and assess the impact of supplemental irrigation on potato yield and water productivity, thereby contributing to improved potato production in the region amidst ongoing challenges such as water stress due to the changing climate.

5.2. Materials and Methods

5.2.1. Description of the study area

Field studies were conducted in Mekelle Agricultural Research Center Sites at Elalla and Aynalem. Elalla is located at 39° 28’14” - 39° 33’18” E Longitude and 13° 29’23” - 13° 34’27” N Latitude and elevation of 2004 meter above sea level (masl) in Mekelle. Aynalem is found in Kilte Awlaelo Wereda, located North of Mekelle City 45 km, and is located at 39° 35’60” E Lon and 13° 46’38” N latitude and elevation 2020 masl (Figure 5.1). The study areas are characterized by unimodal rainfall ranging from June to September with erratic spatial and temporal distributions (Hagos, 2016). The long-term (1992–2019) mean annual rainfall of Mekelle and Kilte Awlaelo is about 541. 5 and 612.7 mm, respectively. More than 70 % of the rainfall occurs in July and August in the study area; however, the dry season extends up to ten months, from October to May (Figure 5.2). The average annual potential evapotranspiration (ETo) estimated based on FAO Penman-Monteith (Allen et al., 1998). The long-term mean maximum and minimum temperatures of Mekelle and Elalla sites are 26.7 and 11.8^{0}C, respectively (Figure 5.2A), and mean maximum and minimum temperatures of Kilte Awlaelo and Aynalem sites are 27.7 and 11.2 ^{0}C, respectively (Figure 5.2B).

The soil type at the Mekelle (Elalla) experimental site is predominantly clay loam, with a field capacity of 32% and a permanent wilting point of 18.5%. In contrast, the Kilte Awlaelo (Aynalem) site is dominated by sandy clay soil, with a field capacity of 30.5% and a permanent wilting point of 15.5% (Table 5.1).

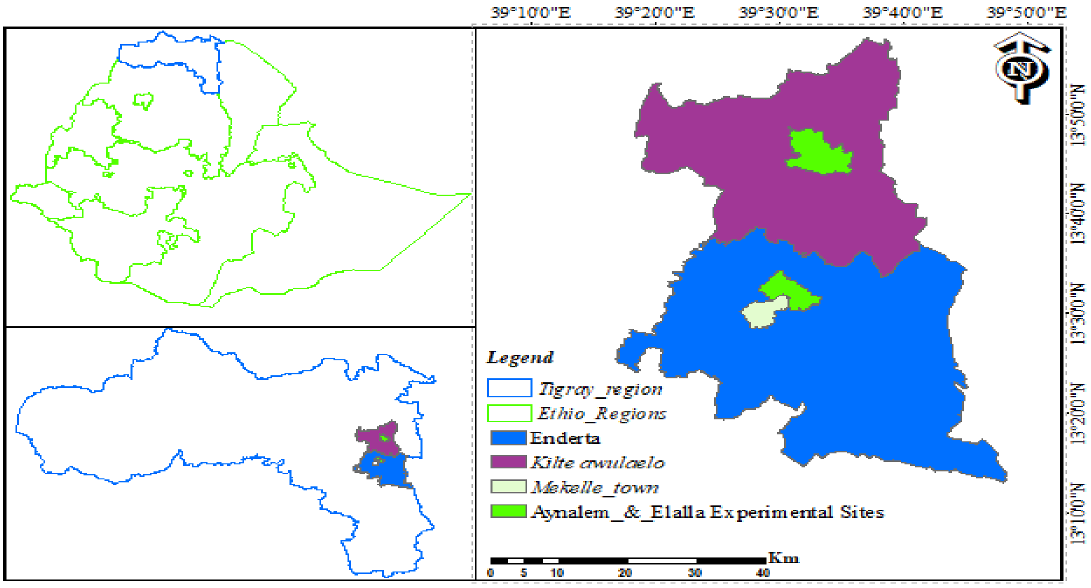


Figure 5.1. The Study areas of Aynalem and Elalla experimental site (from the present study)

The major crops grown in these areas include wheat, barley, teff, and potato. This study site was selected based on their suitability in terms of climate and soil conditions for potato production. During the growing season, supplemental irrigation was applied as needed for the potato genotypes. The growing season for potatoes typically starts at the end June with harvesting done by early October (Fig 5.4)

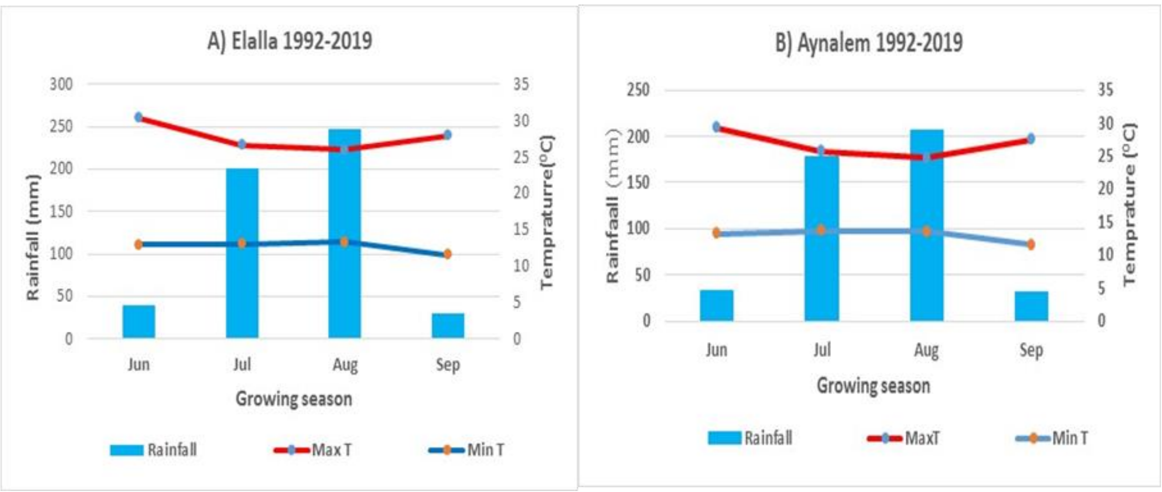


Figure 5. 2. Long-term (1992–2019) monthly rainfall, maximum and minimum temperature of (A) Mekelle, Elalla site and (B) Kilte Awlaelo, Aynalem site under rainfall condition.

5.2.2. Treatments and Experimental design

Five potato genotypes: CIP-390478.90, CIP-394611.112, CIP-392661, Seohong and Gudanie (Standard check) and 2 irrigation treatments: non-irrigated (NI) check where natural rainfed (RF), supplementary irrigation (SI), were tested. The field experiment was conducted using a Randomized Complete Block Design (RCBD) in a split-plot arrangement, with three replications. The genotypes were kept as a subplot, whereas the supplemental irrigation was the main plot. The field experiment was conducted at Mekelle, Elalla site and Wukro, Aynalem site for two consecutive years. The genotype and irrigation kept as fixed effect in the model, whereas, location and year as random effect.

The gross plot size used in each site is 4.5 m x 3m (13.5m^2) with spacing between rows and plants of 75 cm and 30 cm, respectively. A distance of one meter was maintained between plots, 1.5, and 2 meters between subplots and blocks, respectively. The experimental field was well prepared, and the potato crop was grown under optimal planting practices. The recommended fertilizer rate and type were applied uniformly to all treatments. Specifically, a full dose of NPSZn (250.4 kg ha^{-1}, containing 18% N, 35.9% P_2O_5, 7% S, and 2.2% Zn) was applied at planting. Additionally, urea (165 kg ha^{-1}) was applied in a split application: half of the Urea was applied uniformly across all plots at planting, while the remaining half was applied for each treatment at the early flowering stage.

5.2.3. Crop water requirement and Irrigation water application

Supplemental irrigation was applied after the onset of rain during the growing season. The supplemental irrigation was applied to maintain the soil moisture at field capacity from planting to maturity during the rainy season. Crop water requirement depend on climate data (Temperature, wind, humidity, sunshine hours, evaporation, rain), crop type, crop growth stage , and soil type. Potato crop water requirement (ETc) of the study area was determined from the reference evapotranspiration (ETo) and respective crop coefficients (Kc) of each growth stage (Allen et al, 1998). The Kc of potato in the different growth stages was adopted from Allen et al. (1998). The amount of water required by the crop to fulfil its demand was estimated using FAO CROPWAT program versio.8 (Allen et al., 1998) as indicated in Equation (5.1).

Furthermore, irrigation scheduling was determined using the FAO CROPWAT program (Allen et al., 1998). Irrigation was started when the soil moisture depletion reached a critical level of 25% of the field capacity. Irrigation critical depletion (to refine soil to 100% the field capacity) and irrigation efficiency 70% scheduling criteria was adopted in this study. The amount of water required in supplement irrigation treatment had measured and applied using the parshall flume device of 2-inch throat width. The parshall flume had known discharging rate (l/s) for different heads (cm). The irrigation water was pumped from a nearby river to the study sites through a water pump with a specific capacity of 30 m^3ha^{-1}efficiency. The furrow irrigation method was used to irrigate the experimental plots. This method applies water through a series of small furrows between plant rows. The combined mean amount of supplemental irrigation water applied was 85.06mm at Mekelle Elalla site and 94.75 mm at the Kilte Awlaelo Aynalem site, respectively. Furthermore, depending on the genotypes difference in maturity and water requirement 59.0 to 127.7 mm was applied as supplement irrigation. The combined mean total amount of water supplied to the crop was 293.2 and 383.4 mm for non-irrigated and irrigated plots respectively.

$$\mathrm{ETc(mm)} = \mathrm{Kc} * \mathrm{ETo(mm)} \qquad \text{Eq 5.1}$$

Where: - ETc = Crop water requirement, ETo = Reference Evapotranspiration
Kc = Crop coefficient

The amount of water supplied by irrigation during the crop growth period under rainfed condition is termed a supplement irrigation requirement (SIR**)**. SIR is the difference between crop water requirement and effective rainfall, as indicated in Equation 5.2

SIR (mm) = ETcrop (mm) – Effective rainfall (mm) Eq 5.2

Effective rainfall is calculated based on the formula developed by USDA Soil Conservation Service (1999) as followed in equation 5.3 and 5.4.

$$\mathrm{Pe} = \frac{TRF}{125(125-0.2*TRF)} \text{ , if TRF < =250mm per month} \qquad \text{Eq 5.3}$$

$$Pe = 125 + 0.1 * TRF\text{, if rainfall <250 mm per month} \qquad \text{Eq 5.4}$$

TRF is total rainfall on the month and * is multiplication sign

Asefa et al. (2016) also calculated the relative water satisfaction (RWS) as the ratio of effective rainfall (Pe) to crop water requirement (ETc) as given in Equation (5.5).

$$\mathrm{RW}S = \frac{\mathrm{Pe}}{\mathrm{ETc}} \qquad \text{Eq 5.5}$$

5.2.4. Data collection

5.2.4.1. Climatic data

Daily rainfall data and minimum and maximum air temperature, relative humidity, wind speed, and sunshine hours during the study period for each study site were collected from Ethiopian Metrological Service Agency, Mekelle branch and Mekelle Agricultural Research Center.

5 .2 .4.2. Soil data sampling and analysis

Profile pits were excavated at representative places of each experimental field during the growing season before planting to establish critical baseline data on the soil's physical properties. Disturbed and undisturbed soil samples at 0-30 cm depth were collected manually to determine some soil physical properties, including Field Capacity (%FC), Permanent Wilting Point (%PWP), Bulk density, and total available water (mm/m) of the experimental field soil (Table 5.1.). Undisturbed soil samples were collected using a cylindrical core sampler of known volume to preserve the natural soil structure. In contrast, disturbed samples were collected using a soil auger. The soil sample was analyzed in the Mekelle University and Mekelle soil center to determine particle size distribution (texture). Composite soil of the surface layer (0-0.3m) from representative plots was also taken before planting following the standard soil sampling procedure. Each composite soil sample was used for selected physico-chemical analysis, such as Soil texture, pH, total nitrogen (N), organic carbon (OC), cation exchange capacity (CEC), and available phosphorous (P). Soil analysis was conducted at the Mekelle Soil Research Center laboratory following standard procedures; to determine total nitrogen (Kjeldahl method), available phosphorus (Olsen and Dean 1965) organic carbon (Sikora and Moore, 2014) and soil pH (on 1:2.5 soil: water suspension) (Table 5.1)

Table 5.1 Soil physio-chemical properties of Elalla and Aynalem experimental sites at a depth of 0-30cm

Sites											Particle size(%			
	pH	EC (ds/m)	OM (%)	CEC (cmol /kg)	TN (%)	AV.P (ppm)	BD (g/cm^3)	FC (%)	PWP (%)	TAW (mm /m	Sand	Silt	clay	Soil texture
Elalla	7.02	0.63	1.62	43.13	0.09	15.89	1.28	32	18.5	135	40	22	38	Clay loam
Aynalem	7.25	0.37	2.25	27.20	0.12	49.02	1.51	27.5	15.5	140	48	10	42	Sandy clay

Note: EC = Electrical conductivity, OM = Organic matter, CEC= Cation exchange capacity of the soil, TN = Total nitrogen, Av. P = Available phosphorus BD =Bulk density, FC =Field capacity, PWP =Permanent wilting point, and TAW =Total available water.

5.2.4.3. Plant data

Fresh mature leaf samples of potato from each treatment were collected nine weeks after planting and oven dried overnight at 70 ^{0}C for 72 hours until constant weight. Then, the samples were ground and sieved through 2 mm sieve for N content analysis in the Mekelle Soil Research laboratory. Besides, to determine the N content, potato tuber samples were taken at harvest oven dried in an oven for 80^{0}C for 72 hours, ground and sieved in order to analyze the N content in the laboratory as described by Karma *et al.* (2009). The total nitrogen content in tuber and leaf samples were determined using Kjeldahl method as described by Jackson (1967), and Gupta and Saxena (1976).

5.2.4. 4. Growth, yield and yield component data collection:

Days to flowering and physiological maturity number of tubers per plant, tuber diameter, tuber weight, final tuber yield (marketable and unmarketable), and biomass yield and harvest index were collected. Days to flowering and physiological maturity were recorded when 50% of the plant population attained flowering stage and when the leaves of 75% of the plant in the plot turned yellowish, respectively. Plant height was determined by measuring height from the base of the main stem to the apex at full maturity. For tuber number and tuber diameter estimation, an average of 12 hills from the center of the sub plot treatment was used. Healthy tubers with weight > 25gm were considered as marketable, while rotten, diseased, insect attacked, deformed tuber and those having < 25gm in weight were categorized as unmarketable as described by National Potato Research Program (NPRP, 2014). Dry aboveground biomass at harvest and final tuber yield was obtained from two middle rows of each plot with an area of 3 m x 1.5 m (4.5 m^2). The dry weight was recorded after air- drying the fresh samples and further oven drying for 70 °C for 72 hours (constant weight). Harvest index was determined as the ratio of dry total tubers to the total dry biomass and taken at harvest.\

Incremental Yield = (Irrigated Crop Yield - Non-Irrigated Crop Yield) / Non-Irrigated Crop Yield

(Shammi and Meng, 2021)

5.2.5. Determination of potato tuber quality

Samples of potato tuber were taken at harvest, sliced and oven dried at a temperature of 80^0 C for 72 hours. Following the procedures of Karma et al. (2009), the dried samples were ground and sieved in order to analyze the nitrogen (N) contents at Mekelle Soil Research laboratory. The total nitrogen content in tuber samples were determined using Kjeldahl method as described by Jackson (1967). Then, the protein content of potato tuber (%) was calculated by multiplying the nitrogen (N) content of potato tuber with 6.25 (Ranganna, 1977). Likewise, the starch content (%) was obtained indirectly after measuring the specific gravity, as described by Widmann et al. (2008), Hassel *et al.* (1997), using equation 5.6 and 5.7.

$$\text{Starch content (\%)} = 17.565 + 199.07\ (S.G\ -1.0988). \qquad \text{Eq 5.6}$$

$$SG=\frac{Tuber\ weight\ on\ air(gm)}{Tuber\ weight\ on\ air(gm)-Tuberweight\ in\ water\ immersed\ (gm)} \qquad \text{Eq 5.7}$$

Where, S.G:- Specific gravity

To determine the dry matter content of each genotype, five plants from each sub-plot treatments were selected randomly, and from each plant, ten potato tubers were randomly selected. The tubers fresh weight was recorded first, and then the samples allowed to dry in an oven at a temperature of 80 ^{0}C for 72 hours. After a constant weight had attained, the samples were weighed to determine the dry matter (DM). Finally, the dry matter content was calculated as the ratio between dry and fresh mass expressed as a percentage.

5.2.6. Determination of water use efficiency (WUE) and Water productivity

The terms water use efficiency (WUE) and water productivity (WP) are often confused. In the context of crops, water-use efficiency (WUEc) is defined as the ratio of crop output per amount of water lost by the process of actual evapotranspiration (ETa) (Raes et al., 2007). Water use efficiency (WUE) and irrigation water use efficiency (IWUE) of potato were calculated following the procedures described by (Ati et al.(2012). Similarly, crop water productivity (WPc) is calculated as the marketable yield (kg ha^{-1}) divided by the water consumed (m^3 ha^{-1}) during the growing season (Fernández, 2023; Erdem et al., 2006). Following these authors' methods, we calculated the water-use efficiency (WUE), total crop water productivity (TWPC), crop water productivity (WPc), and irrigation water productivity (IWP) of potatoes using Equations 5.8, 5.9, 5.10, and 5.11.

$$WUE_c = \frac{\text{Biomass yield (Kg)}}{\text{Amount of water applied by irrigation(Irr) and rainfall(RF)(m3)}} \qquad \text{Eq 5.8}$$

$$TWPc = \frac{Total\ tuber\ yield\ (kg)}{Total\ effcetive\ rainfall\ (Pe) + Irrigation\ water\ applied\ (m3)} \qquad \text{Eq 5.9}$$

$$\text{WPc} = \frac{\text{Total marketable tuber Yield (kg)}}{\text{Total effective rainfall (Pe)+irrigation water applied (m3)}} \qquad \text{Eq 5.10}$$

WPc is Crop water productivity

$$\text{IWP} = \frac{\text{TMI}\left(\frac{\text{kg}}{\text{ha}}\right) - \text{TMNI}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{I(m3)}} = \frac{\text{Marketable tuber yield under irrigated }\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Irrigation water (m3)}} \qquad \text{Eq 5.11}$$

Where; TMI = Total Marketable tuber yield of an irrigated plot, TMNI = total marketable tuber yield in a non-irrigated plot and I = amount of irrigation supplied during the growing season of potato.

5.2.7. Data analysis

Data on crop yield and yield components were subjected to analysis of variance using ANOVA Mixed model procedure of SAS statistical software (SAS version10). This software also checked ANOVA assumptions (Normality, homogeneity, independence of group variances and means, independence of scores. In ANOVA, genotype and irrigation were considered as fixed effects, while year, location and replication as random effects. Most of the measured data derived from each experiment were non-significant in homogeneity of variance-following this combined analysis were implemented. Analysis of variance (ANOVA) was used to determine whether the treatments (variety and water) and the interaction between them have significant differences or not in response variables. Differences between the treatment means were computed by means of Duncan's Multiple Range Test (DMRT) at < 5 % level of significance, because it is a widely used procedure for comparing all pairs of means.

5.3. Results and Discussion

5.3.1. Climate and potato water requirement during the growing period

During the study period of 2019 and 2020, the total monthly rainfall and maximum and minimum temperature of the study areas are indicated in Figure 5.3. The total seasonal rainfall, mean maximum and minimum temperature of Mekelle, Elalla site is 559.4 mm, 26.8 and 13.6 ^{0}C, respectively (Figure 5.3A). In the same period the seasonal total rainfall, mean maximum and minimum temperature of Kilte Awlaelo, Aynalem site is 423mm, 27.9 ^{0}C and 13.6 ^{0}C, respectively (Figure 5.3B). The study areas Elalla and Aynalem sites received combined effective seasonal rainfall of 301.6 and 289.6 mm, respectively, during the growing season of potato. Furthermore, 97.03 mm and 73.09 mm of supplemental irrigation water were applied at the Elalla site in 2019 and 2020 growing seasons, respectively. In contrast, 89.22 mm and 100.27 mm of supplemental irrigation water were applied at the Aynalem site in the 2019 and 2020 cropping seasons, respectively. In general 85.06 mm and 94.75 mm combined mean of irrigation water was applied as supplement irrigation at Elalla and Aynalem sites, respectively

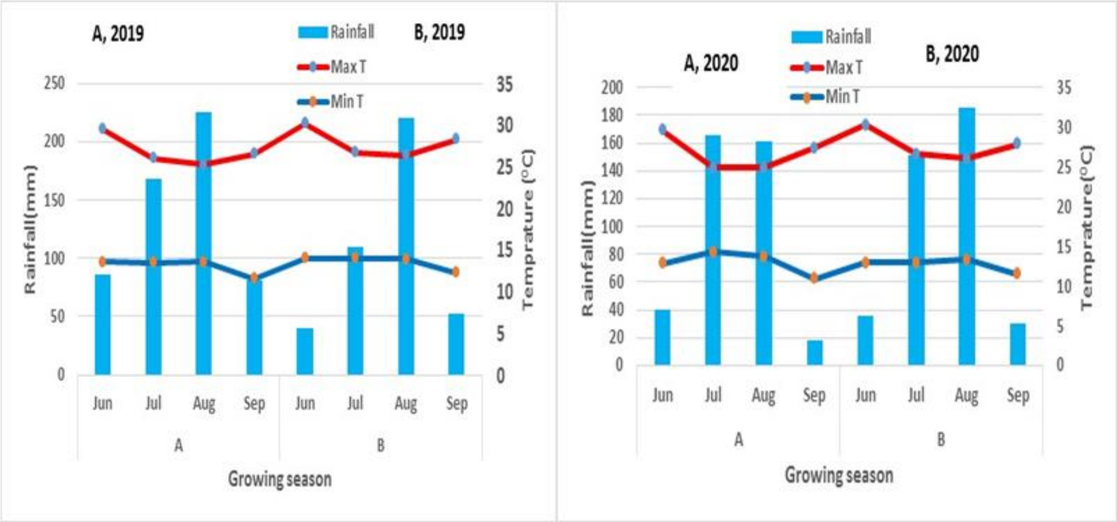


Figure 5.3. Monthly rainfall, mean maximum and minimum temperature of the study areas Mekelle, Elalla site (A) and Kilte Awlaelo, Aynalem site (B) in 2019 and 2020 growing season under rainfall condition.

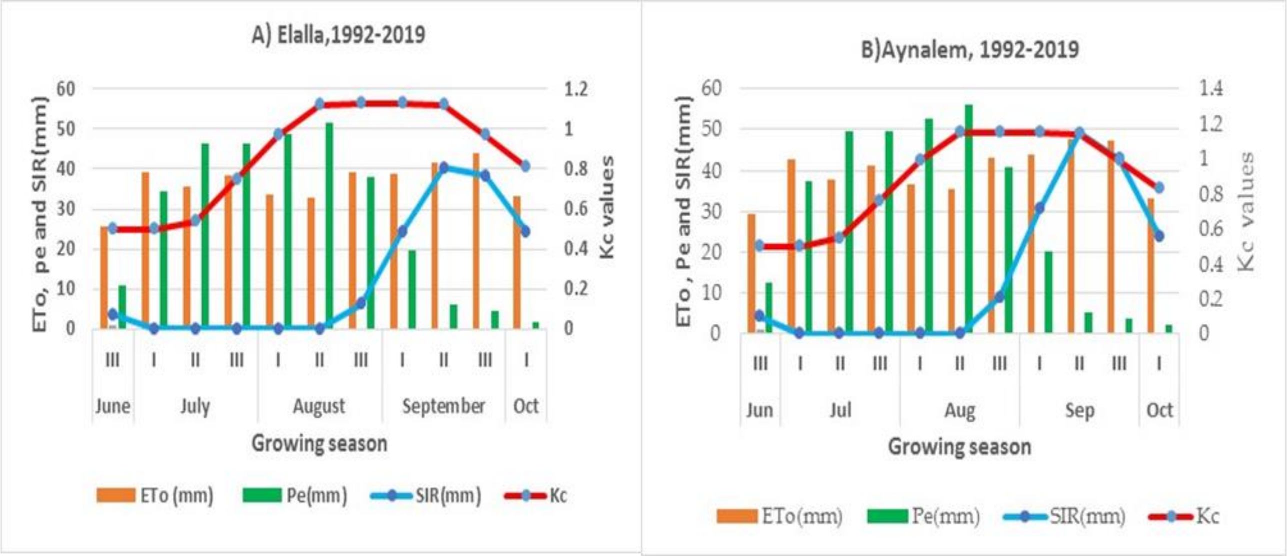


Figure 5. 4. Decadal seasonal crop water requirement (ETc), Reference evapotranspiration (ETo), Crop coefficient (Kc),Effective rainfall (Pe) and supplement irrigation needs (SIR) estimated for potato using long-term mean climate inputs, used for planning purposes under rainfall condition (1992-2019).

Note: I, II, and III, are 1st, 2nd and 3rd decades (10 days) of a month

The long term mean total seasonal rainfall amount was less than the crop water requirement of potato in both locations, indicates potato requires supplement irrigation, in addition the seasonal amount of rainfall during the experiment period was also less than potato water requirement. As a result, water was applied as supplement irrigation relatively similar with the long-term water required to apply as supplement irrigation for potato. The total seasonal amount rainfall was relatively stable in Mekelle, Elalla site than Kilte Awlaelo, Aynalem area. This implies that application of water, as supplement irrigation in the areas was paramount. On the other hand, its high temporal variations could cause an indeterminate drought that deters potato production**.** Similarly, Gebremedhin et al. (2023) reported that the total seasonal amount of crop water requirement of wheat was relatively stable in this area. The number of irrigations depends on the length of the dry periods and potato genotypes growing period. Accordingly, 3–5 irrigations were applied based on the water deficit of the seasons. The long-term and short-term seasonal rainfall results indicate that potato crops require supplemental irrigation due to water deficits in late June (caused by late-onset rainfall during emergence) and late August to early September (caused by early rainfall cessation during flowering and tuber initiation). Applying measured supplemental irrigation based on deficit levels is crucial to minimize yield reduction and improve productivity. This result indicates that natural rainfall alone is inadequate for potato production, hence supplement irrigation based on potato crop water requirement is important in late June, late August, September and even October (depending on potato growing period and planting date) to produce potato (Fig 5.4). Similarly, Gebrehiwot T and Veen.van der, 2011 reported that more than 70% of annual rainfall in the Tigray, Ethiopia is received only in July and August. In addition, the rainfall is either too much at one time and no at another time (Araya and Stroosnijder, 2011).

5.3.2. Growth parameters and yield component of potato genotypes

The result indicated in the Table 5.2 indicates that interaction effects of genotype and supplement irrigation significantly influenced days to flowering and maturity, furthermore the main effect of genotype and irrigation level affected potato growth and yield component parameters (Table 5.2).

5.3.2.1. Days to flowering and maturity

Days to flowering and physiological maturity were significantly affected by the main, and interaction effects of genotype and irrigation. Early averge days to flowering and days to maturity were detremined at the interaction effect of genotypes CIP-394611.112 and CIP-390478.90 with supplement irrigation and no irrigation, while the late average days to flowering days to maturity was recorded at the interaction effect of genotype CIP-392661.18 with supplement irrigation (Table 5.2).

Table 5.2. The Interaction effect of genotype and irrigation on growth parameters of potato.

Genotype	Days to flowering		Days to maturity	
	Supplement irrigation	No irrigation	Supplement irrigation	No irrigation
CIP-394611.112	46.5^{e}	46.25^{e}	85.75^{c}	81.75^{d}
CIP-390478.90	46.58^{e}	46.42^{e}	85.58^{c}	82.25^{d}
CIP-392661.18	56.75^{a}	55.08^{b}	113.67^{a}	107.00^{b}
Gudanie	54.00^{c}	53.75^{c}	112.92^{a}	107.33^{b}
Seohong	51.58^{d}	51.75^{d}	85.67^{c}	81.92^{d}
CV (%)	1.8		1.5	
LSD	0.7289*		1.162***	

Means of the same interaction effect within two column followed by the same letter are not significantly different at 5% of probability level (ns), and different letter are significant (*) at $P < 0.05$, highly significant (**) $0.01 \leq P > 0.001$ and highly significant (***) $P \leq 0.001$, LSD is least significant difference.

The highest average days to physiological, maturity was recorded at the interaction of each genotype with supplement irrigation (SI); this indicates that as water amount increases, days to maturity of potato genotype increase, the reverse is also true. The difference in days to maturity and flowering may be mainly due to the genetic variation of the genotype with similar application of supplement irrigation. In agreement with this result Fantaw et al.(2019) found that varieties affect the days to maturity. Similarly Fantaw et al. (2019) reported varieties could affect the flowering and maturity, and it provides the basis for the selection of late or early maturing varieties depending upon the rainfall duration, temperature and labor availability. Furthermore, Girma (2012) reported that the variation among varieties in the length of the growing period might be due to the difference in genetic makeup. Asefa et al.(2016) also reported that flowering and maturity are heritable traits of potato crop. Therefore, these genotypes having early days to flowering and days to maturity is an important characteristic for the semiarid areas of Tigray when rainfall starts late and early onset with small amount of seasonal rainfall. The present study also confirms that there is early maturing potato genotypes that could be grown in semi-arid areas under the existing insufficient rainfall condition with satisfactory yield. In addition, number of days to flowering and maturity are vital for farmers to plan and develop a suitable production system.

5.3.2.2. Plant height (cm)

According to this study, plant height was significantly influenced by genotype but not by irrigation and location or their interaction. Gudanie and CIP-392661.18 were the tallest to the other genotypes. Whereas, Seohong was the shortest genotype (Table 5.3). The tallest plant height was recorded from genotype Gudanie whereas the shortest from genotype Seohong. This is due to the genetic variation among genotypes. In agreement with this result, Asmita and Rajkumari (2022) and Shrestha et al. (2020) reported that plant height was affected by variety. Bhuwneshwari et al. (2013) and Kumar et al. (2008) also reported that varieties showing differential results in plant height could be due to genetic and inherent characteristics. In contrast to this result, Bilate and Mulualem (2016) found that the environment, cultivar and their interaction in Eastern Ethiopia affected plant height.

5.3.2.3. Yield component

The result of the study also shows that average number of tubers per plant, average tuber weight(g) and average tuber diameter were highly significant infulenced by the main effect of genotype and irrigation (Table 5.3). Whereas, average tuber length (mm) were significantly influenced only by the main effect of genotype. However, both yield components were not been significantly influenced by the interaction effect of the two factors (genotype and irrigation). The largest number of tubers per plant and tuber weight were obtained from CIP-390478.90, Gudanie and CIP-394611.112 (Table 5.3). With respect to the main effect of irrigation, higher and significant average number of tubers per plant and tuber weight was obtained in supplement irrigated treatment while the lowest on no irrigated treatment. The largest tuber diameter and tuber length 48.72 and 68.18 mm, respectively were recorded in the genotype Gudanie (Table 5.3)

Table 5.3. The main effect of genotype and irrigation on growth and yield component of potato genotypes .

Treatment	Plant height (cm)	Average number of tubers per plant	Average tuber weight(gm)	Average tuber diameter (mm)
Genotype				
CIP-394611.112	56.19^{b}	11.14^{a}	64.83^{ab}	48.04^{a}
CIP-390478.90	56.80^{b}	11.39^{a}	62.21^{b}	46.95^{ab}
CIP-392661.18	64.32^{a}	11.24^{a}	67.04^{a}	47.50^{ab}
Gudanie	69.73^{a}	9.99^{b}	62.38^{b}	48.95^{a}
Seohong	49.82^{c}	8.95^{b}	53.28^{c}	45.69^{b}
CV (%)	9.4	10.38	9.8	7.4
LSD	4.059***	1.002***	4.940*	2.848*
Irrigation				
1. No irrigation	58.76^{a}	9.89^{b}	59.71^{b}	46.70^{b}
2.Supplement Irrigation	59.98^{a}	11.19^{a}	64.42^{a}	48.16^{a}
CV (%)	9.4	10.7	9.8	14.8
LSD	1.815^{ns}	0.842***	2.209*	1.274*

Note: Means of the same main effect within column followed by the same letter are not significantly different at 5% of probability level (ns), and different letter are significant (*) at P< 0.05, highly significant (**) 0.01≤ P>0.001 and highly significant (***) P≤ 0.001, LSD is least significant difference.

The result of this study indicates that the major yield component of potato, such as number of tubers per plant and average tuber weight attributes to total potato tuber yield was affected by genotype and irrigation. Therefore, this study identifies potato genotype (s) with high tuber number and tuber weight could possible to produce the potato in the semiarid areas of Tigray with supplement irrigation and selected genotype. The genotypes tested were not affected to the same degree by irrigation. Responsiveness to irrigation in terms of tuber number and tuber weight varied greatly between supplement and no irrigation . In agreement with this study, Lahlou et al .(2003) reported that numbers of tuber per plant were statistically significant affected by water treatment and potato cultivars. Luitel et al . (2015) reported that plant height, marketble tuber number per plant was infulenced by genotype and irrigation. In addition, they reported that genotype by irrigation interaction did not affect plant hight. However, the total tuber number of tubers per plant and marketable tuber weight had not significantly been influenced by genotype and irrigation interaction which was contradictory to this result. Djaman et al. (2021) also reported that the highest number of tubers per plant of irrigated potato compared to rain-fed production. The plant height, tuber number per plant, and tuber weight difference in irrigated treatment among the genotyopes is mainly due to genetic differences. Many researchers like Luitel et al. (2020), Tessema et al., (2020) and Eaton et al. (2017) also reported that number of tubers per plant were affected by variety, similarly Banjade et al. (2019) and Fantaw et al. (2019) found that different varieties had significantly differed in terms of tuber number per plant and weight of tuber.

5.3.3. Effect of supplement irrigation on yield of potato genotypes

5.3.3.1. Tuber yield

The highest significant marketable, total tuber and biomass yield was obtained at the interaction of genotype CIP-394611.112, and CIP-390478.90 by supplement irrigation (Table 5.4). The interaction of these genotypes CIP-394611.112 without irrigation (rainfall only) was also significantly different with the other interaction of genotypes through supplement irrigation (Table 5.4). Each genotypes CIP-390478.90 and CIP-394611.112 interaction with supplement irrigation had the highest marketable yield of 27.13 and 26.65 t ha^{-1}, respectively. Furthermore, the highest total tuber yield 28.71 and 27.14 t ha^{-1} was recorded from genotype CIP-390478.90 and CIP-394611.112 respectivly undersupplement irrigation. However, the lowest marketable yield and total tuber yield were registered at the interaction of genotype Seohong by either no irrigation or supplemental irrigation treatments (Table 5.4). Mean comparisons of attributes among interaction of genotype by irrigation showed that marketable and total tuber yield of genotypes CIP-390478.90 and CIP-394611.112 interaction by either supplement irrigation or no irrigation was higher than the tuber yields of other genotype interaction by irrigation treatments (Table 5.4). Applying water as supplement irrigation (SI) to potato crop resulted in significant difference ($p < 0.05$) on marketable and total tuber yield tuber among genotypes. This result indicates that the genotypes tested were not affected similarly by supplement irrigation. Responsiveness to irrigation in terms of marketable and total tuber yield varied greatly among the different genotypes. Therefore, marketable and total tuber yield differences among the genotyopes are mainly due to genetic differences. In agreement with this result, Luitel et al. (2015) reported that marketable tuber yield was significantly affected of genotype, irrigation, genotype by irrigation interaction. Similarly, Gebremedhin et al. (2023) indicated that grain yield of wheat was significantly affected by supplement irrigation in semi-arid areas. Oweis and Hachum (2003) and Oweis and Hachum (2012) found that Supplemental irrigation, especially during critical crop growth stages, can improve crop yield and water productivity and yield increases are remarkable even when rainfall is as high as 500 mm. Moreover Raja et al. (2011) found that supplemental irrigation at different critical crop growth stages; higher yield and economic returns were achieved with lesser irrigation water usage. Fox and Rockstrom (2003) also reported that Supplemental irrigation had a significant effect on grain yield. Khanna –Chopra and Singh (2011) reported that good yields of potato under irrigation in the temperate and subtropical climates are 25 to 35 t ha^{-1} fresh tubers and in tropical climate yields are 15-to 25 t ha^{-1}. This result implies that tuber yield of potato trait had directly associated with genotype and irrigation as agronomic practice. Therefore, genotype CIP-394611.112 and CIP-3960478.90 are promising potato genotypes for semi-arid areas of Tigray to produce high tuber yield under rainfed condition.

Table 5.4 Interaction effect of genotype and irrigation on yield of potato under rainfall condition

Genotype	Marketable tuber yield (t ha^{-1})		Total tuber yield	
	Supplement irrigation	No irrigation	Supplement irrigation	No irrigation
CIP-394611.112	26.65^{a}	24.45^{b}	28.14^{a}	25.60^{b}
CIP-390478.90	27.13^{a}	22.14^{c}	28.71^{a}	23.17^{c}
CIP-392661.18	22.82^{bc}	20.27^{d}	25.16^{b}	21.47^{c}
Gudanie	19.25^{d}	14.62^{e}	21.82^{c}	16.85^{d}
Seohong	13.62^{e}	13.08^{e}	14.91^{e}	14.13^{e}
CV (%)	10.00		9.60	
LSD	1.666*		1.722*	

Note: Means of the same interaction effect within a column followed by the same letter are not significantly different at 5% of probability level (ns), and different letter are significant (*) at P< 0.05, LSD is least significant difference

The study found that the highest marketable and total tuber yields were obtained by applying 68.77 mm of supplemental irrigation during the rainy season, compared to no irrigation. The lowest yields were associated with the lowest amount of supplemental irrigation at 59.00 mm. Furthermore, the genotypes Gudanie and CIP-392661.18 received the highest amounts of supplemental irrigation at 127.7 mm and 125.9 mm, respectively (Fig 5.5), but these genotypes did not achieve the highest marketable and total tuber yields. Instead, the genotypes CIP-3960478.90 and CIP-394611.112, which received lower amounts of supplemental irrigation and effective rainfall, achieved the highest marketable and total tuber yields (Table 5.4). The increment in marketable and total tuber yield due to the application of supplemental irrigation, compared to rainfed conditions, was also significantly different among the genotypes. The highest increment in total tuber yield (5540.0 kg ha $^{-1}$) and marketable yield (4986.7 kg ha $^{-1}$) was obtained from genotype CIP-3960478.90, while the lowest was from the genotype Seohong (Fig 5.5).

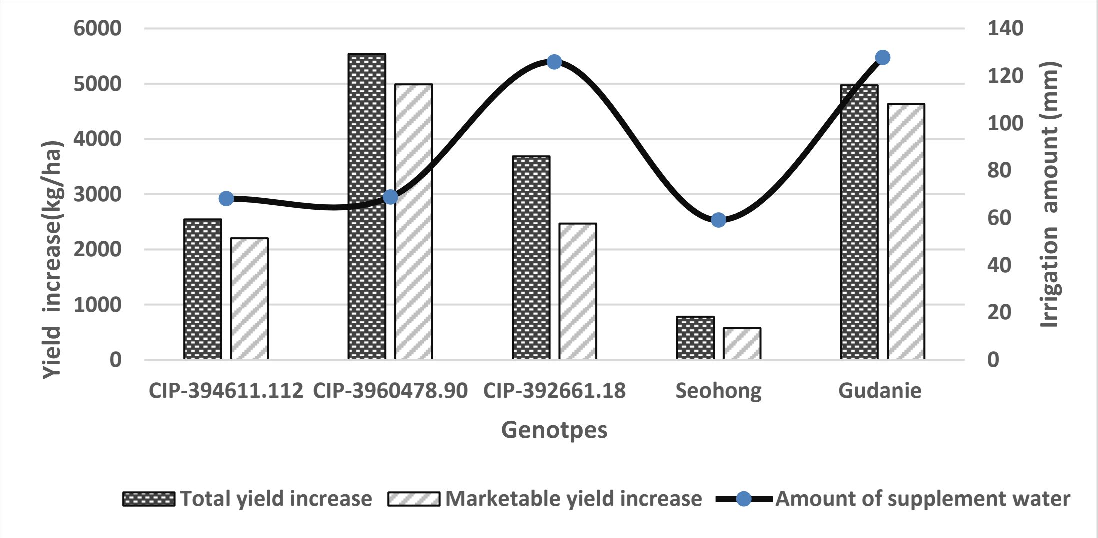


Figure 5.5. Tuber yield increasement (kg ha -1) due to supplement irrigation.

The highest increase in marketable and total tuber yield from irrigated to non-irrigated conditions was not a guarantee that a genotype could have the highest overall yields. The yield gap between irrigated and non-irrigated conditions is more important, as seen with genotype CIP-394611.112, which had high yields under both irrigated and non-irrigated conditions, but a lower yield increase compared to genotypes like Gudanie, which had a larger yield gap between the two conditions and low marketable and total tuber yield. In summary, the application of 68.77 mm and 68.12 mm of supplemental irrigation during the rainy season resulted in the highest marketable and total tuber yields from genotypes CIP-3960478.90 and CIP-394611.112, respectively. However, the genotypic response to supplemental irrigation varied. Moreover, the yield gap between irrigated and non-irrigated conditions was more important than the absolute yield increase from irrigation in this study.

5.3.3.2.Harvest index

The result indicated that the harvest index was affected significantly by genotype and irrigation but not by their interaction (Fig 5. 6) .The, maximum harvest index of 0.88 and 0.87 was found in the genotypes CIP-3960478.90 and Seohong, respectively, while the lowest determined in the genotype Gudanie. In the case of irrigation, the highest harvest index was obtained under supplemental irrigation (Figure 5.6). In the case of irrigation, the highest harvest index was obtained under supplemental irrigation. This result implies that harvest index was affected by genetic difference of a genotype and application of water. In contradictory to this result, Mazurczyk et al. (2009) reported that diverse water supplies did not change harvest index (HI) values of potato. Therefore, HI is a novel trait directly associated with yield of potato and more influenced by genetic trait; it is an important indicator and direct proportional to an economic yield of a crop.

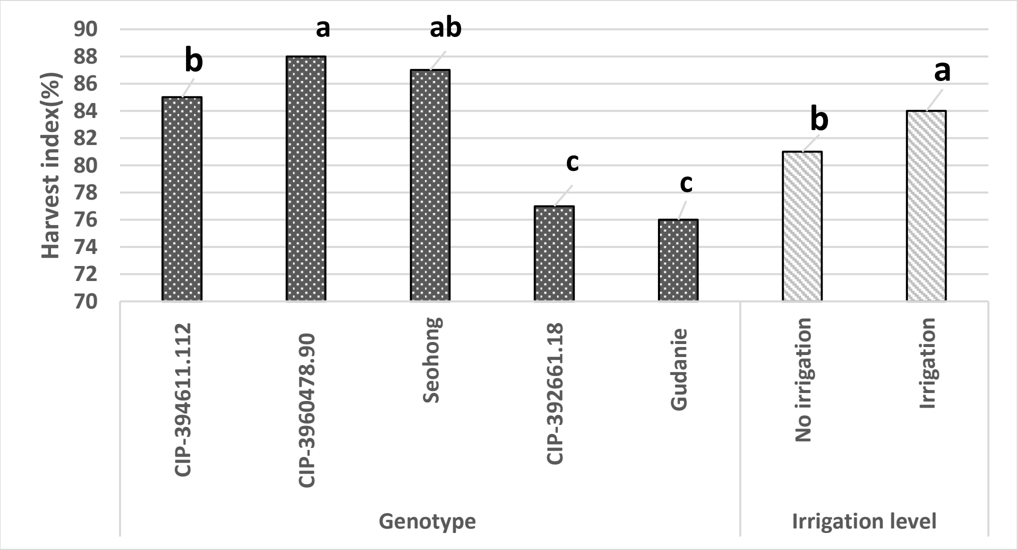


Figure 5.6. Effect of genotype and irrigation on harvest index

Graph with different letters showed significant different of harvest index among genotype at (P <0.001) and between irrigation level at P ≤ 0.05 but similar letter had no significant different

5.3.4. Effect of supplement irrigation on quality of potato genotypes

The analysis of variance indicated that the interaction effect of gentype by irrigation did not significantly affect the tuber quality of potato such as dry matter (DM), specfic gravity (SG) , starch content (%) and protien content. The main effect of genotype and irrigation did not affect specfic gravity, strach content and protien content. Dry matter of potato tuber was affcted by genotype but not by irrigation. Siginficantly the highest dry matter content of potato was found from genotypes CIP-390478.90, CIP-394611.112 and CIP-392661.18 in descending order (Table 5.5). Minimum value of dry matter was recorded from genotype Gudanie. Maximum specific gravity and starch content was found due to the main effect of genotype CIP-390478.90 whereas minimum specific gravity and starch content obtained on genotype CIP-394611.112 and Seohong, respectively (Table 5. 5). The result in this study indicates that quality of potato such as specific gravity, starch content and protein not influenced by genotype or genetic trait of potato and application of irrigation or amount of water applied. Moreover, a slightly higher specific gravity and starch content was recorded in supplement irrigation (SI) treatment than non-irrigated (NI). The highest and the lowest protein contents were found on genotypes Gudanie and Seohong, respectively. Furthermore, almost similar protein content was found on supplemental and no irrigation treatment. However, the difference in specific gravity, starch content and protein content had no significant difference due to genotype and irrigation interaction. This result indicates that genotypes with high specific gravity displayed higher percentage of dry matter content while low dry matter was observed in genotypes with low specific gravity(Table 5.5). In agreement with this result, Kaur and Aggarwal (2014) reported that in most of the cultivars there is no significant difference in specific gravity but significant difference between the lowest and highest specific gravity which is contradictory to this result. While the data show no statistically significant differences in specific gravity among the genotypes or irrigation treatments, the numerical trends align with the established principle that higher specific gravity is linked to better frying quality. Therefore, the observed trend of higher specific gravity, particularly in certain genotypes, may indicate a potential for improved tuber quality for frying. In agreement with this result, Abbas et al. (2015) reported that the specific gravity of tubers from the irrigated treatment was higher than that from the non-irrigated treatment. Previous studies indicated that lower specific gravity of potato tuber obtained by deficient irrigation (Ojala et al., 1990). In contrast, some researchers (Eldredge et al., 1996) observed an increase in specific gravity in Russet Burbank potato cultivar under deficit irrigation. In general, the difference in dry matter, specific gravity, starch content and protein content might be related to genetic variations among different genotypes Similar observations had been reported earlier for different cultivars of potatoes (Dean, 1994). Dry matter was affected by genetic trait but not by amount of water applied as supplement irrigation to potato crop. In harmony with this result, Kaur and Aggarwal (2014) reported that dry matter content of potato was affected by cultivar. Zarzecka and Gasiorowska (2002) reported that variety determined the dry matter and starch contents of potato tuber. Furthermore, Marwaha et al.(2010) defined that dry matter content is an important quality determining trait in potato processing and its higher content (>20%) allow lesser oil uptake, desirable texture and enhanced yield in the finished products. Therefore, the result of this study indicates that regardless of their significant difference all the genotypes had good quality in case of dry matter.

Table 5.5 Effect of genotype and irrigation on tuber quality of potato

Treatment	DM (%)	Specific gravity (g cm^{-3}	Starch content (%)	Protein content (%)
1.Genotype				
CIP-394611.112	24.08^{ba}	1.074^{a}	12.58^{a}	2.13^{a}
CIP-390478.90	24.77^{a}	1.078^{a}	13.28^{a}	2.13^{a}
CIP-392661.18	23.22^{bc}	1.075^{a}	12.78^{a}	2.09^{a}
Gudanie	22.40^{c}	1.072^{a}	12.25^{a}	2.21^{a}
Seohong	22.17^{c}	1.070^{a}	12.20^{a}	2.09^{a}
CV (%)	10.10	2.7	24.9	13.7
LSD($P<0.05$)	1.359**	0.013^{ns}	2.508^{ns}	1.061^{ns}
2. Irrigation				
1. No irrigation	23.29^{a}	1.076^{a}	13.01^{a}	2.13^{a}
2.Suplement irrigation	23.36^{a}	1.072^{a}	12.23^{a}	2.13^{a}
CV (%)	11.09	2.7	24.9	13.70
LSD($P<0.05$)	0.860ns	0.008^{ns}	1.586^{ns}	0.671^{ns}

Means of the same main effect within two column followed by the same letter are not significantly different at 5% of probability level (ns), and different letter are significant (*) at $P< 0.05$, and highly significant (**) $0.01\leq P>0.001$, LSD is least significant difference

5.3.5. Effect of irrigation on water productivity potato genotypes

The result in table 5.6 indicated that total water productivity (TWP) of potato was affected by the main and interaction effect of irrigation and genotype. Irrigation water productivity was only affected by the main effect of genotype (Table 5.6 and Fig 5.7). The highest Water Productivity (WP) of 8.51 kg m^{-3} was observed for the genotype CIP-394611.12 under the no-irrigation treatment (Table 5.6). This indicates that this genotype was the most efficient at utilizing the total water available, which in this case was only rainfall. The genotype CIP-396047.90 demonstrated the highest Irrigation Water Productivity (IWP) of 6.76 kg m^{-3} (Fig 5.7). This shows that this specific genotype was the most effective at converting applied irrigation water into tuber yield.

Table 5.6 Interaction effect of genotype and irrigation on water productivity

Genotype	Water productivity (kg m^{-3})	
	Irrigated	No irrigated
CIP-394611.112	7.42^{b}	8.51^{a}
CIP-390478.90	7.59^{b}	7.71^{b}
CIP-392661.18	3.84^{f}	4.53^{e}
Gudane	5.41^{d}	6.79c
Seohong	4.60^{e}	4.91^{de}
CV (%)	14.54	
LSD	0.541***	

Note: Means of the same interaction effect within two column followed by the same letter are not significantly different at 5% of probability level (ns), and different letter are significant (*) at $P< 0.05$, highly significant (**) $0.01\leq P>0.001$ and highly significant (***) $P\leq 0.001$

Higher water productivity was recorded at the interaction of genotype with no irrigation, whereas the lower water productivity was found at the interaction of genotype with supplement irrigation with in the same genotype. Water productivity is often higher in non-irrigated environments because the plant was forced to use a limited water supply more efficiently.For farmers in water-scarce environments, selecting a drought-efficient genotype like CIP-394611.112 and potentially reducing irrigation could lead to better water use without a proportional loss in yield. This genotype appears to be well adapted to water stress.In this study, plots that received higher amount of water through rainfall at July and August that was not less than the crop evapotranspiration (ETc), however at September and October, the potato water requirement higher than the rainfall the plot received rainfall as a result it is important to supply water as supplement irrigation. In line to this, Gebrehiwot and Veen.van der, 2011 reported that more than 70% of annual rainfall in the Tigray, obtained only in July and August. In addition, the rainfall is either too much at one time and no at another time (Araya and Stroosnijder, 2011). Furthermore, the significant difference in water productivity and irrigation water productivity among genotypes was due to difference in genetic make of the crop in physiological maturity and water requirement. This result also implies that genotypes, which received the lower amount of irrigation water with constant effective rainfall, gave the higher water productivity and irrigation water productivity. There was also significant difference with in the interaction of genotype with supplement irrigation, and no irrigation with genotype; this may be due to the genetic makeup of the genotype. Therefore, the genotypes of the same crop and the amount of irrigation water applied influenced water productivity and irrigation water productivity. Similarly, Badr et al. (2012), and Yuan et al. (2003) confirmed this result as the lower utilizing rate of irrigation water received the higher the water use efficiency. When these genotypes receive lower irrigation, these superior traits are activated, allowing them to produce a disproportionately high yield compared to a non-efficient genotype under the same low-water conditions, resulting in a higher Water Use Efficiency.In agreement with the present result, Ahamd et al. (2018) found that water use efficiencies of potatoes were significantly influenced by irrigation. Many researchers reported variability of water use efficiency with variable variety, and irrigation regimes. In agreement with this result, Oweis and Hachum (2003) indicted that supplemental irrigation, especially during critical crop growth stages, can improve water productivity. This result agrees with the findings of Tolessa et al. (2016) who reported that the highest water use efficiency obtained from Jaleni variety, increased with increased irrigation water amount up to 80%, and disagrees with this result that the interaction effect of variety and supplement irrigation affects water use efficiency. An increase in irrigation water amounts resulted in decrease in water use efficiency; this may be due to accumulation of excess moisture in the root zone and consequently resulted in decreasing the yield of potato. In line with this result, Khanna –Chopra and Singh (2011) reported that water utilization efficiency for harvestable tubers was 4-7 kg m^{-3}. Genotypes having high water use efficiency alone may not be rewarding, as it may be associated with low yield. In this study, we found that genotypes with high tuber yield have high water use efficiency under semi-arid areas of Tigray. Therefore, genetic variation have considerable importance in water productivity and irrigation water productivity of potato in the study area. Considering the cost of water other factors constant the genotype that gave high tuber yield and water productivity with low amount of water is profitable. In this case, genotypes CIP-394611.112 and CIP-390478.90 are appropriate in terms of tuber yield, water productivity, irrigation water productivity and profitability in semi-arid areas of Tigray.

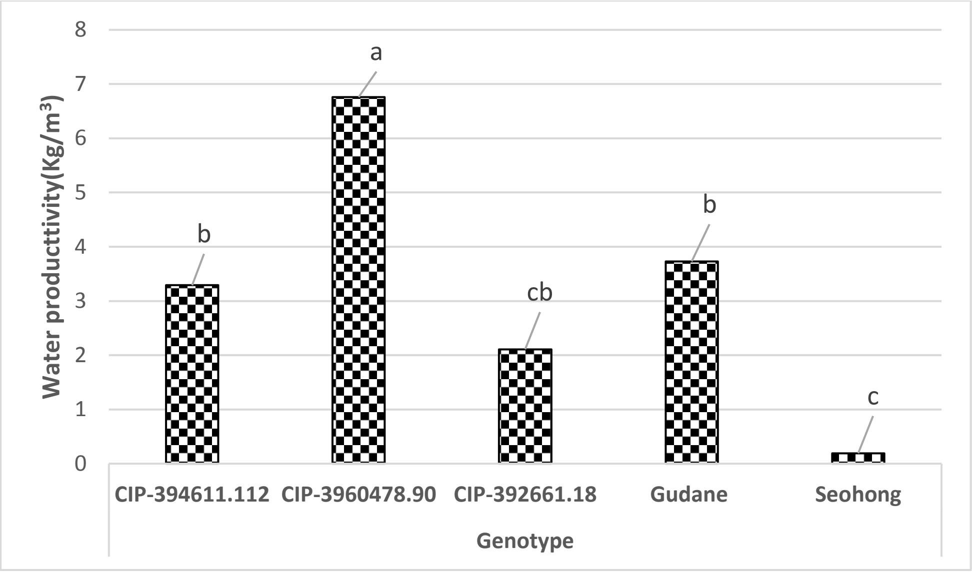


Figure 5.7. Main effect of genotype to irrigation water productivity (IWP)
Graph with t with different letters showed significant different of irrigation water productivity among genotype at $P \leq 0.05$ but similar letter no significant different

5.4. Conclusion and Recommendation

It can be concluded that the main and interaction effects of irrigation and genotypes significantly affected days to flowering, days to maturity, marketable yield, total tuber yield, irrigation, and total water productivity. Whereas, harvest index was affected by the main effect of genotype and irrigation. The highest marketable and total tuber yield with shorter days to flowering and maturity were obtained from genotypes CIP-394611.112 and CIP-390478.90 under supplemental irrigation. In this study 27.13 and 28.71 t ha^{-1} of marketable and total tuber yield, respectively, were obtained from genotype CIP-390478.90 under application of 68.77 mm of water as supplemental irrigation to effective rainfall of 289.1mm followed by genotype CIP-394611.112. The highest marketable (24.45 t ha^{-1}) and total tuber yield (25.60 t ha^{-1}) was recorded from genotype *CIP*-394611.112 under no irrigation. Applying supplemental irrigation improved total tuber yield in the range of 781.7 to 5540.0 kg ha^{-1} depending on the genotype. On the other hand, potato tuber qualities were not significantly influenced by irrigation and genotype. The highest total water productivity (8.51kg m^{-3}) and (7.59 kg m^{-3}) had achieved from genotypes *CIP*-394611.112 interaction with no irrigated and genotype CIP-390478.90 under supplement irrigation , respectively. The genotype(s), which received lower amount of irrigation water, gave high water productivity. It is also conclude from this study that the amount of effective rainfall was less than the crop evapotranspiration at September and early October, and then to fulfill the water requirement of the crop, the rainfall amount of water alone is inadequate for potato production in semi–arid areas of Tigray. Hence, it is recommended to apply supplemental irrigation in September to early October to produce high yield of potato. Genotypes CIP-394611.112 and CIP-3960478.90 can be recommended to semi-arid areas to produce high tuber yield with high water productivity in short growing period. We also recommend these genotypes for National Potato Breeding programs for further verification test and release.

5.5. References

Abbas, H. and Ranjan, R.S. 2015. Effect of soil moisture deficit on marketable yield and quality of potatoes. *Canadian Biosystem Engineering Journal*, *57*.

Ahmad, F.A., Salih, S.A. and Mahmood, Y.A. 2018. The Effect of Different Irrigation Interval on Tuber Yield and Quality of Potato (Solanum tuberosum L.). Kurdistan Journal of Applied Research, 3(2): 27-30.

Ahmadi, S.H, Andersen, M, N., Plauborg, F., Poulsen, R, T., Jensen, C, R., Sepaskhah, A, R, and Hansen, S. 2010. Effects of irrigation strategies and soils on field grown potatoes: Yield and water productivity. Agricultural-productivity. Agricultural Water Management, 97(11):1923-1930.

.Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, *300*(9), D05109.

Araya, A. and Stroosnijder, L. 2011. Assessing drought risk and irrigation need in northern Ethiopia. *Agricultural and Forest meteorology*, *151*(4): 425-436.

Asmita, O. and Rajkumari, A.D. 2022. Varietal evaluation of different potato (Solanum tuberosum L) varieties. The Pharma Innovation Journal, 11(9): 909-918.

Assefa S, Biazin, B., Muluneh, A., Yimer, F. and Haileslassie, A. 2016. Rainwater harvesting for supplement irrigation of onions in the southern dry lands of Ethiopia, Agric.Water Mang, 178: 325-334.

Ati, A.S., Iyada, A.D. and Najim, S.M. 2012 Water use efficiency of potato (Solanum tuberosum L.) under different irrigation methods and potassium fertilizer rates. *Annals of Agricultural Sciences,* 57(2):99-103.

Badr, M. A., El-Tohamy, W. A. and Zaghloul, A.M. 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region, Agric. Water Manage, (110): 9-15.

Banjade, S., Shrestha, S, M., Pokhrel, N., Pandey, D. and Rana, M. 2019.Evaluation of Growth and Yield Attributes of Commonly Grown Potato (Solanum tuberosum) Varieties at Kavre, Nepal. International Journal of Scientific and Research Publications, 9 (11): 134-142.

Beals, K.A. 2019. Potatoes, nutrition and health. *American journal of potato research*, *96*(2): 102-110.doi.org/10.1007/s12230-018-09705-4

Bhuvaneswari, S., Sharma, S.K., Punitha, P., Shashidhar, K.S., Naveenkumar, K.L., and Prakash, N. 2017.Evaluation of morphological diversity of field pea (Pisum sativum subsp. arvense L.) germplasm under sub-tropical climate of Manipur. Legume Research-An International Journal, 40(2): 215-23.

Bilate, B. and Mulualem, T. 2016. Performance evaluation of released and farmers' potato (Solanum tuberosum L.) varieties in eastern Ethiopia. Sky Journal of Agricultural Research, 5(2):034-41.

Central Statistical Agency of Ethiopia (CSA). 2017. Agricultural Sample Survey 2016/2017. Report on Area and Production of Major Crops. Private Peasant holdings, Meher Season, Volume I; 12-18. Addis Abeba, Ethiopia

Chapagain, T.R, Tiwari, D.N., Adhikaari, R.C, Khatri, B.B. and Luitel, B. 2014. *Performance of potato clones in Mid Hill of Western Nepal*. In Proceedings of National Potato Research Workshop, 31st March to 2nd April (pp. 11-16).

Daccache, A, Weatherhead, E, K., Stalham, M, A. and Knox, J.W. 2011. Impacts of Climate Change on Irrigated Potato Production in a Humid Climate. Agric.For.Meteorol, 151: 1641–1653.

Dean, B.B. 1994. Cultivation, fertilization, and irrigation. *Managing the potato production system. Haworth Press, Inc. New York*, 69-83

Devaux, A., Goffart, J. P., Kromann, P., Andrade-Piedra, J., Polar, V. and Hareau, G. 2021. The Potato of the Future: Opportunities and Challenges in Sustainable Agri-food Systems. Potato Research, 64: 681–720.

Devaux, A., Goffart, J.P., Petsakos, A., Kromann, P., Gatto, M., Okello, J., Suarez, V. and Hareau, G. 2020. Global food security, contributions from sustainable potato agri-food systems. The potato crop: Its agricultural, nutritional and social contribution to humankind, 3-35

Djaman, K., Irmak, S., Koudahe, K. and Allen, S. 2021. Irrigation management in potato (Solanum tuberosum L.) production: A review. Sustainability, 13(3): 1504.

Eaton, E .T., Azad, A.K., Kabir, H. and Siddiq, A. B. 2017. Evolution of Six modern varieties of potatoes for yield, Pant Growth Parameters and Resistance to Insects and Diseases. Agricultural Sciences, 8(11): 1315.

Eldredge, E. P., Holumes, Z. A., Mosley, A. R., Shock, C. C. and Steiber, T. D. 1996. Effect of transitory water stress on potato tuber stem-end reducing sugar and fry color .American potato Journal, 73(11): 517- 530.

Erdem, T., Erdem, Y., Orta, H. and Okursoy, H., 2006. Water-yield relationships of potato under different irrigation methods and regimens. *Scientia Agricola*, *63*: 226-231.

Fantaw, S., Ayalew, A., Tadesse, D, and Agegnehu, E. 2019. Evaluation of potato (Solanum tuberosum L.) varieties for yield and yield components. Journal of Horticulture Forestry, 11 (3): 48-53.

Fernández, E. 2023. Editorial note on terms for crop evapotranspiration, water use efficiency and water productivity. Agricultural Water Management, 289: 108548. 10.1016/j.agwat.2023.108548.

Fox, P. and Rockstrom, J. 2003. Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel. Agricultural Water Management, 61:29–50.

Franks, C.D. 1999. Natural Resources Conservation Service-Databases and Analytical Services. *United States Department of Agriculture Forest Service General Technical Report PNW*, 198-204.

Gebrehiwot, T., Van der Veen, A. and Maathuis, B. 2011. Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. *International Journal of Applied Earth Observation and Geoinformation*, *13*(3): 309-321

Gebremedhin, T. Haile, G.G., Gebremicael, T.G., Libsekal, H. and Reda, K.W. 2023. Balancing crop water requirements through supplemental irrigation under rainfed agriculture in a semi-arid environment. *Heliyon*, *9*(8).

Girma, T. 2012. Effect of variety and earthing up frequency on growth, yield and quality of potato (Solanum tuberosum L.) at Bure, northwestern Ethiopia. M.Sc. thesis presented to school of graduates of Jimma University.

Górska-Warsewicz, H., Rejman, K., Kaczorowska, J. and Laskowski, W. 2021. Vegetables, Potatoes and Their Products as Sources of Energy and Nutrients to the Average Diet in Poland. Int. J. Environ. Res. Public Health, 18(6): 3217.

Grewal, J, S., Sharma, R, C. and Saini, S .S. 1992. Agritechniques for Intensive Potato Cultivation in India. Publications and Information Division, Indian Council of Agricultural Research, Krishi Anusandhan Bhauan, New Delhi, 126 p.

Gupta, A. and Saxena, M.C. 1976. Total nitrogen concentration in leaves of potatoes (Solanum tuberosum L.) as an index of nutritional status. *The Journal of Agricultural Science, 87*(2): 293-296.

Hagos, B .G. 2016. Impact of agricultural technology adoption of smallholder farmers on wheat yield: Empirical evidence from Southern Tigray State of Ethiopia. Journal of Agricultural Extension and Rural Development, 8(10):211-223.

Handayani, T., Gilani, S. A. and Watanabe, K.N. 2019. Climatic Changes and Potatoes: How Can We Cope with the Abiotic Stresses? *Breed Sci*, 69: 545. doi.org/10.1270%2Fjsbbs.19070

Hassel, R. L., Kelly, D. M., Wittmeyer, E. C., Wallace, C., Grassbaugh, E. M., Elliott, J, Y, and Wenneker, G, L. 1997. Ohio potato cultivar trials. Ohio State Univ. Horticulture Series, (666).

Iwama, K. and Yamaguchi, J. 2006. Abiotic stresses. In Handbook of potato production, improvement, and postharvest management (pp. 231-278). CRC Press.

Iwona, M., Krystyna Agnieszka, G., Marek, G, and Anna, S. 2023. Total and Protein Nitrogen Content in Potato Tubers under the Influence of Various Care and Nutrition Methods with the Use of Biostimulants. Journal of Ecological Engineering, 24(2): 247–255.

Jackson, M, L., 1967.Soil Chemical Analysis Practice Hall of India. New Delhi, 498

Jennings, S, A., Koehler, A, K., Nicklin, K, J., Deva, C., Sait, S, M. and Challinor, A, J. 2020. Global Potato Yields Increase under Climate Change with Adaptation and CO2 Fertilisation. Front. Sustain. Food Syst., 4: 519324.

.

Johan, R., Lousise, K., Suhas, P,W., Jennie ,B., Nuhu, H., Theib, O., Adriana ,B., Jalali, F, and Zhu, Q. 2010 .Managing water in rain fed agriculture-the need for a paradigm shift, Agric. Water Manag, 97: 543–550.

Karam, F., Rouphael, Y., Ladoud, R., Baried, J. and Colla, G. 2009. Influence of Genotypes and Potassium application rates on the yield and potassium use efficiency of potato. Journal of Agronomy, 8 (1):27-32.

Kaur, S., and Aggarwal, P.2014. Evaluation of antioxidant phytochemicals in different genotypes of potato**.** Int. J. Eng. Res. Appl, 4 (7):167-72.

Khanna-Chopra, R, and Singh, S. 2011. Approaches to increase water use efficiency in horticultural and grain crops – An overview .Plant Stress 5 (Special Issue 1): 52-63, Global Science Books

Kumar, A., Bernier, J., Verulkar, S., Lafitte, H.R. and Atlin, G.N. 2008. Breeding for drought tolerance: direct selection for yield, response to selection and use of drought-tolerant donors in upland and lowland-adapted populations. Field Crops Research, 107(3):221-31.

Lahlou, O., Ouattar, S. and Ledent, J, F. 2003. The effect of drought and cultivar on growth parameters, yield and yield components of potato. Agronomie, 23: 257-268.

Luitel, B.P., Khatri ,B.B., Choudhary, D., Paudel, B.P., Jung-Sook, S., Hur On-S., Baek, H..J., Cheol, K. H. and Yul, R,K. 2015. Growth and Yield characters of potato genotypes grown in drought and irrigated conditions of Nepal. Int J Appl Sci Biotechnol, 3(3): 513-519.

Luitel, B. P., Bhandari, B. B. and Thapa, B. 2020. Evaluation of Potato Variety for Plant and Yield Characters in Field at Dailekh. Nepal Journal of Science Technology, 19(2):16-24.

Maqsood, J., Farooque, A. A., Wang, X., Abbas, F., Acharya, B. and Afzaal, H. 2020. Contribution of Climate Extremes to Variation in Potato Tuber Yield in Prince Edward Island. Sustainability, 12(12): 4937.

Marwaha, R, S., Pandey, S, K., Dinesh Kumar and Singh, S, V. 2010. Potato processing scenario in India: Industrial constraints, future projections, challenges ahead and remedies A review. J Food Sci and Technol, 47(2): 137–156.

Mazurczyk, W., Wierbicka, A. and Trawczynski, C. 2009. Harvest index of potato crop grown under different nitrogen and water supply. *Acta Sci. Pol. Agric*, 8 (4).

Monneveux, P., Ramírez, D.A., and Pino, M., T.2013. Drought tolerance in potato (S. tuberosum L.): Can we learn from drought tolerance research in cereals? *Plant Sci,* 205: 76-86.

Nangia, V., Oweis, T., Francis, H, K. and Schnetzer, J. 2018. Supplemental Irrigation: A Promising Climate-Smart Practice for Dry land Agriculture. Global Alliance for Climate-Smart Agriculture.

National Potato Research Program (NPRP). 2014. Field book for standard evaluation of potato and sweet potato germplasm, (Eds.BB Khatri and BP Luitel). National Potato Research Program, NARC, Khumaltar, Lalitpur, Nepal

Olsen, S.R. and Dean, L.A., 1965. Phosphorus. In: Methods of Soil Analysis. American Society of Agronomy. Madison, Wisconsin, 9: 920 – 926

Ojala, J.C ,Starck, G.E, and Kleinofkopf. 1999. Infulence of irrigation and nitrogen management on yield and quality of Potato. American potato Juornal 67(1): 29-43.

Oweis, T, and Hachum, A . 2003. Improving water productivity in the dry areas of west Asia and North Africa.In: Kijne, W.J., Barker, R., and Molden, D. (eds) Water productivity in agriculture: Limits and opportunities for improvement. CABI, Wallingford, UK, 179-197.

Oweis, T., and Hachum, A. 2009. Supplemental irrigation for improved rainfed agriculture in WANA region. *InRainfed agricultur*e: *Unlocking the potential*. 182-196. Wallingford UK: CABI.

Quiroz, R., Ramírez ,D,A., Kroschel, J., Andrade-Piedra ,J., Barreda ,C., Condori ,B., Mares ,V., Monneveux ,P. and Perez ,W . 2018. Impact of Climate Change on the Potato Crop and Biodiversity in Its Center of Origin. Open Agric, 3: 273–283.

Raes, D., Geerts, S, and Vandersypen, K. 2007.More Food, Less Water. In: Raymaekers, B. (Ed.). Lectures for the 21st century. Leuven University Press, Leuven.

Raja, R., Ravisankarmdin, N. N., Ghoshal, C. S., Ambast, S. K., Subhash, C., Babulal, M, M., Subramani, T, T. and Ahmed, Z. 2011. Effect of supplemental irrigation on yield and water productivity of dry season crops in Andaman and Nicobar Islands. Indian Journal of Agricultural Sciences .82 (2): 122–165.

Ranganna, S. 1977. Manual of Analysis of Fruit and Vegetable products Central Food Technological Research Institute Mysore, USA.

Shayannejad, M. and Moharreri, A. 2009. Effect of every other furrow irrigation on water use efficiency, starch and protein contents of potato .Agriculture Science, 1:107-112.

Shrestha, S., Manandhar, H. K., Shrestha, S.M. and Karkee, A. 2019. Response of local potato cultivars to late blight disease (Phytophthora infestans) under field and laboratory conditions at Pakhribas, Dhankuta, Nepal. AdvCytol Pathol, 4 (1):10-13.

Silveira, A, C., Orena, S., Medel-Maraboli, M. and Escalona, V.H., 2020. Determination of some functional and sensory attributes and suitability of colored- and non-colored-flesh potatoes for different cooking methods. Food Sci.Technol, 40(2): 395–404.

Sikora, F.J. and Moore, K.P. 2014. Soil test methods from the southeastern United States. Southern cooperative series bulletin, 419: 54-58.

Srivastava, R.K., Talla, A., Swain, D.K. and Panda, R. K. 2019. Quantitative Approaches in Adaptation Strategies to Cope with Increased Temperatures Following Climate Change in Potato Crop. Potato Res, 62: 175–191.

Tessema, G., Mohammed, W, and Abebe. T.2019. Evaluation of Potato (Solanum tuberosum L.) Varieties for Yield and Some Agronomic Traits. Open Agriculture, 5:63-74.

Tolessa, E.S., Belew, D., Debela, A. and Kedi, B. 2016. Effect of Nitrogen Rates and Irrigation Regimes on Water Use Efficiency of Selected Potato Varieties in Jimma Zone, West Ethiopia. Adv Crop Sci Tech, 4: 244.

Waglay, A., Karboune, S. and Alli, I., 2014. Potato protein isolates: Recovery and characterization of their properties. Food Chemistry, 142:373-382.

Widmann, N., Goian, M., Ianculov, I., Dumbravă, D. and Moldovan, C. 2008. Method to starch content determination from plants by specific weight. *Scientific Papers Animal Science and Biotechnologies*, *41*(1):.814-814.

Yuan, B.Z., Nishiyama, S. and Kang, Y. 2003. Effects of different irrigation regimes on the growth and yield of drip-irrigated potato, Agriculture Water Management, 63: 153-167.

Zarzecka, K. and Gąsiorowska, B. 2002. The effect of varied care on the consumption value of edible potato. *Zesz. Nauk. AP w Siedlcach, Ro*l, 61: 53–64

CHAPTER 6

6. Effect of Irrigation level and Genotypes on Growth, Yield and Quality of Potato under Semi-Arid Growing Conditions of Tigray, Northern Ethiopia

Abstract

Potato is one of the dominant root and tuber crops grown in Tigray. However, the productivity of the crop is very low due to moisture stress, traditional production techniques and growing low-yielding varieties. Hence, an experiment was conducted to assess the effect of genotypes and irrigation levels on potato growth, yield, quality, water use efficiency, and drought tolerance. The study involved three irrigation levels (100%, 75%, and 50% of potato's water requirement) and five potato genotypes as treatments. The field experiment was arranged in a split plot using randomized complete block design with three replications. All necessary data were collected and analyzed using SAS version. The result indicated that the main and interaction effect of genotype and irrigation level significantly affected the days to maturity, marketable and total tuber yield, and water use efficiency. The highest marketable yield (27.58 t ha^{-1}*) and total tuber yield (29.87 t ha*$^{-1}$*) were achieved from genotype CIP-394611.112 under full irrigation water level. Moreover, regardless of genotypes, higher irrigation water use efficiency was associated with decreasing in irrigation water amounts and the highest value (10.14 kg m*$^{-3}$*) and (*9.90 *kg m*$^{-3}$*) obtained from genotypes CIP-394611.112 and CIP-3960478.90, respectively, under 50% irrigation level application. Genotypes CIP-3960478.90 and CIP-394611.112 showed relatively tolerance characteristics under induced drought conditions. Therefore, genotype CIP-394611.112 with full irrigation is recommended to harvest optimum yield and water productivity in semi-arid areas of Tigray and other similar agro-ecologies of Ethiopia.*

Key words: Irrigation level, Potato, Tuber yield, Water use efficiency

6.1. Introduction

Potato (Solanum tuberosum L.) is a vital of global food security, prized for its high nutritional value and ability to produce more edible energy per unit of land than many other staple crops (Thiele et al.., 2010 ; Devaux et al., 2021). However, its productivity is severely constrained by abiotic stresses, particularly drought. The potato plant's shallow root system renders it inherently susceptible to moisture deficits, which can drastically reduce both yield and tuber quality (Iwama and Yamaguchi, 2006). This vulnerability is critically relevant in the context of climate change, which is projected to increase the frequency and intensity of droughts in tropical and subtropical regions, including the semi-arid highlands of Africa (Quiroz et al., 2018; Jennings et al., 2020).

Ethiopia possesses suitable climatic and soil conditions that fit with for potato cultivation. Approximately 70% of the country's agricultural land lies at an elevation between 1800 and 2500 meters above sea level, and receives annual precipitation exceeding 600 mm - an environment that is conducive to grow potatoes (Abite, 2014). In the Tigray region of Northern Ethiopia, where potato is a vital crop for smallholder farmers, productivity remains dismally low at 8.1 tons per hectare compared to a national average of 13.5 tons (CSA, 2017). Furthermore the yields obtained under experimental conditions, which can reach up to 38 metric tons per hectare (Amare et al., 2022 , Taye et al., 2021). This yield gap is exacerbated by the region's increasing aridity; studies confirm a trend of rising temperatures and decreasing rainfall in Tigray over recent decades (Gebrehiwot and van der Veen, 2013). While factors like traditional farming practices, growing low yielding varities contribute, the fundamental challenge is the crop's exposure to moisture stress, compounded by inefficient irrigation practices (Teklemariam et al., 2014). The potato plant, with its shallow root system and high water requirement (500-700 mm per growing season), is highly sensitive to water deficits (Obidiegwu et al., 2020). Moisture deficiency, especially during the critical growth stages of tuber initiation and bulking, severely disrupts physiological processes, leading to reduced photosynthesis, impaired nutrient uptake, and ultimately, significant losses in tuber yield and quality (Yactayo et al., 2013).

A key strategy to mitigate yield loss under such conditions is the identification and use of drought-tolerant genotypes. Earlier reports and studies have consistently demonstrated that potato genotypes exhibit significant genetic variation in their response to moisture deficiency. Certain varieties possess traits such as deeper root mass, improved osmotic adjustment, or early maturity that confer a degree of low moisture tolerance, enabling them to maintain better growth and yield under water-limited conditions. Leveraging this genetic diversity is essential for building resilience.

While the principle of genotypic variation is established, site-specific evaluations are crucial, as a genotype's performance is often dependent on local growing conditions. In the semi-arid environment of Tigray, there is a pronounced lack of information on how different potato genotypes respond to defined irrigation levels in terms of growth, yield, quality, and water use efficiency. Therefore, this study was initiated to evaluate the effects of irrigation level and genotype on the growth, yield, and quality of potato under the semi-arid growing conditions of Tigray, Northern Ethiopia. The findings aim to identify optimal genotype and irrigation management combinations to enhance potato productivity and resource use efficiency in this drought-prone region.

6.2. Materials and Methods

6.2.1. Description of the study area

A field experiment was conducted in two experimental sites (Elalla and Chelekot) of Mekelle Agricultural research Center under irrigated condition in 2020. Elalla is located at 39°28’14” - 39° 33’18” E Longitude and 13° 29’23” - 13°34’27” N Latitude at an elevation of 2004 m.a.s.l. Likewise, Chelekot is situated 20 km south of Mekelle city at 39° 24’39” - 39° 30’9” E Longitude and 13°19’15” - 13°24’43” N Latitude and at an elevation of 2000 m.a.s.l (Fig 6.1) .

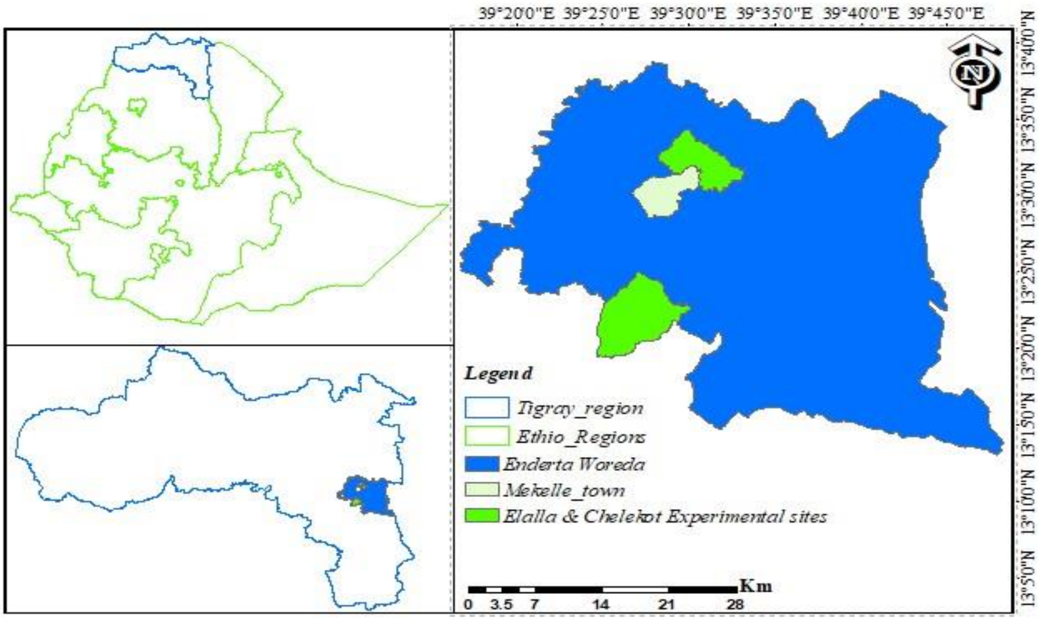
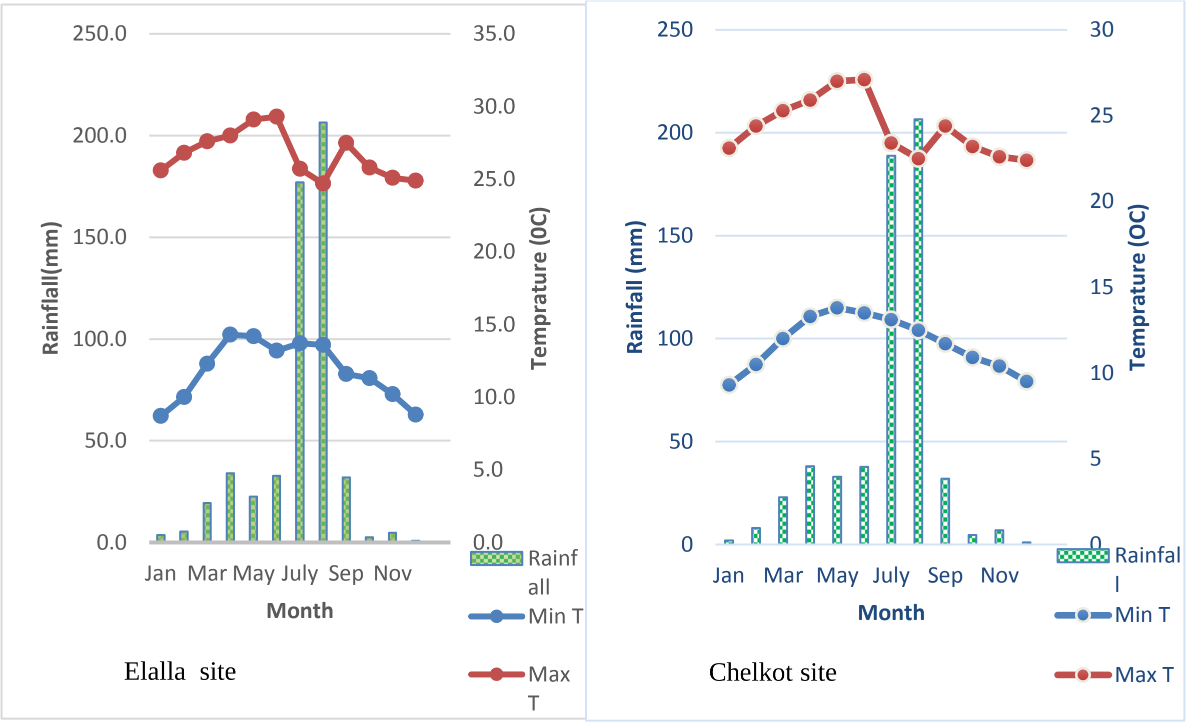


Figure 6.1 The Study areas of Elalla and Chelkot experimental site

The climate of the study areas is described as semi-arid, with a mean annual rainfall of 541.5 mm and 581.4 mm at Elalla and Chelekot, respectively (Figure 6.2). The rainfall pattern follows a bimodal nature, with the main rainy season (locally known as *kiremt*) falling between June and September, and the small rain (locally known as *Belg*) occurring between February and March.

Likewise, the mean annual maximum and minimum temperatures recorded at Elalla are 26.7°C and 11.8°C, respectively, while at Chelekot, the mean annual maximum and minimum temperatures are 24.3°C and 11.8°C, respectively (Figure 6.2). The soil in Elalla has a clay loam texture, a neutral pH, high cation exchange capacity, low organic matter content, low total nitrogen, and high available phosphorus. On the other hand, the soil of Chelekot has a silt clay texture with relatively high pH and cation exchange capacity, while the organic matter content, total nitrogen, and available phosphorus are regarded as medium (Table 6.1).



Elalla site

Chelkot site

Figure 6.2. Long-term (1992-2019) mean monthly rainfall, maximum and minimum temperature of Elalla and Chelkot

6.2.2 Treatments and Experimental Design

Three irrigation levels (100%, 75% and 50%) of potato water requirement (PWR) and five genotypes (CIP-390478.90, CIP-39411.112, CIP-392661.18, Seohong, and Gudanie) were used as experimental treatments. The experimental design employed in each site was randomized complete block design arranged in split-plot and replicated three times. The irrigation levels were assigned to the main plot, while the genotypes administered as sub-plot treatments. The field experiment was conducted at Mekelle, Elalla site and Enderta, Chelkot site for one year under irrigation condition. A spacing of 1m, 1.5m, and 2m maintained between sub-plots, main plots, and replications, respectively. Similarly, a spacing of 75cm between rows and 30cm between plants was maintained. The gross plot size used in each site was 3 m x 3m (9 m^2) for sub plot and 19m x 3 m (57 m^2) for main plot 228m^2.

6.2.3. Field management

The experimental field was prepared using traditional oxen plough. Then after, ridges and furrows were prepared manually using hoe. Planting was carried out on January 15 and 20, 2020 at Elalla and Chelkot sites, respectively. Full irrigation water requirement was applied to all treatments uniformly until intial stage of the crop. The recommended fertilizer NPSZn (18N:35.9 P_2O_5:7.7S and 2.2 Zn) at the rate of 250.4 kg ha $^{-1}$ and Urea at the rate of 165 kg ha^{-1} was applied to all plots uniformly. Whole NPSZn fertilizer was applied at planting using band application method, while Urea applied in split i.e. 50% at planting and the remaining 50% at early flowering. Other agronomic practices and plant protection measures implemented as per recommendation for potato production.

6.2.4. Data collection

6.2.4.1. Climatic and soil data

Daily rainfall data and minimum and maximum air temperature relative humidity, wind speed, and sunshine hours during the study period for each study site were collected from Ethiopian Metrological Service Agency, Mekelle branch and Mekelle Agricultural Research Center.

To determine soil physical properties, including Field Capacity (FC), Permanent Wilting Point (PWP), Bulk density, and soil water content at planting (mm/m), soil samples were collected manually using a core sampler from the 0-30 cm depth of the experimental field before planting. FC and PWP were determined in the laboratory using soil samples. They were measured using a pressure plate apparatus on undisturbed soil cores. Field Capacity was determined at -33 kPa suction, and the Permanent Wilting Point was determined at -1500 kPa suction.Similarly, a composite soil samples from both sites were collected using augur from the 0-30cm following the standards for soil sampling procedures. This soil sample was used to determine selected physico-chemical characteristics of the soil, including soil texture, pH, total nitrogen (N), organic carbon (OC), cation exchange capacity (CEC), and available phosphorous (P). Soil analysis was conducted at Mekelle Soil Research Center laboratory flowing standard methodologies. The Kjeldahl method was used to determine total nitrogen, Olsen and Dean (1965) for available phosphorus, Sikora and Moore (2014) for organic carbon and soil pH (on 1:2.5 soil: water suspension). The soil physical and chemical characteristics of both sites is depicted in Table 6.1.

Table 6.1. Top layer (0-30cm depth) soil chemical and physical properties of the experimental sites

Parameters	**Location**	
	Chelkot	Elalla
E.C (dS/m)	0.38	0.63
pH	8.44	7.02
Total. N (%)	0.154	0.088
Av. P (ppm)	13.44	15.88
OC (%)	1.803	0.942
OM (%)	3.108	1.624
CEC (cmol/kg)	40	43.13
Sand (%)	24	40
Silt (%)	28	20
Clay (%)	48	40
Textural class name	Silt clay	Clay loam
FC %	39.00	31.0
WP%,	21 .00	15.0
BD	1.31	1.26
TAW mm m-1	180	160

Note: EC = Electrical conductivity, OM = Organic matter, CEC= Cation exchange capacity of the soil, TN = Total nitrogen, Av. P = Available phosphorus BD =Bulk density, FC =Field capacity, PWP =Permanent wilting point, and TAW =Total available water.

6.2.4.2. Plant data

Fresh mature leaf samples of potato from each treatment were collected at early flowering (mide-season stage) and oven dried overnight at 70 ^{0}C for 72 hours until constant weight. Then, the samples were ground and sieved through 2 mm sieve for N content analysis in the Mekelle Soil Research laboratory. To determine the nitrogen (N) content, potato tuber samples (at harvest) were collected at harvest, oven-dried at 80°C for 72 hours, ground, and sieved before laboratory analysis, following the method described by Karma et al. (2009). The total nitrogen content in both tuber and leaf samples was measured using the Kjeldahl method, as outlined by Jackson (1967), Gupta, and Saxena (1976).

6.2.4.3. Growth, yield and yield component data collection

Days to flowering, days to maturity plant height, number of tubers per plant, tuber diameter, tuber weight, final tuber yield (marketable and unmarketable), biomass yield and harvest index were collected. Days to flowering and physiological maturity were recorded when 50% of the plant population attained flowering stage and when the leaves of 75% of the plant in the plot turned yellowish, respectively. Plant height was determined by measuring height from the base of the main stem to the apex at full maturity. For tuber number and tuber diameter estimation, an average of 12 hills from the center of the sub plot treatment was used. Following the procedure of National Potato Research Program of Nepal (NPRP, 2014) healthy tuber with weight > 25 g was considered as marketable while rotten, diseased, insect attacked, deformed tuber and those having < 25 g in weight was categorized as unmarketable yield. Final tuber yield was obtained from two middle rows of each plot with an area of 3m*1.5m (4.5m^2).

6.2.5. Determination of potato tuber quality

Samples of potato tuber were taken at harvest, sliced and oven dried at a temperature of 80^0 C for 72 hours. Following the procedures of Karma et al. (2009), the dried samples were ground and sieved in order to analyze the nitrogen (N) contents at Mekelle Soil Research laboratory. The total nitrogen content in tuber samples were determined using Kjeldahl method as described by Jackson (1973). Then, the protein content of potato tuber (%) was calculated by multiplying the nitrogen (N) content of potato tuber with 6.25 (Ranganna 1977). Likewise, the starch content (%) was obtained indirectly after measuring the specific gravity, as described by Widmann et al. (2008), Hassel et al. (1997), using equation 6.1 and 6.2.

$$\text{Starch content (\%)} = 17.565 + 199.07\ (S.G - 1.0988). \qquad \text{Eq 6. 1}$$

Where, S.G is Specific gravity and given using the following formula

$$\text{Specific gravity}=\frac{\text{Tuber weight on air(w1)}}{\text{Tuber weight on air(W1)}-\text{Tuberweight in water immersed (W2)}} \quad \text{Eq 6.2}$$

To determine the dry matter content of each genotype, five plants from each sub-plot treatments were selected randomly, and from each plant, ten potato tubers were randomly selected. The tubers fresh weight was recorded first, and then the samples were allowed to dry in an oven at a temperature of 80 ^{0}C for 72 hours. After a constant weight had attained, the samples were weighed to determine the dry matter (DM). Finally, the dry matter content was calculated as the ratio between dry and fresh mass expressed as a percentage.

6.2.6. Estimation of crop water and irrigation requirement

Water requirement of a crop depends on climate, crop type, and crop growth stage where it grows. In this study, the water requirement (ETc) of potato was determined from the reference evapotranspiration (ETo) and respective crop coefficients (Kc) for each growth stage, as indicated by Allen et al. (1998). The Kc values of potato in the different growth stages were adopted from Allen et al. (1998). The crop water requirement, irrigation water requirement and the irrigation schedule were estimated using FAO CROPWAT software program version 8 following Allen et al. (1998). The crop water requirement was calculated using equation 6.3.

$$\text{ETc (mm)} = \text{Kc} \times \text{ETo (mm)} \qquad \text{Eq 6.3}$$

Where ETc is Crop evapotranspiration (mm/day); K_c is crop coefficient and ETo is reference crop evapotranspiration (mm/day).

The total amount of irrigation water applied during the crop growth period under full irrigation condition is termed as irrigation water requirement (IWR**)**. IWR is the difference between crop water requirement and effective rainfall, as indicated in Equation (6.4).

$$\text{IWR (mm)} = \text{ETcrop (mm)} - \text{Effective rainfall (mm)} \qquad \text{Eq 6.4}$$

The amount of water required for the crop was calculated from climate data, including maximum and minimum temperatures, wind speed, humidity and sunshine hour; soil data mainly the texture, bulk density and soil moisture characteristics; Kc values; and effective rainfall of the specific location. The amount of irrigation water required in each treatment was measured and applied using the parshall flume device of 2-inch throat width. The parshall flume had known discharging rate (l/s) for different heads (cm). All the plots irrigated with no difference in all treatments until 20 days after planting then the plots irrigated based on their irrigation level through furrow irrigation method with fixed depletion irrigation timing. Nine and twelve times of irrigation with different depth were irrigated at Chelekot and Elalla respectively.

The long-term characteristics crop water requirement, reference evapotranspiration, irrigation water requirement and effective rainfall was used for planning purpose (Fig 6.3). The actual irrigation water plus effective rainfall had applied at the rate of 269.30, 397.42 and 515.3 mm based on irrigation level of 50 %, 75 and 100% of water requirement of potato, respectively at Mekelle, Elalla site. In addition, 195.19, 281.5 and 392.5 mm of water applied at 50%, 75% and 100 % of potato water requirement, respectively at Chelkot site. The treatments received the combined mean amount of water 443.9, 339.5 and 230.24 mm at the water level of 100, 75 and 50 %, respectively.

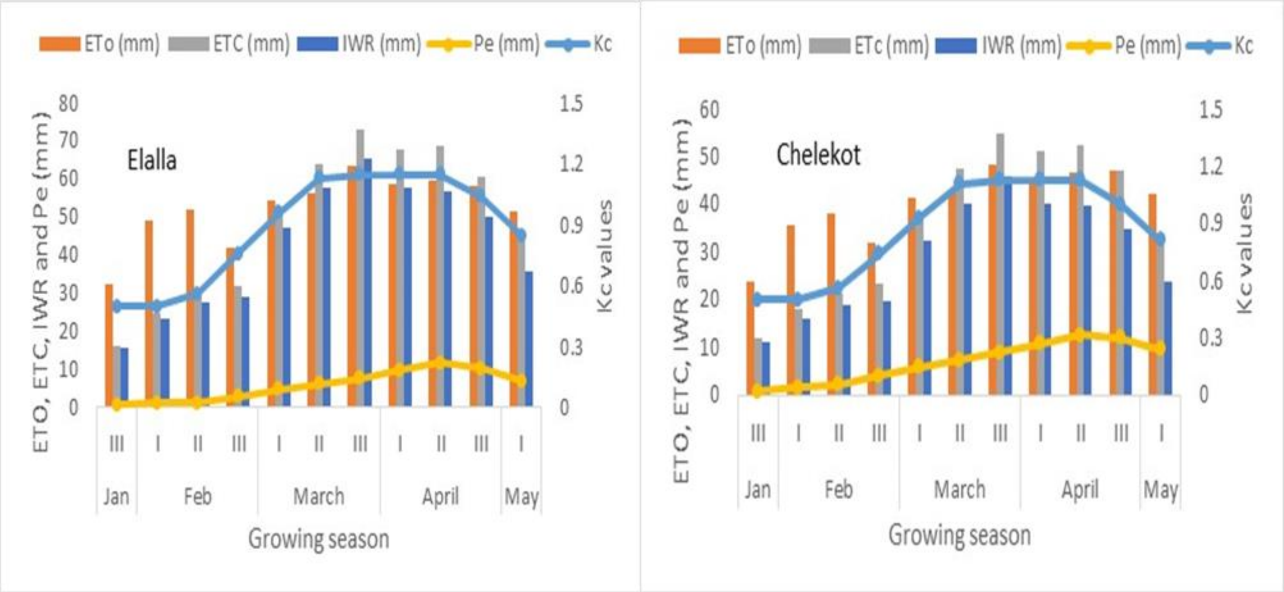


Figure 6.3 depicted the long-term (1992-2019) characteristics of crop water requirement, potential evapotranspiration, irrigation water requirement, effective rainfall in each potato growing stages for the locations of Elalla and Chelekot.

Note: I, II, III, and I are 1st, 2nd and 3rd decades of (10 days) a month.

6.2.7. Determination of water and irrigation water use efficiency

Water use efficiency (WUE), which is also called crop water productivity, is expressed as the ratio of crop output per amount of water lost by the process of evapotranspiration (ETa) (Erdem et al., 2006, Zhang et al., 1999). Water use efficiency (WUE), irrigation water use efficiency (IWUE)/ total crop water productivity (TWPc) and Crop water productivity (WPc) of potato were calculated following the procedures as described by Ati et al. (2012),) as indicated in Equation 6.5 6.6, 6.7 and 6.8 respectively.

$$\text{WUE}= \frac{\text{BiomassYield (kg)}}{\text{ETa(m3)}} \qquad \text{Eq 6.5}$$

ETa is Actual evapotranspiration

$$\text{IWUE}= \frac{\text{Total tuber Yield (kg)}}{\text{Total irrigation water applied (m3)}} \qquad \text{Eq 6.6}$$

$$TWPc = \frac{Total\ tuber\ Yield\ (kg)}{Total\ water\ applied\ (RF+Irrigation)(m3)} \qquad \text{Eq 6.7}$$

$$WPc = \frac{Total\ marketable\ tuber\ yield(kg)}{Total\ amount\ of\ water\ applied(m^3)} \qquad \text{Eq 6.8}$$

6.2.8. Determination of drought tolerance indices

Yield-based drought tolerance indices like Stress Susceptibility index (Fischer and Maurer, 1978; Gupta et al ., 2001), Stress Tolerance Index (Fernández, 1992), Tolerance Index, Mean Productivity (Rosielle and Hamblin, 1981), and Yield Stability Index (Bouslama and Schapaugh, 1984) were calculated under water stress and non-stress conditions using Equations (6.9), (6.10), (6.11), (6.12) and (6.13), respectively.

Stress susceptibility index (SSI) for yield of each genotype calculated as follows (Fischer and Maurer, 1978)

$$\text{SSI} = \frac{\left(1-\frac{\text{Yws}}{\text{Yns}}\right)}{(1-\frac{\bar{\text{Y}}\text{.ws}}{\bar{\text{Y}}\text{.ns}})} \qquad \text{Eq 6.9}$$

Where: Yws is the mean yield of a given genotype in water stress condition, Yns is the mean yields of a given genotype in non-stress condition. $\bar{\text{Y}}$.ws and $\bar{\text{Y}}$.ns are mean yield of all genotypes under water stress and non-stress conditions, respectively.

In addition, Stress Tolerance index (STI) or drought tolerance index (DTI) was calculated based on the formula developed by Fernandez (1992)

$$STI = DTI = \frac{(Yns * Yws)}{(\bar{Y}ns)^2} \qquad \text{Eq 6.10}$$

Tolerance index (TOl) and Mean productivity (MP) was calculated based on Rosielle and Hamblin (1981) Gupta et al. (2001).

$$TOl = Yns - Yws \qquad \text{Eq 6.11}$$

$$MP = \frac{(Yws + Yns)}{2} \qquad \text{Eq 6.12}$$

Yield Stability Index (YSI) was calculated according to Bouslama and Schapaugh (1984)

$$YSI = \left(\frac{Yws}{Yns}\right) * (100) \qquad \text{Eq. 6.13}$$

Where Yws is the yield of a given genotypes in water stress conditions, Yns is the yields of a given genotypes in non-stress conditions, and $\bar{Y}$.is mean yield of a given genotype under non stress condition.

According to the scale suggested by Fischer and Maurer (1978) , for Stress Susceptibility Index (SSI), the genotypes with the lowest values are more tolerant to droughts; values closer to 1, are neutral; and values above 1 are susceptible.

6.2.9. Data analysis

The data collected in this study, including plant growth, physiological parameters, water use efficiency, tuber yield, and yield components were subjected to analysis of variance (ANOVA) using a mixed model in SAS software (Version 10). The software also used to check ANOVA assumptions, including normality, homogeneity, independence of group variances and means, and independence of scores. Before performing a combined analysis, Levene’s test for equality of variances was conducted to assess homogeneity between the experimental sites (Chelkot and Elalla). Since Levene’s test for equality of variance indicated non-significant differences between the experimental sites, a combined analysis of data from both locations was performed. Irrigation level and genotype were treated as fixed effects, while location was considered a random effect. Treatment means and interactions were compared using Duncan’s test at a significance level of $P < 0.05$.

6.3. Results and Discussion

6.3.1. Climate and Potato water requirement during the growing period

During the study period, January to May 2020, the total monthly effective rainfall (Pe), Irrigation water requirement (IWR), and Potato Crop water requirement (ETc) of the study areas are indicated in Figure 6.4. The results revealed that the total water requirement for potato varies slightly with location, with a higher level used at Ellala compared to Chelekot. This might be due to the fact that Elalla had higher temperature during the crop growing season compared to Chelekot (Enderta), which in turn resulted in higher evapotranspiration demand and hence higher irrigation demand. On the other hand, as there was a small amount of rainfall in the season and subsequently small amount of effective rainfall, almost the entire water requirement of the crop in both sites was satisfied through irrigation water.

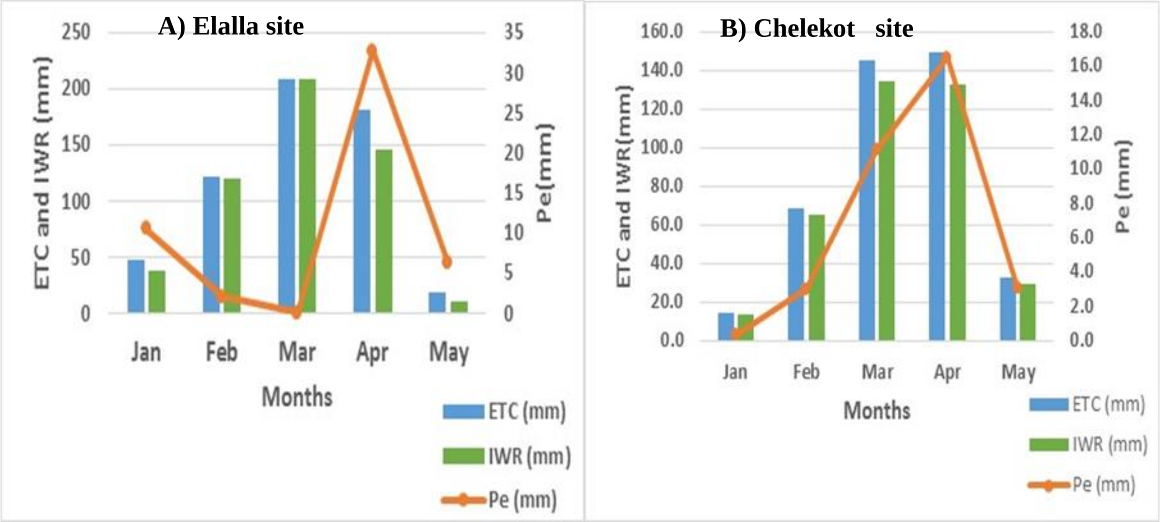


Figure 6.4 depicted the characteristics of crop water requirement (ETc), irrigation water requirement (IWR), and effective rainfall (Pe) in each potato growing stages for the locations of Elalla and Chelekot during the growing season (2020)

6.3.2. Growth parameters and yield component of potato genotypes

6.3.2.1. Days to flowering and maturity

The study revealed that genotype and irrigation significantly influenced the growth and yield characteristics of potatoes, such as days to flowering, days to maturity, plant height, average tuber diameter and tuber count per plant. These effects attributed to the main factors of genotype and irrigation level (Table 6.2). Genotypes Gudanie and CIP-392661.18 exhibited the longest time to flowering and maturity while CIP-394611.112 and CIP-390478.90 displayed the earliest flowering and maturity times, differing significantly from other genotypes. In addition, days to maturity had significantly influenced by the interaction of genotype with irrigation level (Fig 6.5). In general, regardless of genotypes, the days to flowering and maturity of potato genotypes increases with increasing level of irrigation water. This implied that any intervention that reduces the amount of crop water requirement for potato would subsequently reduce the crop development. On the other hand, different potato genotypes vary in their response to water level. In particular, Gudanie was late to flower and maturity compared to genotype CIP-394611.112 under both full and deficit irrigation conditions (Fig 6.5). Hence, earliness to maturity is an important characteristic of a crop to produce in areas where rainfall or irrigation water is low. Generally, the study highlights the importance of genotype selection and irrigation management choice in potato cultivation to optimize growth and yield characteristics. In agreement with this result, Fantaw et al. (2019) noted that flowering and maturity could be affected by varieties, and this provides the basis for the selection of late or early maturing varieties depending upon the rainfall duration or irrigation water availability. Furthermore, Tamer et al. (2012) reported that the variation in the length of the growing period among varieties might be due to the difference in their genetic makeup. Asefa et al. (2016) also reported that flowering and maturity are heritable traits of potato crop. Therefore, genotypes having early days to flowering and days to maturity are important characteristics for the semi-arid areas of Tigray where rainfall is small in amount, erratic distribution, starts late, and ceases early in the growing season.

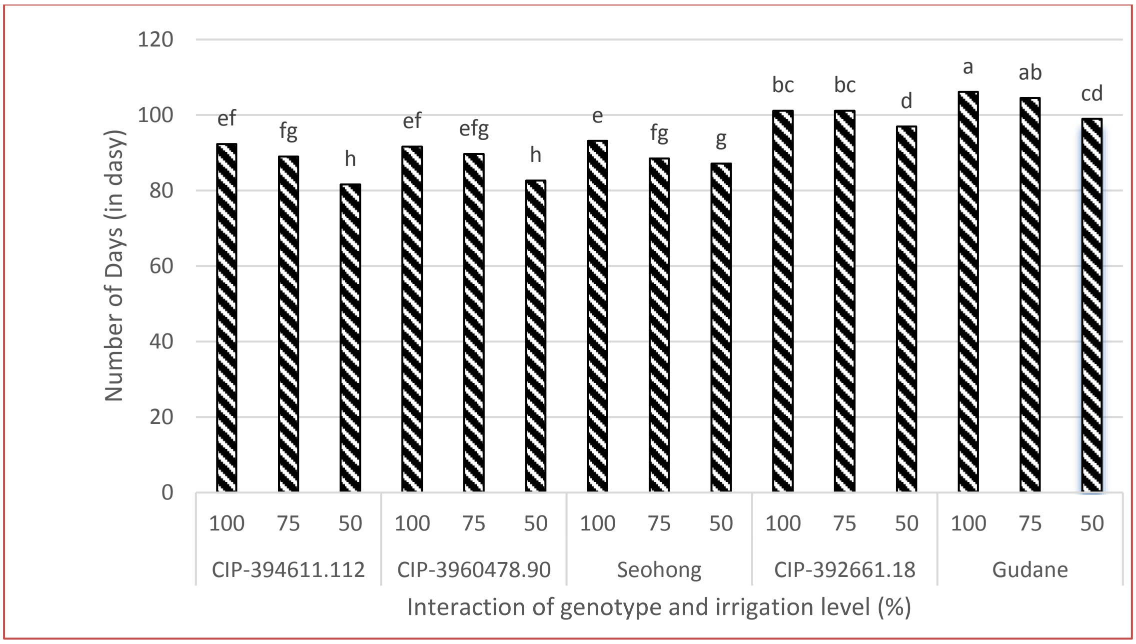


Figure 6.5. Interaction effect of genotype and irrigation level on days to maturity

Note: Bars leveled with the different letters indicated significant difference but with the same letter showed non-significant difference on days to maturity of potato (at P <0.05).

6.3.2.2. Plant height (cm)

The effect of genotype and irrigation water level on the plant height of potato is indicated in Table 6.2. The result showed that the main effect of genotypes and irrigation level had a significant effect on plant height, but their interaction did not have a significant influence. In this regard, Gudanie followed by CIP-392661.18 recorded the tallest plant height than the other genotypes. This might be due to the difference in genetic makeup of the genotypes. With respect to irrigation level, full irrigation resulted in the tallest plant height than the 50% and 75% irrigation level, which might be due to sufficient water required for optimum crop growth of the plant. In line with this, Asmita and Rajkumari (2022) and Shrestha et al. (2024) reported that plant height was affected by variety. Bhuwneshwari et al. (2017) and Kumar et al. (2008) also noted the differential reponse of varieties to in plant height could be due to genetic and inherent characteristics. Similarly, Aytekin and Caliskan (2023) found significant difference on plant height of potato, the tallest being recorded at full irrigation level compered to deficit. Bilate and Mulualem (2016) also found that the environment and the cultivar had significant effect on plant height in Eastern Ethiopia. However, Elhani et al. (2019) did not find significant difference in plant height among full irrigation and deficit irrigation regimes when potatoes were grown under glasshouse conditions. The difference between the present findings and the previous scholar's work could be due to the experimental conditions.

6.3.2.3 Yield component

The main effects of genotype and irrigation level significantly influenced the number of tubers per plant and tuber diameter, while their interaction did not (Table 6. 2). The study showed that the highest average tuber diameter and number of tubers per plant were obtained under full irrigation. Most importantly, the number of tubers per plant and tuber diameter were significantly reduced when the irrigation level dropped beyond 75%, which indicates intense moisture stress. Likewise, genotypes CIP-394611.112 and CIP-390478.90 were produced the highest number of tubers per plant and average tuber diameter. The study highlights the importance of genotype selection and proper irrigation management in achieving optimal yield in terms of yield component production. Similarly, Abubaker et al. (2014), Kifle and Gebretsadikan (2016), Shrestha et al. (2024) reported that irrigation has significant influence on the number of tubers per plant, and a lower value was recorded on the treatments that received deficit irrigation (Aytekin and Caliskan, 2023). With respect to genotype, Lahlou et al. (2003) reported that tuber number had significantly affected by variety and early maturing varieties more affected. In contrast, significant difference on the number of tubers per plant was not observed due to irrigation levels (Akkamis and Caliskan, 2023). The discrepancy between the findings could be due to a number of factors, including differences in experimental conditions, plant varieties, soil characteristics, or environmental factors.

Table 6.2. The main effect of genotype and irrigation level on growth and yield components of potato

Factors	Days to flowering	Days to maturity	Plant height (cm)	Average tuber diameter(mm)	Number of tubers per plant
Genotype					
CIP-394611.112	45.83^{d}	87.6^{c}	45.26^{c}	45.42^{a}	16.16^{a}
CIP-390478.90	46.89^{dc}	88.0^{c}	40.70^{d}	45.29^{a}	15.38^{a}
Seohong	47.89^{c}	89.61^{c}	41.69^{dc}	42.81^{ba}	11.03^{c}
CIP-392661.18	52.50^{b}	99.78^{b}	51.83^{b}	41.57^{b}	12.68^{b}
Gudane	54.61^{a}	103.2^{a}	57.39^{a}	42.93^{ba}	10.08^{c}
CV (%)	4.58	3.7	14.35	12.03	16.407
LSD	1.157***	1.988***	4.567***	3.077^{ns}	1.429***
Irrigation level (%)					
100	50.57^{a}	96.57^{a}	51.4^{a}	49.19^{a}	14.75^{a}
75	49.13^{b}	94.90^{b}	47.7^{b}	46.04^{a}	13.10^{b}
50	48.86^{b}	89.50^{c}	43.03^{c}	39.44^{b}	11.35^{c}
CV (%)	4.58	3.7	14.35	12.03	13.34
LSD	0.8044*	2.343***	2.715***	3.025*	0.825*

Means of the same main effect within a column followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant, * significant at 5%, **significant at 1%, and ***significant at 0.1%

6.3.3. Effect of irrigation levels on yield of potato genotypes

6.3.3.1 Marketable yield

The marketable yield was significantly influenced by the interaction and main effect of genotype, as well as irrigation level as shown in table 6.3. The highest average marketable yield of 27.58 t ha^{-1} was obtained through the interaction effect of genotype CIP-394611.112 and an irrigation level of 100 %. Furthermore, the maximum marketable tuber yield of 23.39 t ha^{-1} and 23.21 t ha^{-1} was obtained through the interaction effect of genotype CIP-390478.90 with 100% irrigation level and CIP-394611.112 with an irrigation level of 75% respectively. However, the lower marketable tuber yields were recorded at the interaction effect between the genotype with 50% irrigation level in general and Gudanie and Seohong interaction with irrigation level of 50%, in particular (Table 6.3). Comparisons of attribute means among the interaction genotype CIP-394611.112 with irrigation levels at 100% and 75% showed significantly higher marketable tuber yields compared to other genotypes with their respective interaction irrigation levels. The 100% irrigation level interaction with genotype CIP-392661.18, Gudanie and Seohong had no statistically significant difference in marketable tuber yield compared to genotype CIP-394611.112 and CIP-390478.90 interaction with 50% irrigation level (Table 6.3). In general, regardless of their significance, marketable yields tend to increase as irrigation levels increase from 50% to 100% within the same genotype. In summary, the study found that the interaction and main effects of genotype, and irrigation level influenced the marketable yield of the crop. Genotype CIP-394611.112 generally performed well, particularly when combined with higher irrigation levels. Numerous researchers who have reported an increase in tuber yield with higher irrigation levels (Yuan et al., 2003; Kashyap and Panda, 2003; Shock et al., 1998; Ferreira and Carr, 2002; Kang et al., 2004; Wang et al., 2009) support this observation. Additionally, Cantore et al. (2014). Abubaker et al. (2014); Kifle and Gebretsadikan (2016), Shrestha et al. (2024) found a significant variation in marketable yield based on water availability. The highest marketable tuber yield observed from the irrigation level 100 % treatment interaction with genotype; although it was significantly different from the irrigation level 75% treatment interaction with in the same genotype. In contrast to this Kifle and Gebretsadikan (2016), Shrestha et al. (2024) reported that there had no significant difference on 25 % deficit irrigation with the full irrigation. The discrepancy between the findings of the current experiment and the previous scholar's work could be due to a number of factors, including differences in experimental conditions, plant varieties, soil characteristics, or environmental factors.

Table 6.3. Interaction effect of irrigation level and genotypes on marketable tuber yield (t ha^{-1}) of potato

Genotype	Irrigation level (%)		
	Full (100)	75	50
CIP-394611.112	27.58^{a}	23.21^{b}	15.07^{de}
CIP-390478.90	23.39^{b}	19.31^{c}	16.14^{de}
Seohong	17.75^{cd}	15.56^{de}	9.91^{gh}
CIP-392661.18	22.60^{b}	14.26^{ef}	12.2^{efg}
Gudanie	17.29^{cde}	10.86^{gh}	7.9^{h}
CV (%)	13.07		
LSD	2.829**		

Note: CV is coefficient of variance; LSD is least significant difference at 5%; and ** significant at 1% probability level

6.3.3.2. Total tuber yield

The interaction of genotype and irrigation water level had significant effect on total tuber yields of potato (Table 6.4). In general, the result indicated that, regardless of genotypes, total tuber yield of potato increased with increasing irrigation water levels. In other words, all genotypes have recorded higher yield under full irrigation and lower yield at 50% irrigation level. Likewise, regardless of irrigation levels, genotype CIP-394611.112 recorded higher tuber yield (29.87 t ha^{-1}) when grown under full irrigation levels, while the lowest yield was obtained from Gudanie grown at 50% irrigation levels. This implies that optimum levels of irrigation positively influenced tuber yield and varies with genotype. In line with this, Yuan et al. (2003); Kashyap and Panda (2003); Shock et al. (1998); Ferreira and Carr (2002); Kang et al. (2004); Wang et al. (2009) and Salih et al.(2018) have reported the positive impact of increased irrigation levels on tuber yield. Furthermore, Cantore et al. (2014); Abubaker et al. (2014); Kifle and Gebretsadikan (2016) and Shrestha et al. (2024) found that irrigation level significantly influenced total tuber yield, with fully irrigated plants exhibiting higher biomass and overall yield. Elhani et al. (2019) also reported that 40% tuber yield loss per plant had recorded due to decrease of irrigation amount by 50% as compared to full irrigation. These findings strongly suggest that increasing irrigation levels is an effective way to enhance potato tuber productivity.

Table 6. 4. Interaction effect of irrigation level and genotypes on total tuber yield (t ha^{-1}) of potato in the study area

	Irrigation levels		
Genotypes	Full (100%)	75%	50%
CIP-394611.112	29.87^{a}	24.88^{b}	17.96^{ef}
CIP-3960478.90	25.31^{b}	21.62^{cd}	17.98^{ef}
Seohong	19.12^{de}	16.9^{ef}	11.31^{hi}
CIP-392661.18	24.11^{bc}	15.71^{fg}	13.56^{gh}
Gudanie	18.98^{de}	12.28^{hi}	9.97^{i}
CV (%)	13.43		
LSD	2.867*		

Note: CV is coefficient of variance; LSD is least significant difference at 5%; and *significant at 5% probability level

6.3.3.3. Biomass yield and harvest index

The potato biomass yield had been found significantly influenced by both the main effects of genotype and irrigation level, as well as the interaction effect between genotype and irrigation level. The highest biomass yield of 33.59 t ha^{-1} had been observed under the interaction effect of genotype CIP-394611.112 and irrigation level of 100%, which was significantly higher than the other interactions of genotype and irrigation level. In harmony to this result, Cantore et al. (2014) reported aboveground biomass and total tuber yield were significantly affected by irrigation level. Fully irrigated plants gave higher biomass and greater total yield.

Analysis of variance revealed that irrigation level was the only factor with a significant main or interaction effect on harvest index (HI). Although higher irrigation levels produced significantly higher tuber yields, they did not alter the fundamental biomass partitioning strategy of the potato genotypes. Specifically, HI values of 89%, 85%, and 82% were observed at 100%, 75%, and 50% irrigation levels, respectively. The highest, though non-significant, genotypic HI values were 86.7% for CIP-394611.112 and 86.1% for CIP-3960478.90. This indicates that the plants used the additional water for overall growth rather than for increasing the efficiency of biomass allocation to tubers.On the other hand, genotype Seohong had the lowest harvest index at 83.9%, although it did not show a significant difference compared to the other genotypes. In summary, the results indicate that irrigation level has a significant effect on the harvest index, with higher irrigation levels leading to higher harvest indexes. While there were no significant differences among genotypes and no significant interaction effects, certain genotypes showed higher harvest indexes on average. However, it is important to note that these differences were not statistically significant, so further investigation may be needed to draw more conclusive findings. In line to this result Cantore et al, (2014) found Harvest index (HI) was not affected by the irrigation regime over the two experimental years

6.3.4. Irrigation water use efficiency and water productivity

The interaction effect of genotypes and irrigation level significantly influenced irrigation water use efficiency (Table 6.5) and water productivity of potato in the study area (Table 6.6). The result revealed that, regardless of genotypes, higher IWUE and WPc was observed when the irrigation level applied was induced water stress. In this regard, all genotypes were recorded higher IWUE and WPc values under 50% irrigation levels followed by 75% level. On the other hand, IWUE and WP varies with genotypes, the highest IWUE and WP being recorded on CIP-394611.112 under all levels of irrigation water used, and the lowest value recorded from Gudanie (Table 6.5 and 6.6). However, at 50% irrigation level the genotype CIP-3960478.90 have statistically similar IWUE and WPc values with that of CIP-394611.112. Briefly, the study demonstrates that genotype and irrigation level interaction play a significant role in determining the water use efficiency and water productivity of potato. Increasing irrigation levels lead to a decrease in IWUE, and Vis versa. In agreement to this, Badr et al. (2010), Hassanpanah (2010) and Badr et al. (2012) found that water stress increased water use efficiency, but decreased with increasing stress intensity (Yarnia et al ., 2009) in potato crops. Wright and Stark (1990) reported that water use efficiency in potato crops ranged from 5.4 to 12.0 kg m^{-3}, depending on factors like the growing region, irrigation management, and fertilizer amounts. Similarly, Shrestha et al. (2024) found that water use efficiency had significantly influenced by irrigation and variety. Cantore et al. (2014) noted lower yield WUE for rainfed plants under higher stress levels. Therefore, it can be concluded that proper use of irrigation water and use of responsive genotype are required to achieve high water use efficiency on potato.

Table 6.5. The interaction effect of irrigation levels and genotypes on irrigation water use efficiency (kg m^{-3}) of potato in the study area

Genotype	Irrigation level (%)		
	100 (Full)	75	50
CIP-394611.112	7.10^{c}	8.3^{b}	10.14^{a}
CIP-3960478.90	6.11^{de}	7.17^{c}	9.90^{a}
Seohong	4.50^{gh}	5.81^{de}	5.88^{de}
CIP-392661.18	5.23^{ef}	4.57^{fg}	6.20^{d}
Gudanie	4.06^{gh}	3.50^{h}	4.49^{fg}
CV (%)	11.68		
LSD	0.8474 ***		

Note: CV is coefficient of variance; LSD is least significant difference, Means within both column means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1%

Table 6.6. The interaction effect of irrigation levels and genotypes on water productivity (Marketable tuber yield kg m^{-3}) of potato in the study area

Genotype	Irrigation level (%)		
	1 00 (Full)	75	50
CIP-394611.112	6.59^{b}	7.44^{a}	7.65^{a}
CIP-3960478.90	5.66^{cd}	6.19^{bc}	7.72^{a}
Seohong	4.18^{fg}	5.11^{de}	4.52^{efg}
CIP-392661.18	4.90^{def}	4.00^{gh}	5.00^{ef}
Gudanie	3.71^{ghi}	3.00^{i}	3.23^{hi}
CV (%)	13.11		
LSD	0.7847***		

Means within both column followed by the same letter are not significantly different at p > 0.05; ns: - non significant while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1%

6.3.5. Effect of irrigation levels on quality of potato genotypes

The main effects of genotypes and irrigation levels on specific gravity, starch content and dray matter content of potato is indicated in Table 6. 7. The results indicate that, within the study area, neither irrigation level nor genotype had a significant main effect on potato specific gravity or starch content. In contrast, tuber dry matter content was significantly influenced by genotype. This finding suggests that the typical strong correlation between irrigation, specific gravity, and starch content was not the dominant factor determining tuber quality in this specific environment. Instead, genotypic selection for dry matter content emerged as the primary lever for quality control, independent of the irrigation regimes tested. Among the genotypes evaluated, CIP-394611.112 and CIP-3960478.90 produced the highest dry matter content; however, they were not statistically different from the other genotypes, with the exception of Gudanie. The genotype Gudanie recorded the lowest dry matter content and was statistically on par with CIP-392661.18 and Seohong. These results have critical implications for potato breeders and growers in the region, suggesting that selection for high dry matter genotypes and management of uniform environmental factors (soil and climate) may be a higher priority for quality control than fine-tuning irrigation practices.In line to this, Barbara and Piotr (2005) reported that the varietal factor significantly influenced dry matter content of tubers. Ierna and Mauromicale (2012) also reported that tuber dry matter content is responsive to cultivar and climatic conditions.

Regarding specific gravity, no significant differences had been observed among the genotypes and irrigation level. However, genotype CIP-394611.112 showed the highest starch content compared to other genotypes. Conversely, Gudanie had lower starch content compared to other genotypes. Genotype CIP-394611.112 recorded the highest specific gravity (1.074) and starch content (12.64), although the difference was not significant compared to other genotypes. The lack of significant differences in specific gravity and starch content among genotypes could be attributed to genetic similarity, particularly in terms of the specific genes responsible for specific gravity and starch content. In agreement with this result, Kaur and Aggarwal (2014) reported that in most of the cultivars there is no significant difference in specific gravity. Overall, these findings suggest that genotype plays a significant role in determining tuber dry matter content, with genotype CIP-394611.112 exhibiting the highest dry matter and starch content among the genotypes studied.

Table 6.7 Main effect of genotype and irrigation level on potato tuber quality

Genotype	Specific gravity (SG)	Starch content (SC)	Dray matter (DM %)
CIP-394611.112	1.074^{a}	12.64^{a}	24.13^{a}
CIP-3960478.90	1.072^{a}	12.24^{a}	23.67^{a}
Seohong	1.073^{a}	12.52^{a}	22.37^{b}
CIP-392661.18	1.070^{a}	11.39^{a}	22.03^{b}
Gudanie	1.070^{a}	11.17^{a}	21.64^{b}
CV (%)	2.700	24.03	6.98
LSD	0.009^{ns}	1.945^{ns}	1.175**
Irrigation level (%)			
100 %	1.071^{a}	12.08^{a}	22.80^{a}
75%	1.070^{a}	11.93^{a}	22.65^{a}
50%	1.070^{a}	11.97^{a}	22.78^{a}
CV (%)	2.7	24.03	6.98
LSD	0.010^{ns}	1.762^{ns}	0.613^{ns}

Means of the same main effect within a column followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant, but different letters with level of significant *:- significant at 5%, **:-significant at 1% and ***:- significant at 0.1%

6.3.6. Drought performance of potato genotypes

Table 6.8 shows drought stress evaluation of potato genotypes in terms of stress susceptibility index (SSI), stress tolerance index (STI), yield stability index (YSI), mean productivity (MP) and tolerance index (TOI). The result revealed that the genotypes differed in their stress susceptibility. Based on the scale developed by Fernandez (1992), genotypes CIP-3960478.90 classified as tolerant, CIP-394611.112 as neutral and Seohong, CIP-392661.18 and Gudanie as susceptible to stress conditions. Darvhankar and Bera (2016) also noted that drought-resistant genotypes should have a low stress susceptibility index (SSI) and a high stress tolerance index (STI). Similarly, based on the stress tolerance index, genotypes CIP-3960478.90 and CIP-394611.112 were tolerant compared to other genotypes. In line with this, Rosielle and Hamblin (1981) reported that genotypes with higher STI values demonstrate greater tolerance. Hassanpanah (2010) and Schafleitner et al. (2007) also reported differences in SSI and STI indices among potato genotypes under water stress. Seohong and CIP-3960478.90 had the lowest value of tolerance index (TOL), indicating consistent performance regardless of environmental conditions. Mean Productivity (MP) shows the mean yield produced between the treatment with irrigation and the dry treatment. On the other hand, in terms of mean productivity index, the result showed that genotypes CIP-3960478.90 and CIP-394611.112 were more advantageous even under stress conditions. Similarly, genotypes CIP-3960478.90 and CIP-394611.112 recorded higher value of yield stability index (YSI) as compared to the remaining genotypes. In summary, all drought index indicators revealed that genotypes CIP-3960478.90 was highly stress tolerance, good stability and productivity under stress. CIP-394611.112 also relatively tolerant and best suited to water stress conditions while genotypes Gudanie and CIP-392661.18 and Seohong were susceptible to drought stress. This finding has significant implications for agriculture and crop breeding

Table 6.8 Stress tolerance indices under full-irrigation and water stress condition based on yield of potato genotypes.

Genotype	SSI	STI	TOL	MP	YSI (%)
CIP-394611.112	0.98	0.62	11.58	24.08	62.02
CIP-390478.90	0.75	0.71	7.34	21.64	70.84
Seohong	1.01	0.61	7.6	15.33	60.81
CIP-392661.18	1.12	0.57	10.56	18.83	57.3
Gudane	1.23	0.53	9.02	14.48	52.32

Note: SSI is stress susceptibility index, STI is stress tolerance index, TOI is tolerance index, MP is mean productivity, and YSI is yield stability index

6.4. Conclusion and Recommendation

The interaction effect of genotypes and irrigation level affected significantly the days to maturity, marketable, total tuber yield as well as water use efficiency. Moreover, main effect of genotype and irrigation level significantly influenced days to flowering, days to maturity, plant height, average tuber diameter and number of tubers per plant. On the other hand, the quality measurements like specific gravity and starch content not affected by the main and interaction effect of genotype and irrigation level. The result further indicated that application of full irrigation level has positively influenced the marketable and total tuber yield of all genotypes, while application of irrigation water lower than 75% has significantly reduced the yield and yield components of the crop. On the other hand, increasing irrigation water has decreased the water use efficiency of all genotypes. The potato genotypes have variable response in terms of plant growth, development and yield components. Genotypes CIP-394611.112 and CIP-3960478.90 recorded significantly higher marketable and total tuber yield compare to remaining genotypes and their response increased with increasing irrigation water level. Likewise, both genotypes were also recorded the highest water use efficiency. Further mover, in terms of drought tolerance level, genotypes CIP-390478.90 and CIP-394611.112 were relatively stress tolerant and advantageous even under stress conditions. Therefore, genotype CIP-394611.112 with full and limited irrigation water is recommended to harvest optimum yield and water productivity in semi-arid areas of Tigray and other similar agro-ecologies of Ethiopia.

6.5. References

Abite, S. 2014. Problems and prospect of Potato Production and Marketing a Case Study on Snnpr Gamogofa Zone Chencha Woreda Gendogembela and Doko Yoyera Rural Kebele, Ethiopia. Doctoral dissertation, St. Mary's University.

Abubaker, B.M.A., Y. Shuang-en, S., Guang-Cheng, M. and Alhadi, A. 2014. Elsiddig. Effect of irrigation levels on the growth, yield and quality of potato. Bulg. J. Agric. Sci, 20: 303-309.

Allen, R. G., Pereira,L.S., Raes,D. and Smith,M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO irrigation and Drainage. Paper No. 56. FAO Food and Agriculture Organization of the United Nations, Rome, Italy, 300(9): D05109.

Amare, T., Bazie, Z., Alemu, E., Alemayehu, B., Tenagne, A., Kerebh, B., Taye, Y., Awoke, A., Feyisa, T., Kidanu, S. 2022. Yield of potato (Solanum tuberosum L.) increased by more than two-folds through nitrogen and phosphorus fertilizers in the highlands of North-Western Ethiopia. Heliyon, 8(10):e10941.

Asefa, G., Mohammed, W. and Abebe, T. 2016. Genetic variability studies in potato (Solanum tuberosum L.) variety in Bale highlands, South Eastern Ethiopia. Journal of Biol. Agric.Healthc, 6:117-119.

Asmita, O., and Rajkumari, A.D. 2022. Varietal evaluation of different potato (Solanum tuberosum L) varieties. The Pharma Innovation Journal, 11(9): 909-918.

Ati, A.S., Iyada, A.D. and Najim, S.M. 2012. Water use efficiency of potato (Solanum tuberosum L.) under different irrigation methods and potassium fertilizer rates. *Annals of Agricultural Sciences, 57*(2): 99-103.

Aytekin, R.I. and Caliskan, S. 2023. Irrigation and potassium fertilization effects on plant growth, tuber yield, quality, and water use efficiency of potato. Irrig. Sci, 42: 367–385.

Badr, M.A., Abou Hussein, S.D., El-Tohamy, W.A. and Gruda, N. 2010. Efficiency of subsurface drip irrigation for potato production under different dry stress conditions. Gesunde Pflanzen, 62: 63-70.

Badr, M.A., El-Tohamy, W.A. and Zaghloul, A.M. 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. Agric. Water Manage, 110: 9-15.

Barbara, S. and Piotr, P. 2005. Dry matter and carbohydrates content in the tubers of very early potato varieties cultivated under coverage. Acta Sci. Pol., Hortorum Cultus, 4(2): 111-122

Bhuvaneswari, S., Sharma, S.K., Punitha, P., Shashidhar, K.S., Naveenkumar, K.L. and Prakash, N. 2017.Evaluation of morphological diversity of field pea (Pisum sativum subsp. Arvense L.) Germplasm under sub-tropical climate of Manipur. Legume Research-An International Journal, 40(2):215-23.

Bilate, B. and Mulualem, T. 2016. Performance evaluation of released and farmers' potato (Solanum tuberosum L.) varieties in eastern Ethiopia. Sky Journal of Agricultural Research, 5(2):034-41.

Bouslama, M. and Schapaugh, W. 1984. Stress tolerance in soybean, Evaluation of three screening techniques for heat and drought tolerance. Crop Science, 24(1): 933-937.

Cantor, V., Stellacc, A.M., Wassar F., Yamaç, S.S., Sellami, M.H., Albrizio R., and Todorovic M. 2014.International Journal of Plant Production, 8(3): 409-428.

Central Statistics Authority (CSA) .2017. The federal democratic republic of Ethiopia Central statistical agency Agricultural sample survey 2016/2017. Report on Area and Production of Major crops .Private peasant holdings. Meher season. Volume I. Pp 18-20. Addis Abeba, Ethiopia.

Darvhankar, M.S. and Bera, S.K. 2016. Studies on Drought Tolerance in Recombinant Inbred Lines of Groundnut. *Advances in Life Sciences*, *5*(10: 4310-4316.

Devaux, A., Goffart, J. P., Kromann, P., Andrade-Piedra, J., Polar, V., and Hareau, G. 2021. The potato of the future: Opportunities and challenges in sustainable agri-food systems. Potato Research, 64(4), 681-720.

Elhani, S., Haddadi, M., Csákvári, E., Zantar, S., Hamim, A., Villányi, V., Douaik, A. and Bánfalvi, Z. 2019. Effects of partial root-zone drying and deficit irrigation on yield, irrigation water-use efficiency and some potato (Solanum tuberosum L.) quality traits under glasshouse conditions. Agric. Water Manag, 224: 105745.

Erdem, T., Erdem, Y., Orta, H. and Okursoy, H. 2006. Water-yield relationships of potato under different irrigation methods and regimens. Sci. Agric, 63: 226–231.

Fantaw, S., Ayalew, A., Tadesse, D. and Agegnehu, E. 2019. Evaluation of potato (Solanum tuberosum L.) varieties for yield and yield components. Journal of Horticulture Forestry, 11(3):48-53.

Fernández, E. 2023. Editorial note on terms for crop evapotranspiration, water use efficiency and water productivity. Agricultural Water Management, 289:108548. 10.1016/j.agwat.2023.108548.

Fernandez, G. 1992. Effective selection criteria for assessing stress tolerance. Proceedings of the international Symposium on Adaptation of Vegetables and other Food Crops in Temperature and Water stress. Taiwan.

Fernandez, G. 1992. Effective selection criteria for assessing stress tolerance. Proceedings of the International Symposium on adaptation of vegetables and other food crops in temperature and water stress. Asian vegetable research and Development Center, 257-270

Ferreira, T.C. and Carr, M.K.V. 2002. Response of potatoes (Solanum tuberosum L.) to irrigation and nitrogen in a hot, dry climate: I. Water use. Field Crops Research, 78:51-64.

Fischer, R. and Maurer, R. 1978. Drought resistance in spring wheat cultivars, Grain yield responses. Australian Journal of Agriculture Research, 29(1): 897–912.

Gupta, A. and Saxena, M.C. 1976. Total nitrogen concentration in leaves of potatoes (Solanum tuberosum L.) as an index of nutritional status. *The Journal of Agricultural Science*, *87*(2): 293-296.

Gupta, J.J., Yadav, B.P.S., Gupta, H.K., Sahoo, S.K, and Agrahar, D. 2001.Nutritive value of detoxified jack bean (*Canavalia ensiformis*) seed for young chicks. Indian J. Anim. Sci., 71 (12): 1169-1171.

Hassanpanah, D., 2010. Evaluation of potato cultivars for resistance against water deficit stress under in vivo conditions. Potato Res., 53; 383-392.

Hassen, R. L., Kelly, D. M., Wittmeyer, E. C., Wallace, C., Grassbaugh, E. M., Elliott, J. Y. and Wenneker. G. L. 1997. Ohio potato cultivar trials. Ohio State Univ. Horticulture Series No. 666.

Iwama, K. and Yamaguchi, J. 2006. Abiotic Stresses. In Handbook of potato production, improvement, and postharvest management, ed. J. Gopal and S.M.P. Khurana, 231–278. New York: The Haworth Press.

Jackson, M.L.1973. Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India, 498* :151-154.

Jennings, S.A., Koehler, A.K., Nicklin, K.J., Deva, C., Sait, S.M. and Challinor, A.J. 2020.Global Potato Yields Increase under Climate Change with Adaptation and CO2 Fertilisation. Front. Sustain. Food Syst., 4: 519324.

Jennings, S., Mullen, C., and Vanya, C. 2020. Climate projections and agricultural vulnerability in the semi-arid highlands of East Africa. Global Environmental Change, 62: 102–115.

Kang, Y., Wang ,F.X., Liu, H.J. and Yuan, B.Z. 2004 .Potato evapotranspiration and yield under different drip irrigation regimes. Irrigation Science, 23:133-143

Karam, F., Rouphael, Y., Ladoud, R., Baried, J., Colla, G. 2009. Influence of Genotypes and Potassium application rates on the yield and potassium use efficiency of potato. Journal of Agronomy, 8 (1):27-32.

Kashyap, P.S. and Panda, R.K. 2003. Effect of irrigation scheduling on potato crop parameters under water stressed conditions. Agriculture and Water Management, 59:49-66.

Kaur, S. and Aggarwal, P. 2014. Studies on Indian Potato Genotypes for their Processing and Nutritional Quality Attributes .Int.J.Curr.Microbiol.App.Sci, 3(8): 172-177.

Kifle, M. and Gebretsadikan, T.G. 2016. Yield and water use efficiency of furrow-irrigated potato under regulated deficit irrigation, Atsibi-Wemberta, North Ethiopia. *Agricultural Water Management*, 170: 133-139.

Kumar, A., Bernier, J., Verulkar, S., Lafitte, H.R. and Atlin, G.N. 2008. Breeding for drought tolerance: direct selection for yield, response to selection and use of drought-tolerant donors in upland and lowland-adapted populations. Field Crops Research, 107(3):221-31.

Lahlou, O., Ouattar, S. and Ledent, J.F. 2003. The effect of drought and cultivar on growth parameters, yield and yield components of potato. Agronomie, EDP Sciences, 23 (3); 257-268.

National Potato Research Program (NPRP). 2014. Field book for standard evaluation of potato and sweet potato germplasm, (Eds.BB Khatri and BP Luitel). National Potato Research Program, NARC, Khumaltar, Lalitpur, Nepal.

Olsen, S.R. and Dean, L.A. 1965. Phosphorus. In: Methods of Soil Analysis. American Society of Agronomy. Madison, Wisconsin, 9: 920 – 926.

Quiroz, R., Ramírez, D.A., Kroschel, J., Andrade-Piedra, J., Barreda, C., Condori, B., Mares, V., Monneveux, P. and Perez, W. 2018. Impact of Climate Change on the Potato Crop and Biodiversity in Its Center of Origin. Open Agric, 3; 273–283.

Quiroz, R., Rojas, O., and Mbululo, Y. 2018. Drought risk and climate trends in the tropical and subtropical regions: A meta-analysis. Journal of Arid Environments, 155:12–25.

Ranganna, S. 1977. Manual of Analysis of Fruit and Vegetable products Central Food Technological Research Institute Mysore, USA.

Rosielle, A. and Hamblin, J. 1981. Theoretical aspects of selection for yield in stress and non-stress environments. Crop Science, 21(1): 943-946.

Salih, S.A., Abdulrahman, F.A. and Mahmood, Y.A. 2018. The effect of different irrigation interval on tuber yield and quality of potato (Solanum tuberosum L.). *Kurdistan Journal of Applied Research*, *3*(2):27-31.

Schafleitner, R., Gutierrez, R., Espino, R., Gaudin, A., Perez, J., Martinez, M., Dominguez, A., Tincopa, L, Alvarado, C., Numberto, G. and Bonierbale, M. 2007. Field screening for variation of drought tolerance in Solanum tuberosum L. by agronomical, physiological and genetic analysis. Potato Research, 50: 71–85.

Shi, S., Fan, M., Iwama, K., Lic, F., Zhang, Z. and Jia, L. 2015. Physiological basis of drought tolerance in potato grown under long-term water deficiency. International Journal of Plant Production, 9(2): 305-320.

Shock, C.C., Feibert, E.B.G. and Saunders, L.D. 1998. Potato yield and quality response to deficit irrigation. Horticultural Science, 33: 655-659.

Shrestha, B., Stringam, B.L., Darapuneni, M.K., Lombard, K.A., Sanogo, S., Higgins, C. and Djaman, K. 2024. Effect of Irrigation and Nitrogen Management on Potato Growth, Yield, and Water and Nitrogen Use Efficiencies. Agronomy, 14:560.

Sikora, F.J. and Moore, K.P. 2014. Soil test methods from the southeastern United States. Southern cooperative series bulletin, 419: 54-58.

Tamer, G., Belew, D., Dessalegne, Y. 2012. Effect of variety and earthing-up frequency on growth, yield and quality of potato (Solanum tuberosum L.) at Bure, northwestern Ethiopia. MSc thesis, Jimma University.

Taye, B., Tsigereda, A. and Woldemariam, W. 2021. Effect of Plant Spacing on Yield and Yield Components of Potato (Solanum tuberosum L.) Cultivars at Wolaita Sodo University, Ethiopia. Inc. Curr.Res.Aca.Rev, 9(01): 103-125.

Teklemariam, T.M. 2014. The impact of international Potato Center's nutrition project on smallholder farmers' income and adoption of improved potato varieties: Tigray region, Northern Ethiopia .Doctoral dissertation, University of Sussex.

Thiele, G., Theisenm, K., Bonierbalem, M. and Walker, T. 2010 .Targeting the poor and hungry with potato science, Potato J., 37: 75–86.

Wang, F., Feng, S., Hou, X., Kang, S. and Jiang Han, J. 2009. Potato growth with and without plastic mulch in two typical regions of Northern China. Field Crops Research, 110:123-129.

Widmann, N., Goian, M., Ianculov, I., Dumbravă, D. and Moldovan, C. 2008. Method to starch content determination from plants by specific weight. *Scientific Papers Animal Science and Biotechnologies*, *41*(1): 814-814.

Wright, J.L. and Stark, J.C. 1990. Potato. In: Stewart, B.A., Neilsen, D.R. (Eds.), Irrigation of Agricultural Crops. ASA-CSSA-SSSA Pub., Agron. Monog. N. 30, WI, 859-888.

Yarnia, M., Khorshidi, M.B., Nasseri, A. and Hassanpanah, D. 2009. Drought stress effects in different growth stages on potato cultivars. Potato Res, 53: 383-392.

Yuan, B.Z., Nishiyama, S. and Kang, Y. 2003.Effects of different irrigation regimes on the growth and yield of drip-irrigated potato. Agriculture and Water Management.63:153-167.

Zhang, H., Wang, X., You, M. and Liu, C. 1999. Water-yield relations and water-use efficiency of winter wheat in the North China Plain. *Irrigation Science*, *19*: 37-45.

CHAPTER 7

7. Effects of Zinc fertilizer rates and irrigation levels on growth, yield and quality of potato genotypes under screen house condition

Abstract

Water management, varietal selection, and zinc (Zn) application are critical for sustainable potato (Solanum tuberosum L.) production. A pot experiment was conducted to assess the effects of different Zn fertilizer rates, potato genotypes, and irrigation levels on yield, quality, nutrient use efficiency, and nutrient uptake in potatoes. The study involved three potato genotypes (CIP-39411.112, Seohong, and Gudanie), five Zn fertilizer rates (0, 2.5, 5, 7.5, and 10 kg ha $^{-1}$*), and three irrigation levels (50%, 75%, and 100%) under controlled screen house conditions in the semi-arid regions of Tigray. Treatments were arranged in a factorial complete randomized design with three replications. Results indicated that genotype, irrigation, and Zn rates along with the interaction between genotype and irrigation level, significantly influenced key metrics such as days to maturity, plant height, tuber yield, starch content, and Zn uptake. Notably, the interaction between genotype and Zn application significantly affected marketable and total tuber yields, Zn uptake, and agronomic efficiency. The highest marketable and total yields were observed for CIP-394611.112 interaction with 100% irrigation and 5 kg Zn ha*$^{-1}$*. The highest Zn concentration and uptake of potato tuber was recorded at the interaction of each genotype with the highest Zn fertilizer rate. The highest Zinc concentration and uptake of potato tuber was obtained from genotype Gudanie interaction with 10 kg ha*$^{-1}$ *of Zn fertilizer rate. The maximum agronomic efficiency was recorded at the interaction of each genotype with the lowest (2.5 kg ha*$^{-1}$*) Zn rate. Overall, genotype interactions with irrigation and Zn application greatly affected yield, quality, and nutrient uptake efficiency, suggesting the need for further field trials to confirm the potential of the genotypes with Zn fertilizer*

Keywords: Genotype, Irrigation level, Zinc rate

7.1. Introduction

Potato is one of the main tubers and nutritious crops, is which very important due to nutritive and economical value. This crop with high performance in unit level is containing abundant carbohydrate and high biological value of protein (Mousavi et.al, 2007). The application of inorganic fertilizers, along with micronutrients, is considered essential for achieving high tuber yields. To improve productivity, potato plant requires a balanced dose of NPK along with adequate amount of micronutrients like, sulphur, zinc and manganese (Singh and Kathayat, 2018). Nutrient elements especially zinc, sulphur and magnesium not only increase the yield of potato but also improve the quality of potato tubers (Taya et al., 1994). Water significantly affects the high yield crop production of potato and is needed in sufficient amount to ensure optimum yield. Water, variety and nutrients are the three most important inputs that influence potato production. Water is supplied to the potato plants through either precipitation or irrigation whereas minerals supplied with synthetic fertilizers and organic manures.

Water stress in plants causes stomatal closure, reducing transpiration and water transport (He and Dijkstra 2014). Inefficient nutrient management results in low nutrient use efficiency and significant nutrient losses, while poor water management leads to low water use efficiency, contributing to high nutrient leaching (Li et al ., 2009). Zinc (Zn) is a crucial micronutrient, playing a vital metabolic role in energy production and the Krebs cycle (Hosamani et al., 2020). Zinc considered as the most important micronutrient for potato and low recovery of applied Zn is the main limitation in enhancing the yield of potato (Singh et al. 2014). Depending upon the duration of variety, potato crop is highly sensitive to Zn application. Zn application is found to increase ascorbic acid content, but reduce the tyrosine and total phenol content in tubers, which are important criteria for the processing quality (Mondal et al. 2015). Zinc deficiency in potato results in stunted growth and small leaves. Furthermore, it causes younger leaves show interveinal chlorosis and necrosis, which occurs in irregular patches. Whitish spots develop within the brown necrotic tissue. Zn is important for healthy green foliage also improved tuber yield and quality. Water stress, lack of drought tolerance variety and nutrient depletion are the major constraints of potato productivity, in Tigray region. Zinc is one of the forgotten element in the past is now fast receiving attention because of its widespread deficiency in potato growing areas. The yield of the crops can be further increased with proper management practices like use of high yielding varieties, irrigation, application of fertilizer etc.

While previous studies have explored the individual effects of variety, irrigation, or Zn fertilizer on potato yield and quality, few have examined the combined effects of these factors. Therefore, the objective of this study was to evaluate the effects of different zinc fertilizer rates, irrigation levels, and potato genotypes on yield, nutrient use efficiency, and quality, and to identify the optimal levels of zinc and irrigation for maximizing these outcomes.

7.2. Materials and Methods

7.2.1. Description of the study areas

The Screen house experimental study was conducted at the Mekelle Agriculture Research Center, Mekelle Tigray, Ethiopia. The screen house was located at 39° 32′ 55”E Longitude and 13° 38’49’’ N Latitude with an elevation 2004 m.a.s.l. The screen house’s temperature ranged from 11.8 to 27.1 ^{0}C, which aligns with the optimal conditions requirements for potato growth. The area of the Screen house is 28m*12m (336m^2) with 4.5m height

7.2.2. Treatments and Experimental Design

The experiment was arranged in a factorial completely randomized design (CRD) with three replications. The 5 × 3 × 3 factorial treatments consisted of five Zn fertilizer rates (0, 2.5, 5, 7.5, and 10 kg ha^{-1}), three potato genotypes (CIP-39411.112, Seohong, and Gudane), and three irrigation levels (100%, 75%, and 50% of the potato water requirement). For each treatment, two pots were used, with one tuber planted per pot. The diameter and height of the pot was 30cm with base area and volume 0.071m^2 and 0.0212 m^3, respectively. To determine the Zinc (Zn) fertilizer requirement rate for the pot experiment the fertilizer rates per hectare (ha) were converted and adjusted to correspond to the surface area of the pots. The irrigation treatments were defined based on the amount of water applied, with reference to the full irrigation treatment (100%).

7.2.3. Agronomic and irrigation management

Plastic pots with a diameter of 30 cm and a depth of 30 cm were used as planting media for the treatments. Each pot was filled with 20 kg of air-dried soil collected from a depth of 0–30 cm in the outdoor experimental field. Prior to filling the pots, the soil was analyzed for Field Capacity (FC), Permanent Wilting Point (PWP), and Total Available Water (mm/m) at the 0–30 cm soil depth. The different amount of water level measured and applied to the pots using plastic-can with measuring scale manually. All the pots irrigated with no difference in the treatments until well established in early initial stage of the plant then the pots are irrigated based on their irrigation level. In non-stress (Full irrigation) treatment, water was maintaining at field capacity. The rates of Zn were applied at planting based on the surface area of the pot and then calculate the corresponding amount of Zn fertilizer rates to use for the potato planted on pot. ZnO was used as source of Zinc in powder form. Full recommended rate of 237kg ha^{-1} NPS (19N:38P_2O_5:7S) was applied at the time of soil filling. Half of the recommended rate of Urea (165kg ha $^{-1}$) was applied to all pots uniformly at planting and the remaining half of Urea at early flowering to all treatment with spot application. The fertilizer rates kg ha^{-1} were converted in to correspond surface area of the pot. Weeding, fertilizer application and other agronomic practices of the crop applied as per the recommendation of regional and national research institutions.

7.2.4. Data collected

7.2.4.1. Climatic and soil data

Climate data such as daily rainfall, minimum and maximum air temperature, relative humidity, wind speed and sun shine hours collected from Mekelle Agricultural Research center, Metrological station. Furthermore representative composite soil samples had been taken from the field that used for the pot before planting, following the standard soil sampling procedure. The composite soil sample was used for selected physico-chemical analyses, including soil texture; pH, EC, OC, CEC, total N, and available Zn. The samples analyzed at the Mekelle Soil Research Center and Ezana Mining Development Private Limited Company, Analytical Laboratory, Mekelle (Table 7.1). Composite soil samples from the surface layer (0-0.30 m) of representative soils were collected prior to sowing to determine total nitrogen using the

Kjeldahl method, available phosphorus using the Olsen and Dean. (1965) method, Sikora, and Moore (2014) for organic carbon and soil pH (on 1:2.5 soil: water suspension). The soil physical and chemical characteristics of both sites is depicted in Table 7.1

Table 7.1 Pre -planting soil chemical and physical properties of the soil

Sites	pH	EC (ds/m)	OM (%)	CEC(cmol/ kg)	TN (%)	AV.P (ppm)	Zn (ppm)	BD (g/cm^3)	FC (%)	PWP (%)	TAW (mm/m)	Particle size(%			Soil texture
												Sand	Silt	Clay	
Elalla	7.02	0.63	1.62	43.1	0.09	15.9	76.0	1.28	32.5	16.5	160	40	21	39	Clay loam

Note: EC = Electrical conductivity, OM = Organic matter, CEC= Cation exchange capacity of the soil, TN = Total nitrogen, Av. P = Available phosphorus BD =Bulk density, FC =Field capacity, PWP =Permanent wilting point, and TAW =Total available water.

7.2.4.2. Plant sampling and analysis

Fresh mature leaf samples of potato from each pot were collected from the petiole of the fourth leaf from the top of the plant nine weeks after planting, which was at the stage of tuber intuition, then oven dried overnight at 70 ^{0}C for 72 hours. Then the samples were ground and sieved through a 2 mm sieve for N and Zn content analysis. Besides being determined, the N and Zn content of potato tuber samples was taken at harvest, dried in an oven at 80 °C for 72 hours, ground, and sieved in order to analyze the N and Zn contents in the laboratory as described by Karma et al . (2009). The nitrogen content analyzed at the Mekelle Soil Research Center laboratory, while the Zn content analyzed at the Ezana Analytical Laboratory, Mekelle. The total nitrogen content in tuber and leaf samples was determined using the Kjeldahl method as described by Gupta and Saxena (1976).

7.2.4.3. Crop data collection

Data were collected on various parameters, including days to 50% flowering, days to maturity, plant height, number of tubers per plant, tuber diameter, tuber length, and marketable and total tuber yield. Days to flowering and physiological maturity were recorded when 50% of the plant population attained flowering. Days to physiological maturity were noted when the leaves of 75% of the plants in each pot turned a yellowish color. Plant height was determined by measuring height from the base of the main stem to the apex at full maturity. Tuber number per pot was determined by count the total number of tubers produced per plant or pot harvested. Following the procedure of National Potato Research Program of Nepal (NPRP, 2014) healthy tuber with weight > 25 g was considered as marketable while rotten, diseased, insect attacked, deformed tuber and those having < 25 g in weight was categorized as unmarketable yield (NPRP, 2014). Finally, tuber yield was obtained from each pot with an area of 0.0707m^2. Dry aboveground biomass was also collected at harvest.

7.2.5. Determination of potato tuber quality

Protein content (%) calculated by multiplying N content by 6.25 (Ranganna, 1977). Starch content (%) and specific gravity were determined based on Widmann et al. (2008) procedures as indicated Equation 7. 1 and 7.2, respectively.

The specific gravity calculated with the following relation:

$$SG = \frac{W1}{W1 - W2} \qquad \text{Eq 7.1}$$

Where:

SG= Specific gravity

W1 = air weight of the tuber

W2 = the weight of the tuber completely immersed in water.

For determination of the total starch content are used the following relation (Vasanthan and colab, 1999):

$$SC = 17546 + 199.07\ (SG - 1,\ 0988) \qquad \text{Eq 7. 2}$$

Where:

SC = starch content of potato tuber in %

The dry matter content of each genotype was determined to be three to five tubers per pot or plant. The tubers had weighed while fresh and later dried in an oven at 80 °C for 72 hours (until a constant weight) and reweighted.

7.2.6. Estimation of crop water and irrigation requirement

The water requirement of a crop is influenced by factors such as climate, crop type, growth stage, and soil type, with the soil used in this study being collected from the field surrounding the screen house. In this study, the water requirement (ETc) of potato was determined from the reference evapotranspiration (ETo) and respective crop coefficients (Kc) for each growth stage, as indicated by Allen et al. (1998). The Kc values of potato in the different growth stages were adopted from Allen et al. (1998). The crop water requirement, irrigation water requirement and the irrigation schedule were estimated using FAO CROPWAT software program version 8 following Allen et al. (1998). The crop water requirement was calculated using equation 7.3.

$$ETc(mm) = Kc * ETo\ (mm) \qquad \text{Eq 7.3}$$

Where ETc is crop water requirement (mm/day); K_c is crop coefficient and ETo is reference crop evapotranspiration (mm/day).

The total amount of water applied per pot during the crop growth period under screen condition is termed as water requirement of the crop. The amount of water required in each treatment was measured and applied using measuring cane. All the pots watered with no difference in all treatments until 20 days after planting (well established of the plant) then the pots watered based on their irrigation level manually daily (one-day lap) until maturity. The total amount of water applied was 230.38, 319.95 and 500.93 mm based on irrigation level of 50 %, 75 and 100% of water requirement of potato, respectively or, 16.36, 27.72 and 35.56 liter of water per pot of was applied at 50%, 75% and 100 % of potato water requirement, respectively during the growing season.

7.2.7. Determination of water and irrigation use efficiency

Water use efficiency (WUE), irrigation water use efficiency (IWUE), total water productivity (TWP) and water productivity (WPc) of potato were calculated following the procedures described by Ati et al. (2012), Erdem et al. (2006), and Fernández (2023) as indicated in Equation 7.4, 7.5, and 7.6, respectively.

$$\text{WUE}=\frac{\text{Total biomass Yield (kg)}}{\text{ETa(m3)}} \qquad \text{Eq.7.4}$$

ETa is actual Evapotranspiration

$$\text{IWUE}= \frac{\text{Total tuber Yield (kg)}}{\text{Total water applied (m3)}}$$ Eq.7.5

$$\text{WP}_{\text{c}=} \frac{\text{Marketable tuber yield }(\frac{\text{kg}}{\text{ha}})}{\text{Total water applied (m3)}}$$ Eq 7.6

7.2.8. Determination of Nutrient use efficiency

Nutrient use efficiency (NUE) was calculated according to (Fixen *et al* ., 2014; Ladha et al . 2005) using the following formulas;

$$Agronomic\ efficiency (AE) = \frac{Y_{zna} - Y_C}{zna}$$ Eq 7.8

$$Physiological\ effeciency\ of\ Zn (PE_{Zn}) = \frac{Y_{Zn} - Y_C}{U_{Zn} - U_C}$$ Eq 7.9

$$Recovery\ efficiency\ of\ Zn (RE_{Zn}\ ) = \frac{U_{Zn - U_C}}{Zna}$$ Eq 7.10

Where Y_{Zn} = yield of harvested portion of crop with Zinc applied, Y_C = yield with not nutrient applied (Control), Zn = amount of Zinc applied, U_{Zn} = total nutrient uptake of the plant with nutrient applied and U_C = nutrient uptake of the plant with no nutrient applied; (control) and, Zn applied (Zna).

Nutrient uptake by potato was determined at harvest by multiplying the dry weight of potato plant (kg ha $^{-1}$) (above ground stem and leaf +underground tuber) by their respective concentrations content of the plant (tuber + above ground plant) Tarafder et al. (2008).

$$Nutrient\ uptake\ \left(\frac{kg}{ha}\right) = \frac{Nutrient\ concentration\ (\%) * Yield (kg/ha)}{100}$$

Eq 7.11

7.2.9. Data analysis

The data collected in this experiment included plant growth, tuber yield, and yield components. The statistical software GenStat were used to analyze the data and to check ANOVA assumptions. Analysis of Variance (ANOVA) was employed to determine whether there were significant differences among the treatments and their interactions. Differences between treatment means were computed using Duncan's Multiple Range Test (DMRT) at a 5% level of significance. If a significant difference was found.

7.3. Results and Discussion

7.3.1. Effect of irrigation levels and Zn fertilizer on growth and yield component of potato genotypes

7.3.1.1 Growth parameters of potato genotypes

The results showed that the main effect of genotype, irrigation level, Zinc fertilizer rate, and the interaction effect of genotype with irrigation level significantly influenced the days to maturity and plant height (Table 7.2). The longest number of days to maturity (105) was significantly recorded due to the interaction effect of genotype Gudanie with an irrigation level of 100% of the water requirement for potato. However, the shortest number of days to maturity was observed due to the interaction effect between genotype CIP-39411.112 and an irrigation level of 50% of the water requirement for potato (Table 7.2). The highest plant height recorded because of the significant interaction effect between genotype Gudanie and irrigation level of 100%. This result demonstrates the interaction between genotype and irrigation level, which influences days to maturity and plant height. Specifically, as the irrigation level increases, the days to maturity also increase. Conversely, a decrease in irrigation level results in a reduction of days to maturity for the same genotype (Table 7.2). Additionally, the days to maturity of the genotypes in the experiment is more responsive to the interaction with irrigation level than to the Zinc fertilizer rate. In line to this study Kumar et al. (2008reported that application of Zn significantly influenced potato plant height. Banerjee et al. (2017) indicated that growth of potato plant is highly responsive to micronutrient application, especially Zinc. Sibirev (2024) reported that certain genotypes respond better to higher irrigation levels, leading to increased days to maturity. He also found that specific genotypes exhibited varying growth responses under different irrigation regimes, affecting traits such as plant height and tuber yield,

7.3.1. 2. Yield components of potato genotypes

The result showed that average tuber diameter (ATD), total number of tubers per plant and number of marketable tuber number per plant was significantly influenced due to the main and interaction effect of genotype and irrigation level (Table 7.2). The highest average tuber diameter (58.5 mm) had been obtained from the interaction effect of genotype CIP-394611.112 and an irrigation level of 100%. Conversely, the lowest average tuber diameter (34.54 mm) was found from the interaction effect of genotype Gudanie and an irrigation level of 50%. This result demonstrates that the variation in average tuber diameter is attributable to differences in genotype and irrigation level. Specifically, as the irrigation level increases for a given genotype, the average tuber diameter also increases (Table 7.2). The highest total and marketable number of tubers per plant had been obtained from the interaction of genotype CIP-394611.112, and irrigation level of 100%. In contrast, the smallest total and marketable number of tubers per plant had been recorded from the interaction of genotype Gudanie, and irrigation level of 50%. Similar to this study Sibirev (2024) reported that certain genotypes respond better to higher irrigation levels, leading to greater tuber production. These findings are also consistent with the research conducted by Banerjee et al. (2017), Sarkar et al. (2018) which indicated that zinc fertilization has a significant positive impact on tuber number. Additionally Mahamud et al. (2021); Sarkar et al. (2018); and Kumar et al. (2008) reported that the application of Zn in potatoes resulted in an increase in the number of tubers, average tuber weight, yield, as well as qualitative indices.

It is worth noting that previous studies have focused more on addressing the effects of macronutrients on irrigation levels and potato varieties than on micronutrients. Therefore, this study serves as an indicator of the interaction effect of Zn fertilizer with moisture and potato variety on all the attributes.

Table 7.2 Interaction effect of genotype and irrigation level on growth and yield component of potato

Treatments		Growth and yield component				
Genotype	Irrigation level (%)	Days to maturity	Plant height (cm)	Average tuber diameter	Number of total tubers per plant	Number of marketable Tuber yield
CIP-394611.112	100	97.3^{c}	57.1^{c}	58.5^{a}	12.26^{a}	10.67^{a}
CIP-394611.112	75	95.7^{d}	47.8^{e}	57.1^{a}	8.33^{b}	7.05^{b}
CIP-394611.112	50	93.7^{e}	42.0^{e}	46.9^{c}	8.00^{bc}	6.67^{b}
Gudanie	100	105.2^{a}	68.1^{a}	34.7^{e}	5.73^{e}	4.27^{d}
Gudanie	75	99.9^{b}	60.7^{b}	40.0^{d}	4.80^{ef}	3.87^{d}
Gudanie	50	99.0^{b}	60.5^{b}	34.5^{e}	3.87^{f}	2.80^{e}
Seohong	100	95.6^{d}	53.3^{d}	50.1^{b}	7.07^{cd}	5.47^{c}
Seohong	75	93.6^{e}	50.1^{e}	49.6^{bc}	6.00^{de}	4.47^{d}
Seohong	50	93.0^{e}	47.0^{e}	38.4^{d}	4.80^{ef}	3.93^{d}
CV (%)		1.58	7.78	8.60	24.30	24.60
LSD		0.986*	3.064*	2.82***	1.195**	0.976*

Means within a column followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1%

7.3.2. Effect irrigation levels and Zn fertilization on tuber yield of potato genotypes

7.3.2.1. Marketable tuber yield (Kg pot^{-1})

The main and interaction effect of genotype, irrigation level, Zn rate, interaction of genotype with irrigation level, and genotype interaction with Zn fertilizer significantly affected the marketable tuber yield (Table 7.3). The highest marketable tuber yield 0.267 kg pot^{-1} and 0.252 kg pot^{-1}had been obtained at the interaction effect of genotype CIP-394611.112 with 100% irrigation level and CIP-394611.112 with 5.0 kgha-^{1}Zn fertilizer rate, respectively .Whereas the lowest marketable tuber yield kg pot^{-1} was recorded at genotype Gudanie with 50%

irrigation level and Gudanie with 0 kg ha^{-1} Zn fertilizer interaction, respectively (Table 7.3).. Total tuber number is a primary indicator of its yield potential. From this potential, the marketable tuber number is derived, representing the portion that meets quality standards after accounting for defects and losses. Therefore, it is logically consistent and commonly observed that the marketable tuber yield shows a positive and significant correlation with both the total and marketable number of tubers per plant.

This result indicates that marketable tuber yield was more responsive to genotype interaction with irrigation level than Zn rate. This suggests that certain genotypes respond more favorably to specific Zn levels, enhancing their growth and productivity. Regardless of its interaction in harmony to this result Al-Jobori and Al-Hadithy (2014), Mousavi et al. (2007) and Banerjee et al. (2017) reported that Zn fertilization in increasing yield and qualitative parameters of potato crop. Similarly Banerjee et al. (2016) observed that application of 4.5 kg Zn ha^{-1} recorded significantly A-grade potato tuber and increased qualitative tuber yield or marketable tuber yield or application of Zn in potato had resulted in increase in yield, quality and postharvest soil nutrient status at different levels of Zn application under varying initial soil Zn status. With respect to irrigation level in agreement to this, many researchers have reported that increased tuber yield with increase in irrigation level (Yuan et al., 2003; Kashyap and Panda, 2003, Shock et al., 1998; Ferreira and Carr, 2002; Kang et al., 2004; Wang et al., 2009). Similarly Cantore et al. (2014) reported that marketable yield varied significantly in relation to water availability: the highest marketable tuber yield had been recorded at 100% irrigation level although it was not significantly different from irrigation level 75%. To prove and disprove the interaction effect of Zn fertilizer with irrigation level and genotype in this study there had lack of published information in the previous years because previous studies gave more attention to the effects of macronutrients on irrigation level and variety than on micronutrient and most of the studies focused on individual factor.

7.3.2.2. Unmarketable tuber yield

The study revealed that unmarketable tuber yield had significantly influenced by the main effect of genotype and irrigation level, whereas the main effect of Zn fertilizer rate had not significantly influenced unmarketable tuber yield. Unmarketable tuber yield was also not affected by the interaction effects of genotype, irrigation level and Zn fertilizer rate. The highest unmarketable tuber yield was recorded from main effect of genotype CIP-394611.112 and irrigation level 100% while the lowest due to the main effect of genotype gudane and irrigation level at 50%. In harmony to this study, Banerjee et al. (2016) observed that application of Zn fertilizer did not significantly improveed small sized tuber yield or unmarketable yield. In general, this study indicates that application Zn is non-profitable in potato production.

Table 7.3. Interaction effect of genotype with Zn fertilizer rate and irrigation level on marketable tuber yield (kg pot^{-1})

Zn rate (kg ha^{-1})	Genotypes		
	CIP-39411.112	Gudanie	Seohong
0	0.237^{c}	0.207^{e}	0.220^{d}
2.5	0.246^{ab}	0.214^{de}	0.233^{c}
5	0.252^{a}	0.215^{de}	0.235^{c}
7.5	0.250^{a}	0.215^{de}	0.248^{a}
10	0.248^{a}	0.215^{de}	0.248^{a}
CV (%)	3.66		
LSD	0.0073**		
Irrigation level (%)			
100	0.267^{a}	0.220^{ef}	0.254^{b}
75	0.247^{c}	0.211^{g}	0.234^{d}
50	0.226^{e}	0.209^{g}	0.217^{f}
CV (%)	3.66		
LSD	0.0057***		

Means within both column followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1%

7.3.2.3. Total tuber yield (Kg pot^{-1})

The result of the study revealed that total tuber yield was significantly affected due to the main effects of genotype, irrigation level and Zn rate and the two way interaction effect of genotype with irrigation level and Zn rate, and irrigation level with Zn rate but not interaction of triple effect (Table 7.4). Regarding the interaction effect, the highest total tuber yield (0.28 kg pot^{-1}) was obtained at the interaction effect of genotype CIP-394611.112 with 100% irrigation level followed by the interaction of genotype CIP-394611.112 with 5 kg ha^{-1} Zn rate (Table7.4). This study indicates that total tuber yield was more responsive to genotype interaction with irrigation level than genotype with Zn rate (Table 7.4). In general, the total tuber yield of potato was increased inconsistently in response to increase in Zn rate and irrigation level with interaction of each genotype. In harmony to this result, Banerjee et al .(2016 , 2017) found that total tuber yield was significantly influenced with the increase in the levels of Zn and registered the highest tuber yield with 4.5 kg Zn ha^{-1}. Kahlon and Khera (2015) also observed that tuber yield significantly affected by planting methods and irrigation levels, Tiwari and Dwivedi (1991); Mousavi et al. (2007) and Mahamud et al. (2021) demonstrated that positive influence of Zn fertilization on yield and qualitative parameters of potato crop. Studies on the response of potato to water stress conclude that even moderate water deficits can result in a low above ground biomass, tuber yield and tuber grade (Hang and Miller ,1986: Kashyap and Panda ,2003: Steyn et al (2007)

Table 7.4 Interaction effect of genotype with Zn fertilizer rate and irrigation level on total tuber yield of potato (kg pot^{-1})

Zn rate (kg ha^{-1})	Genotypes		
Zn rate (kg ha -1)	CIP-39411.112	Gudanie	Seohong
0	0.247^{b}	0.210^{f}	0.225^{d}
2.5	0.256^{a}	0.217^{ef}	0.241^{bc}
5	0.261^{a}	0.219^{de}	0.239^{c}
7.5	0.260^{a}	0.218^{de}	0.246^{bc}
10	0.258^{a}	0.218^{de}	0.256^{a}
CV (%)	3.49		
LSD	0.0071**		
Irrigation level (%)			
100	0.280^{a}	0.224^{f}	0.263^{b}
75	0.256^{c}	0.213^{g}	0.241^{d}
50	0.234^{e}	0.212^{g}	0.220^{f}
CV (%)	3.49		
LSD	0.0055***		

Means within both column followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1%

7.3.2.4. Biomass yield (kg pot^{-1})

The results of the present study revealed that Biomass yield was significay affected due to the main effect of genotype, irrigation level and Zn fertilizer rate as well by the interaction of genotype and irrigation level. The highest and significant biomass yield 0.316 and 0.291 kg pot^{-1}were obtained from the interaction effect of 100%irrigation level with genotype CIP-394611.112 and Seohong, respectively (Table 7.5). As the fertilizer rate and irrigation level increase, biomass yield of potato increase. This result indicated that potato biomass yield was more responsive to water than to Zn fertilizer with in same genotype. In line to this result Khan et al. (2004) found that biomass production significantly decrease due deficiency of Zn fertilizer in all genotypes but the sensitivity to Zn deficiency varied with genotype.

Table 7.5 Interaction effect of genotype with irrigation level on Biomass yield (kg pot^{-1}) of potato

Genotype	Irrigation level		
	100%	75%	50%
CIP-394611.112	0.316^{a}	0.288^{b}	0.259^{c}
Gudanie	0.287^{b}	0.268^{c}	0.260^{c}
Seohong	0.298^{b}	0.264^{c}	0.235^{d}
CV (%)	5.90		
LSD	0.0118**		

Means within both column followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant while means flowed by different letters with level of significant, **:- significant at 1%,

7.3.3. Effect of Irrigation levels and Zn fertilizer on irrigation water use efficiency of potato genotypes

The interaction effect of genotype, Zn fertilizer rate and irrigation level was not significantly influenced Irrigation Water use efficiency (IWUE) and water productivity (IWP/WPc) of potato. The main effect of genotype and irrigation level influenced significantly irrigation water use efficiency and water productivity of potato (Fig 7.1). The highest and significant water productivity value was obtained at the main effect 50% irrigation level and genotype CIP-39411.112. Contrarily, the lowest WPc was obtained due to the genotype Gudanie and 100% irrigation level in comparison with the other genotypes and irrigation level, respectively

(Fig 7.1). This result also indicates that addition of Zn fertilizer was less important to increase WPc than irrigation management and selection of genotype.

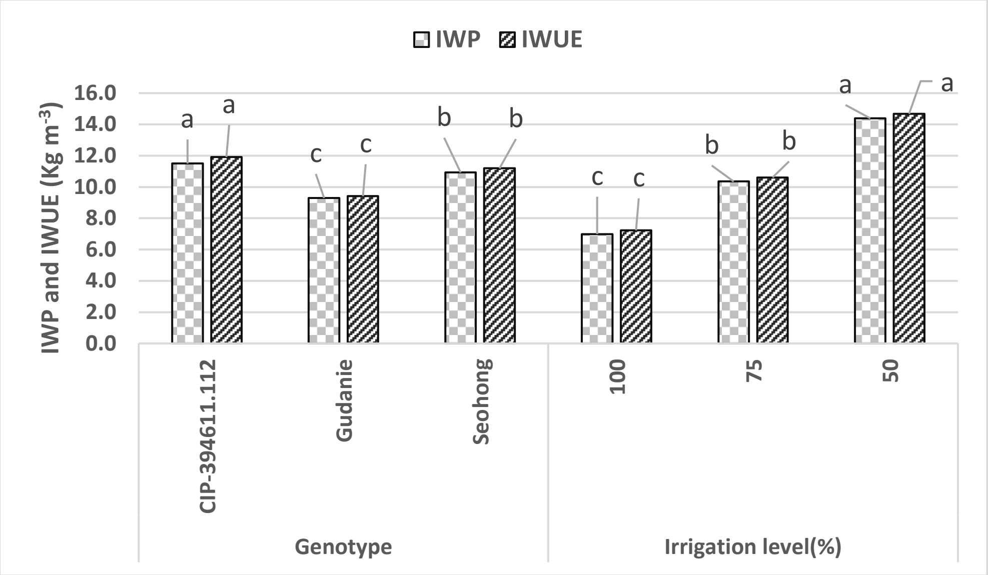


Figure 7.1 Effect of Zn rate, genotype and irrigation level on water use efficiency and productivity

Note: Bars with the same color with different letter indicates significant difference but with the same letter not significant at 5%

In line to this result Khan et al. (2004) reported that Zn deficiency significantly reduced water use efficiency and higher under water stress when Zn applied. Several studies have also reported that increase in water use efficiency (WUE) to the increase in water stress (Badr et al., 2010; Badr et al., 2012). Moreover, Cantore et al., 2014 reported that on average lower Yield WUE values were observed for rainfed plants, which encountered higher stress levels. In contrary to this Yarnia et al. (2009) indicated that increasing stress intensity decreased Yield WUE, as observed also by Kashyap and Panda (2003). Nevertheless Yarnia et al. (2009) reported that under severe stress a higher yield WUE occurred, as compared with mild stress conditions. Therefore in addition to availability of water level and crop variety /genotype WUE could be affected by such other factors like agronomic management, irrigation management, and fertilizer application and soil characteristics. In general, under mild water stress, when slight stomata closure occurs, transpiration decreases more than photosynthesis and, consequently, WUE increases.

7.3.4. Effect of genotype, irrigation level and Zn fertilization on quality of potato tuber

7.3.4.1. Dry matter content

The results of the present study indicated that the interaction effect of genotype, zinc (Zn) fertilizer, and irrigation level did not significantly influence the dry matter content of potato tubers. However, the main effects of genotype, Zn fertilizer and irrigation level did significantly influenced the dry matter content of the potato tubers (Fig 7.2). Genotype CIP-39411.112 produced significantly highest dry mater (23.69 %) compared to Seohong and Gudanie, which produced 22.79 and 20.81 %, respectively. Furthermore, the application of fertilizer showed significant differences compared to the control. However, there were no significant differences among the various fertilizer rates (Fig 7.2). With respect to irrigation level, the highest significant dry matter content was produced at 100% water requirement of potato, which was not significant to 75 % irrigation level whereas significant with the lowest DM content produced at 50% irrigation level. These findings suggest that the genetic makeup of the potato genotype, Zn fertilizer rate and the irrigation management practices are the factors driving variations in the dry matter content of the potato tubers, while the their interaction does not appear to be a significant contributor under the conditions studied. Understanding the relative importance of these agronomic factors is crucial for optimizing potato production and ensuring consistent tuber quality. The physiological reasons for the increase in dry matter content of potatoes with increasing irrigation levels could be -adequate water availability ensures proper plant hydration and facilitates the process of photosynthesis. With ample water supply, the photosynthetic rate and efficiency increases, leading to higher production of dry matter. In addition, adequate water supply promotes cell expansion and enlargement in the potato tubers, leading to their increased size and volume. As the tubers grow in size, the dry matter content per unit of fresh weight also increases, even though the total fresh weight of the tuber increases. However, under water-stress conditions plants tend to allocate more resources towards maintaining basic metabolic functions, rather than growth and storage. This can result in increased respiratory losses, where some of the photosynthetically produced dry matter is utilized for respiration, leading to lower net dry matter accumulation in the tubers. Similar to this result Cantore et al. (2014) reported that tuber dry matter content is influenced by irrigation regime. Barbara and Piotr (2005) also reported that varietal factor significantly differentiated the dry matter in tubers. Banerjee et al. (2017) also indicated that applications of Zn significantly increased dry matter accumulation of potato tuber. Mousavi et al. (2007) and Kanwa et al. (2019) reported that application of Zn fertilizer increase dry matter percentage of potato. Sukhpreet and Poonam (2014) found that dry mater content of potato quality characteristics were affected by cultivars. Ierna and Mauromicale (2012) reported that tuber dry matter content is responsive to cultivar, climatic conditions and cultural practices, above all irrigation. Furthermore, Similar to this result Hengjia et al. (2024) reported that moderate water deficiency at starch accumulation stage was significantly reduced dry matter content of potato tuber compared to full irrigation at all stages. However, most of water deficit treatments at different stages were no significantly different from full irrigation at all stages. In addition, the dry matter content of potato tubers under water deficit treatments was 20.86-22.64%.

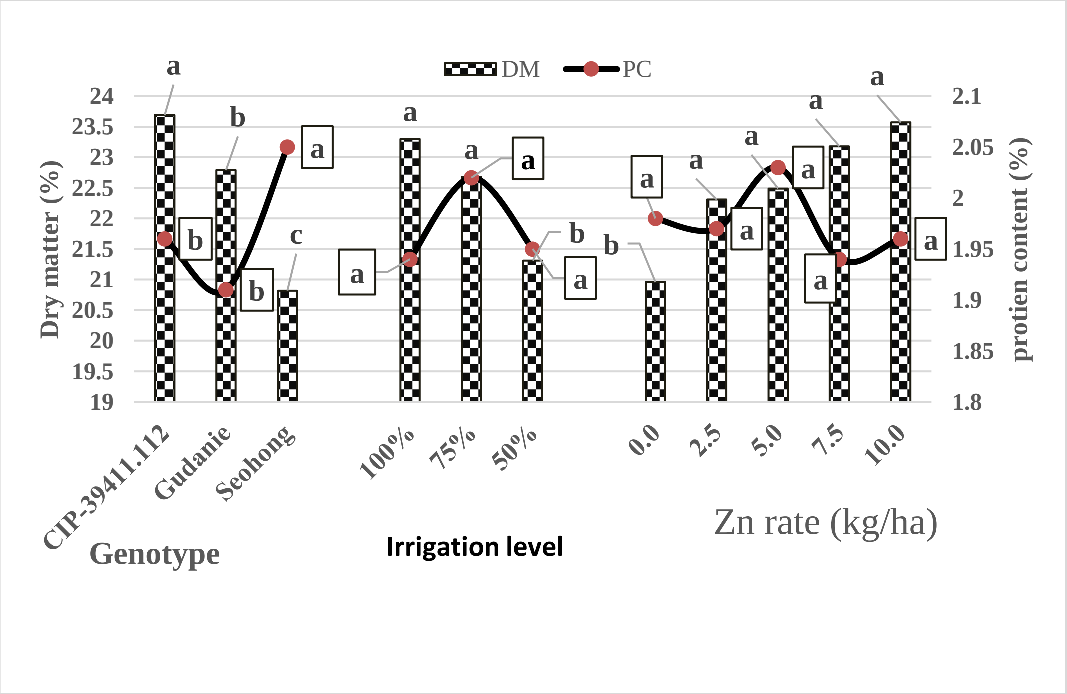


Figure 7.2. Main effect of genotype, irrigation level and Zn fertilizer rate on DM and PC potato tuber

Note: Bars with the same color with different letter indicates significant different but with the same letter not significant at 5%, DM is dry matter, PC is protein content

7.3.4.2. Protein content

The combined effect of genotype, irrigation level, and Zn fertilizer application did not produced a statistically meaningful change in the crude protein levels. However, the results show that the main effect of genotype alone had a significant influence on the crude protein (Fig 7.2). Genotype Seohong produced significantly higher protein content (2.05%) compared to CIP-39411.112 and Gudanie (Fig 7.2). The protein content of the genotypes in this study ranged 1.91 – 2.05%. This indicates that the genetic makeup of the plant was the primary driver of crude protein content, independent of the irrigation and Zn fertilizer treatments. Similar to this result Sukhpreet and Poonam (2014) found that protein content of potato quality characteristics were affected by cultivars. They reported also that the protein content difference among cultivars ranged from 1.40-5.40%.

7.3.4.3. Specific gravity and Starch content

The interaction effect of genotype with both Zn fertilizer rate and irrigation level significantly influenced specific gravity (Table 7.6) and starch content of potato tuber (Table 7. 7). The highest specific gravity (1.0895) and starch content (15.71%) were produced at the interaction effect of genotype Gudanie with 10 kg ha^{-1} Zn fertilize rate followed by Genotype CIP-39411.112 with 7.5 kg ha^{-1} Zn fertilizer rate (Table 7.6 and 7.7). Significantly, the highest specific gravity of 1.0895 and 1.0874 was produced at the interaction effect of genotype Gudanie with 10.0 kg ha^{-1} Zn fertilizer rate and Genotype CIP-39411.112 with 7.5 kg ha^{-1} Zn fertilizer rate, respectively. With respect genotype interaction with irrigation level, the highest specific gravity was obtained at the interaction of genotype CIP-39411.112 with 50% irrigation level and genotype Seohong with 50% irrigation level. In general, most of the interaction effect of each genotype with irrigation level 50% and fertilizer rate 10 kg ha $^{-1}$ gave the highest specific gravity (Table 7.6).

Table 7.6.Interaction effect of genotype with Zn fertilizer rate and irrigation level on specific gravity of potato

Zn rate (kg ha^{-1})	Genotypes		
	CIP-39411.112	Gudanie	Seohong
0	1.0584^{f}	1.0553^{f}	1.0644^{def}
2.5	1.0738^{bcd}	1.0591^{ef}	1.0717^{bcde}
5	1.0797^{abc}	1.0667^{cdef}	1.0724^{bcd}
7.5	1.0874^{a}	1.0818^{ab}	1.0732^{bcd}
10	1.0871^{a}	1.0895^{a}	1.0765^{abcd}
CV (%)		1.2	
LSD		0.0117*	
Irrigation level (%)			
100	1.0731^{bc}	1.0701^{bc}	1.0752^{abc}
75	1.0748^{abc}	1.0733^{bc}	1.0603^{d}
50	1.084^{a}	1.0681^{cd}	1.0794^{ab}
CV (%)		1.20	
LSD		0.009*	

Means within a column and rows followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1

This finding implies that the optimal Zn fertilizer rate and irrigation level for maximizing specific gravity and starch content could vary depending on the potato genotype. Different genotypes may respond differently to Zn fertilizer application and irrigation management in terms of specific gravity and starch content. Likewise, the highest and significant starch content was obtained at the interaction of genotype CIP-394611.112 with 10 kg ha^{-1} Zn fertilizer rate and 50% irrigation level compared to genotypes Gudanie and Seohong (Table 7.7). Overall, as Zn fertilizer increase the starch content of any of the genotype increase while as irrigation level decrease the starch content of the genotypes increase (Table 7.8). In line to these Banerjee et al. (2017) and Mousavi et al. (2007) reported that Zn fertilization significantly increased specific gravity and starch content in potato tubers over no Zn application as evidenced. Kanwar et al. (2019) also reported that starch content and specific gravity of potato tuber increase as Zn fertilizer increase none significantly. Furthermore, Barbara and Piotr (2005) reported that varietal factor significantly differentiated the starch levels in tubers.

Table 7.7 Interaction effect of genotype with Zn fertilizer rate and irrigation level on starch content

Zn rate (kg ha^{-1})	Genotypes		
	CIP-39411.112	Gudanie	Seohong
0	9.53^{f}	8.9^{f}	10.71^{def}
2.5	12.59^{bcd}	9.64^{ef}	12.17^{bcde}
5	13.75^{abc}	11.18^{cdef}	12.31^{bcd}
7.5	15.29^{a}	14.18^{ab}	12.47^{bcd}
10	15.25^{a}	15.71^{a}	13.12^{abcd}
CV (%)		19.9	
LSD		2.321*	
Irrigation level (%)			
100	12.44^{bc}	11.85^{bc}	12.86^{abc}
75	12.79^{abc}	12.48^{bc}	9.91^{d}
50	14.62^{a}	11.45^{cd}	13.70^{ab}
CV (%)		19.9	
LSD		1.797*	

Means within a column and rows followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1

7.3.5. Effect of Irrigation levels and Zinc fertilizer rate on nutrient concentration, uptake and use efficiency of potato genotypes

7.3.5.1. Zn concentration

Main effect of genotype ,Irrigation level, and Zinc fertilization as well as the interaction of genotype with Zinc rate ,and genotype with irrigation level was significantly influenced the Zinc concentration on potato tube and leaf (Table 7.8 and Fig 7.4), but Zn fertilization interaction with irrigation level not significantly affected Zn concentration of potato tuber and leaf. The highest Zn concentration in tuber of potato was recorded 21.18 and 18.77 mg kg^{-1} of dry weight with genotype Gudanie interaction with 75% irrigation level and genotype CIP-39411.112 interaction with 100% irrigation level respectively (Fig 7.3). The highest Zn concentration in potato tuber 24.3mg kg^{-1} was obtained at 10 kg ha^{-1} Zn fertilizer rate interaction with Gudanie genotype (Table 7.8). The maximum Zn concentration (21.8mg kg^{-1})

on potato leaf was recorded due to the interaction effect of genotype Seohong with 100 % irrigation level. In case of genotype with Zinc, fertilizer interaction the highest Zinc concentration (18.1 mg kg^{-1}) recorded at genotype Seohong interaction with 10 kg ha^{-1} Zn rate (Table 7.8). The zinc concentration of potato tubers and leaves increases as the zinc fertilizer application rate increases, within the same genotype, for most of the genotype-zinc fertilizer interactions. However, there were significant differences among the genotypes in their interactions with zinc fertilizer. As the zinc fertilizer rate increases, the zinc concentration in both the tubers and leaves increases. The zinc concentration in the potato tubers was higher than the zinc concentration in the potato leaves for each interaction (Table 7.8). This study indicates that the accumulation of Zn concentration in potato tuber and leaf significantly differ due to Zn fertilizer and water amount.

Table 7.8.Interaction effect of genotype with Zn fertilizer rate and irrigation level on potato tuber concentration (ppm)

Zn rate (kg ha^{-1})	Genotypes		
	CIP-39411.112	Gudanie	Seohong
0	13.17^{f}	13.48^{f}	9.29^{g}
2.5	16.35^{e}	16.74^{de}	16.92^{de}
5	18.16^{cde}	19.19^{bcde}	16.88^{de}
7.5	17.81^{de}	20.88^{bc}	19.75^{bcd}
10	19.25^{bcde}	24.02^{a}	21.68^{ab}
CV (%)	16.02		
LSD	2.67*		
Irrigation level (%)			
100	19.25^{b}	16.49^{c}	16.85^{c}
75	15.14^{c}	23.15^{a}	17.07^{c}
50	16.45^{c}	16.95^{c}	16.79^{c}
CV (%)	16.02		
LSD	2.07***		

Means within three column followed by the same letter are not significantly different at $p > 0.05$; ns: - non significant while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1%

Similar to this result Banerjee et al. (2017) found that Zinc fertilization significantly increased Zn concentration in potato tuber over control. They reported that Zn concentration of potato tuber 18.46mg kg^{-1} dry weight due to 6.0 kg ha^{-1}Zn ha with recommended NPK application In addition to this Mousavi et al. (2007) discovered that foliar Zn application caused increased Zn concentration and of potato tuber significantly. Furthermore Sarkar, et al. (2018); Kanwar et al. (2019); Mahamud et al. (2021); Nagar et al. (2024) also reported that Zinc content of potato tuber increase as Zn fertilizer increase. Likewise White et al. (2012) reported that Zn concentration in potato tuber may be as high as 30 mg kg^{-1} of dry weight though Zn uptake by potato also a genetically controlled trait which may differ cultivar to cultivar. Hazra et al. (2012) indicates that indicate that potato is one of the highest Zn accumulators compared to cereal crops. To prove the interaction effect of irrigation level, variety and Zn fertilizer rate no evidence on pervious researches.

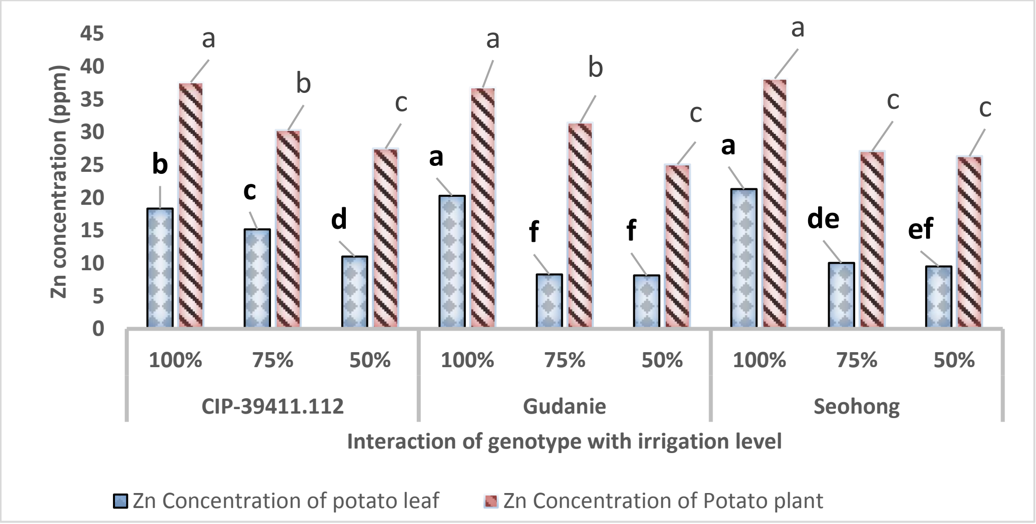


Figure 7.3. Interaction effect of genotype and irrigation level on Zn concentration of potato

Note: Bars and Lines with the same color with different letter indicates significant different but with the same letter not significant at 5%

7.3.5.2. Zinc uptake of potato

Zinc uptake of potato tuber was significantly influenced by the main effect genotype, irrigation level and Zn fertilizer rate as well as with the interaction effect of genotype with Zinc fertilizer rate and Irrigation level (Table 7.9). The higher zinc uptake of potato tuber was recorded due to the interaction effect of the each genotype with the highest Zn fertilizer rate (i.e 10 kg ha^{-1}). (Table 7. 9).

Table 7.9 .Interaction effect of genotype with Zn fertilizer rate and irrigation level (%) on Zn uptake of potato tuber (g/kg)

Zn rate (kg ha^{-1})	Genotypes		
	CIP-39411.112	Gudanie	Seohong
0	0.0132^{f}	0.0135^{f}	0.0093^{g}
2.5	0.0164^{e}	0.0168^{de}	0.0169^{de}
5	0.0182^{cde}	0.0192^{bcde}	0.0169^{de}
7.5	0.0178^{de}	0.0208^{bc}	0.0197^{bcd}
10	0.0192^{bcde}	0.0240^{a}	0.0217^{ab}
CV (%)	16.02		
LSD	0.00267*		
Irrigation level (%)			
100	0.0193^{b}	0.0165^{c}	0.0169^{c}
75	0.0151^{c}	0.0231^{a}	0.0171^{c}
50	0.0165^{c}	0.0170^{c}	0.0168^{bc}
CV (%)	16.02		
LSD	0.00207***		

Means within a column and row followed by the same letter are not significantly different at p > 0.05; while means flowed by different letters with level of significant *:- significant at 5%, **:- significant at 1%, and ***:- significant at 0.1%

In contrast, the lowest zinc uptake of potato tuber was observed at the interaction effect of the each genotype interaction with no zinc fertilizer or control (Table 7.9). Furthermore, Zinc uptake by tuber of potato plant increased with the progressive increase in Zn application levels from 0 to 10 kg ha^{-1} interaction with any of the genotype. The highest and significant Zinc uptake by tuber was recorded at the interaction of genotype Gudanie interaction with 10 kg ha^{-1} zinc fertilizer, and with irrigation level 75% (Table 7.9). This study also found that as irrigation level increase from 50% to 100 % Zn uptake by the potato plant and leaf of each genotype increase. The highest Zn uptake of potato plant and leaf was obtained at the interaction of genotype Seohong with 100% irrigation level (Fig7.4). This study indicates that Zn uptake by potato was as affected by genotype, amount of water applied and Zn rate (amount of fertilizer added to the soil). In agreement to this result, Banerjee et al. (2016) reported that Zinc uptake in potato tuber, haulm, as well as in total plant significantly increased with the progressive increase in Zn application level. Furthermore Sarkar et al (2018) ; Nagar et al.(2024) reported that Zn tuber uptake increase as Zn rate increase .Not much research work on the main and interaction effect of Zinc, amount of water and genotype had done on potato crop Zn uptake. This may explain that little attention was given to the effects of water and genotype/variety on micronutrient uptake by plants. Therefore, there is a significant difference in utilization efficiency or differences in Zinc acquisition by potato genotypes, amount of water and Zn fertilizer.

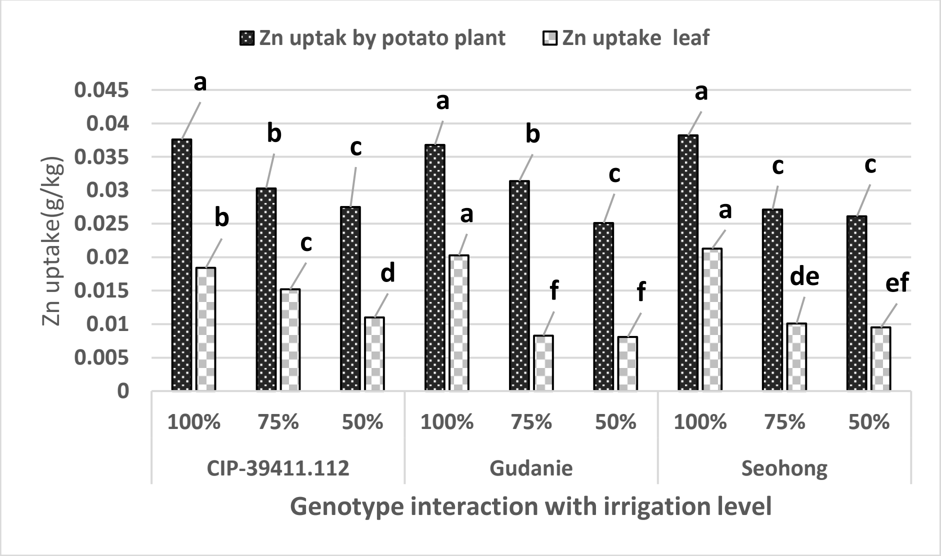


Figure 7.4. Interaction effect of genotype with irrigation level on zinc uptake by leaf and the potato plant

Note: Bars with the same color with different letter indicates significant different but with the same letter not significant at 5%

7.3.5.3. Zinc use efficiency of potato

The main effect of genotype, irrigation level, Zn fertilizer was significantly influenced agronomic, physiological and recovery efficiency of potato (Fig 7.6). Agronomic efficiency also influenced significantly by the interaction effect of Zn fertilizer rate and genotype (Fig 7.5). Recovery and physiological efficiency were not significantly affected by any of the interaction effects of the factors. The greatest and significant agronomic efficiency was obtained at the interaction of each genotype with 2.5 kg ha^{-1} Zn rate; in addition, this result indicates that agronomic efficiency is higher at the lower rate and lower at the highest rate of Zn (Fig 7.6). The highest agronomic efficiency was produced due to the interaction effect of each genotype with higher irrigation level.

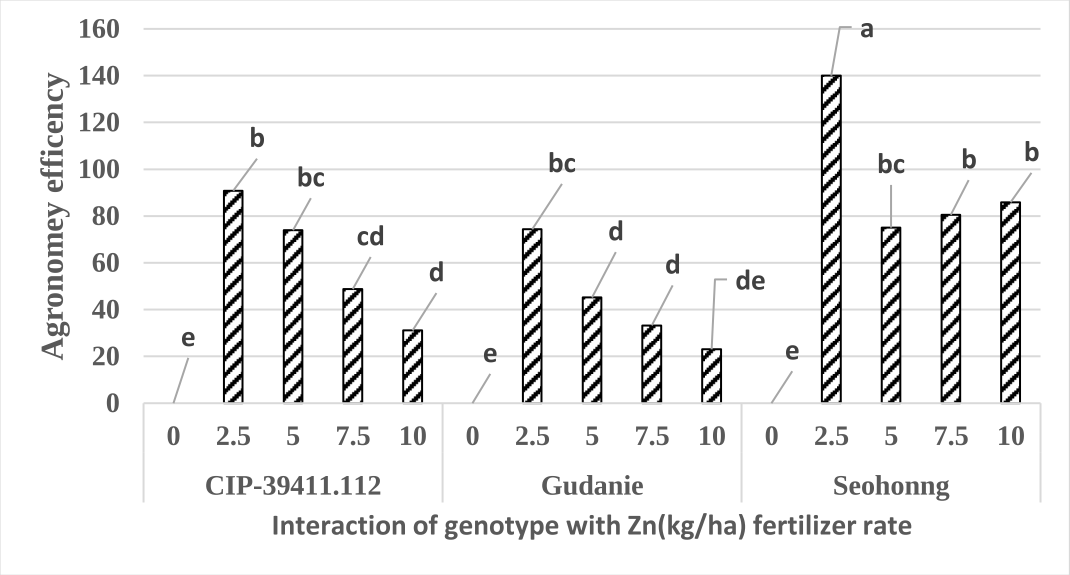


Figure 7.5. Interaction Effect of genotype and Zn fertilizer rate on Agronomic efficiency

Note: Bars with the same color with different letter indicates significant different but with the same letter not significant at 5%

Furthermore the highest recovery and physiological efficiency were recorded at 2.5 kg ha^{-1} of Zn fertilizer and full irrigation. This observation pertains to the main effects of both Zn fertilizer and irrigation level (Fig 7.6).This study indicates that as the irrigation level increase from 50% to 100% physiological and recovery efficiency increase whereas physiological and recovery efficiency decrease as Zn fertilizer rate increase from 2.5kg ha^{-1} to 10 kg ha^{-1} (Fig 7.6). Banerjee et al. (2016) agree with this result, concluding that Zn-use efficiencies vary in terms of agronomic efficiency (AEZn) and physiological efficiency (PEZn) due to Zn fertilization. Furthermore Nagar et al. (2024) reported that Agronomic efficiency, Recovery efficiency increase than decrease as Zn rate increase as Zn fertilizer increase

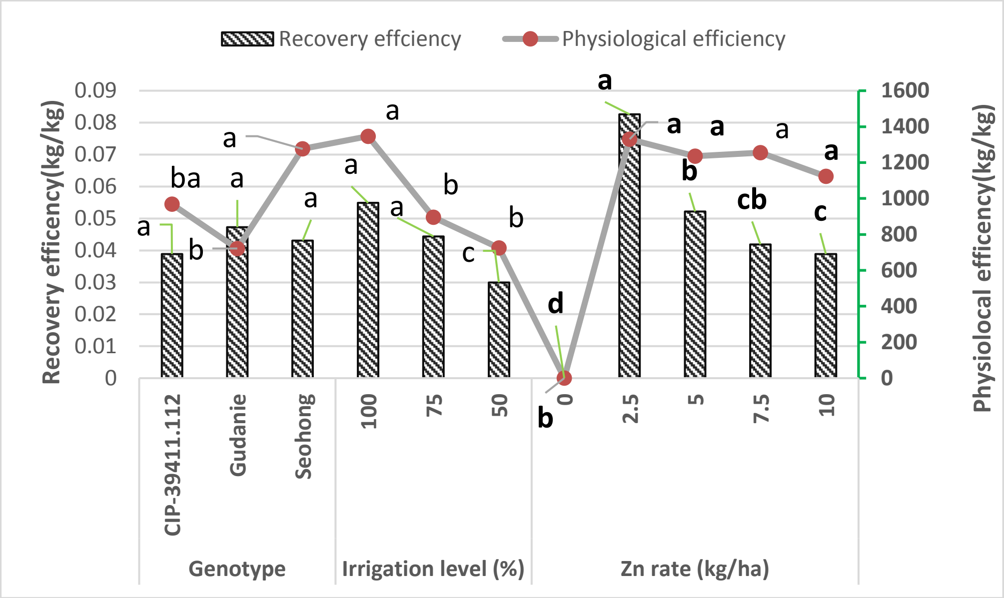


Figure 7.6. Main effect of genotype, irrigation level and Zn fertilizer rate on physiological (PE) and recovery (RE) efficiency

Note: Bars and Lines with the same color with different letter indicates significant difference but with the same color and no letter are not significant at 5%

7.3.6. Economics of Potato Cultivation with different Zn Fertilization rates

It was difficult to analyze and conclude the economic significance or gross return of Zn fertilizer under the pot experiment, but it gave some highlights on the economic significance. This study showed that the application of the main effect of Zn fertilizer rate had a significant effect on the yield and quality of potato. Tuber yield and quality of potato in this study had more influenced by irrigation level and genotype than Zn fertilizer; therefore, yield and quality had a greater responsiveness to irrigation level and genotype. In general, this study indicates that application of Zn fertilizer on potato was profitable because marketable tuber yield had yield advantage due to application of Zn fertilizer as compared to control. In line to this result Banerjee et al. (2017) found that application of Zn up to a dose of 4.5kg ha $^{-1}$ is economically beneficial for potato production. Banerjee et al. (2016) also reported that Zn fertilization significantly improved gross returns. There for production condition (Field vs Pot), soil type and environmental condition had an influence on Zn fertilizer response

7.4. Conclusions and Recommendations

It can be concluded that the main effect of genotype, irrigation level and Zinc fertilizer rate significantly influenced the growth, yield and yield component of potato. The main and interaction effect of genotype and irrigation level were more responsive to yield, and quality of potato whereas Zn fertilizer rate and its interaction to genotype and irrigation level was less responsive. The highest marketable and total yields were recorded due to the interaction of genotype CIP-394611.112 with 100% irrigation and 2. 5 kg ha $^{-1}$Zn rate. The main effects of genotype, Zn fertilizer, and irrigation level significantly influenced the dry matter content of the potato tubers. However, genotype alone had a significant impact on crude protein. The interaction between genotype and both Zn fertilizer rate and irrigation level significantly affected the specific gravity and starch content of the potato tubers. The highest starch content and specific gravity were observed with the interaction of each genotype with the highest Zn rate and with lower irrigation level. The highest specific gravity and starch content was produced from the interaction effect of genotype Gudane with 10 kg ha $^{-1}$ Zn fertilizer rate, as well as from the interaction effect of the genotype CIP-39411.112 with 50% irrigation level. The highest Zn uptake of potato tuber was recorded at the interaction of each genotype with the highest Zn rate while agronomic efficiency of potato was recorded at the interaction effect of each genotype with the lowest Zn fertilizer rate. It can be recommended that verifying the performance of genotype CIP-39411.112 and others under field conditions, and then releasing them as varieties for high-yield potato production in the study areas and other similar regions.

7.5 References

Alloway ,B.J. 2008.Zinc in soils and crop nutrition. International Zinc Association (IZA), Brussels.

Al-Jobori, K.M, Al-Hadithy ,S.A. 2007.Response of Potato (Solanum tuberosum) to Foliar Application of Iron, Manganese, Copper and Zinc. International J. Agri. and Crop Sci,7(7):358.

Ati, A.S., Iyada, A.D. and Najim, S.M. 2012. Water use efficiency of potato (Solanum tuberosum L.) under different irrigation methods and potassium fertilizer rates. *Annals of Agricultural Sciences, 57*(2): 99-103.

Badr, M.A., Abou Hussein, S.D., El-Tohamy, W.A., Gruda, N. 2010. Efficiency of subsurface drip irrigation for potato production under different dry stress conditions. Gesunde Pflanzen, 62: 63-70.

Badr, M.A., El-Tohamy, W.A. and Zaghloul, A.M. 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. Agric. Water Manage, 110: 9-15.

Banerjee ,H., Sarkar, S., Deb, P , Chakraborty, I. , Ray, K. and Sau ,S. 2017. Zinc Fertilization in Potato: A Physiological and Bio-chemical Study. International Journal of Plant & Soil Science, 16(2): 1-13.

Banerjee ,H., Sarkar, S, , Deb, P., Dutta, S.K., Ray, K., Rana, L.and Majumdar,K. 2016. Impact of Zinc Fertilization on Potato (Solanum tuberosum L.) Yield, Zinc Use Efficiency, Quality and Economics in Entisol of West Bengal. Journal of the Indian Society of Soil Science, 64 (2): 176-182 .

Barbara ,S. and Piotr, P. 2005. Dry matter and Carbohydrates Content in the Tubers of Very Early Potato Varieties Cultivated under Coverage. Acta Sci. Pol., Hortorum Cultus, 4(2):111-122.

Cantore,V., Stellacci, A.M., Wassar, F., Yamaç S.S., Sellami, M.H., Albrizio, R. and Todorovic M. 2014. Yield and water use efficiency of early potato grown under different irrigation regimes. International Journal of Plant Production, 8(3): 409-428.

Erdem, T., Erdem, Y., Orta, H. and Okursoy, H. 2006. Water-yield relationships of potato under different irrigation methods and regimens. Sci. Agric, 63: 226–231.

Fernández, E. 2023. Editorial note on terms for crop evapotranspiration, water use efficiency and water productivity. Agricultural Water Management, 289:108548.

Ferreira, T.C. and Carr, M.K.V. 2002. Responses of potatoes (Solanum tuberosum L.) to irrigation and nitrogen in a hot, dry climate: I. Water use. *Field Crops Research*, *78*(1): 51-64.

Fixen,P.E. and Bruulsema,T.W. 2014. Potato management challenges created by phosphorus chemistry and plant roots. Am.J. Potato Res,91:121–131.

Gupta, A. and Saxena, M.C. 1976. Total nitrogen concentration in leaves of potatoes (Solanum tuberosum L.) as an index of nutritional status. *The Journal of Agricultural Science*. *87*(2): 293-296.

Hazra, G.C., Saha, B. and Mandal, B. 2012. Micronutrient Research in West Bengal. Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India. Pp 1−73.

Hang A.N. and Miller, D.E., 1986. Yield and physiological responses of potatoes to deficit, high frequency sprinkler irrigation. Agronomy Journal, 78: 436–440.

He, M. and Dijkstra, F.A. 2014. Drought effect on plant nitrogen and phosphorus: a meta-analysis. New Phytologist, 204: 924–931.

Hengjia, Z., Changlong, Z., Xietian, C., Daoxin, X., Wanheng, Z., Fuqiang, L., Anguo, T., Lian, L. and Yuchun, B. 2024. Dry Matter Accumulation, Water Productivity and Quality of Potato in Response to Regulated Deficit Irrigation in a Desert Oasis Region. Plants, 13(14): 1927.

Hosamani, V., Yalagi, M., Sasvihalli, P., Hosamani, V., Nair, K.S., Harlapur, V.K., Hegde, C.R. and Mishra, R.K. 2020. Importance of micronutrients (Zinc) in crop production: A review. *International Journal of Chemical Studies*, *8*(1): 1060-1064.

Ierna, A. and Mauromicale, G. 2012. Tuber yield and irrigation water productivity in early potatoes as affected by irrigation regime. Agric. Water Manage, 115: 276-284.

Ladha, J.K., Pathak, H., Krupnik, T.J., Six, J. and van Kessel, C. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in agronomy, 87*: 85-156.

Li, S.X., Wang, Z.H., Malhi, S.S., Li, S.Q., Gao, Y.J. and Tian, X.H. 2009. Nutrient and water management effects on crop production, and nutrient and water use efficiency in dryland areas of China. *Advances in agronomy*, *102*: 223-265.

Jackson, M.L. 1973. Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India*, *498*:151-154.

Kahlon, M.S. and Khera, K.L. 2015. Irrigation Water Productivity and Potato (Solanum tuberosum L.) Yield in Different Planting Methods under Mulch Conditions. Journal of Agriculture and Ecology Research International, 3(3): 107-112.

Kanwar, P., Raghav, M.L. and Chandra, S.U. 2019. Effect of zinc application on quality of potato. Journal of Pharmacognosy and Phytochemistry, 8(1): 1921-1923.

Karam, F., Rouphael, Y., Ladoud, R., Baried, J. and Colla, G. 2009. Influence of Genotypes and Potassium application rates on the yield and potassium use efficiency of potato. Journal of Agronomy, 8 (1):27-32.

Kashyap, P.S. and Panda, R.K., 2003. Effect of irrigation scheduling on potato crop parameters under water stressed conditions. Agriculture and Water Management, 59:49-66.

Khan, H.R., McDonald, G.K. and Ren, Z. 2004. Zinc fertilization and water stress affects plant water relations, stomatal conductance and osmotic adjustment in chickpea. Plant and Soil Journal, 267: 271-284.

Kumar, P, Pandey, S.K., Singh, S.V., Singh, B.P., Rawal, S. and Kumar, D. 2008. Evaluation of nutrient management options for Potato processing cultivars. Potato J, 35(1-2):46−52.

Mahmud, N. U., Ferdous, Z., Ullah, H., Ahmed, N. U., Molla, S. H. and Anwar, M. 2021. Effect of zinc on grading, quality and yield of potato (Solanum tuberosum) in Bangladesh. International Journal of Agricultural Technology, 17(5):1821-1832.

Mondal, S.S., Patra, B.C. and Banerjee, H. 2015. Micronutrient management. In Advances in Potato Cultivation Technology. Kalyani Publishers, New Delhi, 115-121.

Mousavi,S.R., Mohammad, G. and Goudarz, A.2007. Effect of zinc and manganese foliar application on yield, quality and enrichment on potato (Solanum tuberosum L.). Asian J Plant Sci, 6(8):1256−1260.

Nagar, B. L., Jagdish, Singh, Yadav, D.L., Hanuman Prasad Verma and Meena, R.R. 2024. Agronomic zinc biofortification of potato (Solanum tuberosum) through soil and foliar zinc sulphate application in Rajasthan. Indian Journal of Agricultural Sciences, 94 (1):

016–020.

National Potato Research Program (NPRP). 2014. Field book for standard evaluation of potato and sweet potato germplasm, (Eds.BB Khatri and BP Luitel). National Potato Research Program, NARC, Khumaltar, Lalitpur, Nepal

Olsen, S.R. and Dean, L.A. 1965. Phosphorus. In: Methods of Soil Analysis. American Society of Agronomy. Madison, Wisconsin,9: 920 – 926.

Ranganna, S. 1977. Manual of analysis of fruit and vegetable products central food. *Technological Research Institute Mysore, USA.*

Sarkar, S., Banerjee, H. and Sengupta, K. 2018. Agronomic fortification of zinc in potato production in Indian context: A review. Journal of Applied and Natural Science, 10(3): 1037 – 1045.

Shock, C.C., Stewart, B.A. and Howell, T.A. 2003. Soil water potential measurement by granular matrix sensors. *The Encyclopaedia of Water Science, 899*.

Singh, N. and Kathayat, K. 2018. Integrated Application of Micronutrients to Improve Growth, Yield, Quality and Economic Yield in Potato A Review. Int.J.Curr.Microbiol.App.Sci. 7.

Singh, S., Kumar, D., Chandel, B.S., and Singh, V. 2014. Effect of balanced fertilization on yield, nutrients uptake and economics of potato (Solanum tuberosum) in alluvial soil. Indian Journal of Agronomy, 59(3): 451-454.

Sibirev, A. V. 2024. Comprehensive evaluation of fertilizer treatments on biometric traits and marketable tuber weight across diverse potato varieties. *Frontiers in Sustainable Food Systems*, *8*: 1453885.

Sikora, F.J. and Moore, K.P. 2014. Soil test methods from the southeastern United States. Southern cooperative series bulletin, 419: 54-58.

Steyn, J.M., Kagabo, A.M. and Annandale, J.G. 2007. Potato growth and yield responses to irrigation regimes in contrasting season of a subtropical region. African crop Science Conference proceedings, 8:1647-1651.

Sukhpreet, K. and Poonam, A. 2014. Studies on Indian Potato Genotypes for their Processing and Nutritional Quality Attributes. Int.J.Curr.Microbiol.App.Sci, 3(8):172-177.

Tarafder, M.A., Haque, M.Q., Rahman, M.M. and Khan, M.R. 2008. Direct and residual effect of sulphur and zinc on potato-boro-T. Aman rice cropping pattern. *Progressive Agriculture*, *19*(1): 33-38.

Taya, J. S., Malak, Y. S. M. L., Pandila, S. C. and Khurana, S. E. 1994. Fertilizers management in potato based cropping system: Growth and yield of potato. J. Indian Potato Assoc. 21(3-4), 164-188.

Tiwari, K.N. and Dwivedi, B.S. 1991. Effect of native and fertilizer Zn on the tuber yield and Zn uptake by potato in Udic Ustocherpts of Uttar Pradesh. Journal of the Indian Society of Soil Science, 39: 396-398.

Vasanthan, T., Bergthaller, W., Driedger, D., Yeung, J. and Sporns, P. 1999. Starch from Alberta potatoes: wet-isolation and some physicochemical properties. *Food Research International*, *32* (5): 355-365.

Wang, Z., Gerstein, M. and Snyder, M. 2009. RNA-Seq: a revolutionary tool for transcriptomics. *Nature reviews genetics*, *10*(1): 57-63

White, P.J., Broadley, M.R., Hammond, J.P, Ramsay, G., Subramanian, N.K. and Thompson, J. 2012. Bio-fortification of potato tubers using foliar zinc-fertilizer. J Horticultural Sci and Biotechnology, 87 (2):123−129.

Widmann, N., Goian, M., Ianculov, I., Dumbravă, D. and Moldovan, C. 2008. Method to starch content determination from plants by specific weight. *Scientific Papers Animal Science and Biotechnologies, 41*(1): 814-814.

Yarnia, M., Khorshidi, M.B., Nasseri, A. and Hassanpanah, D. 2009. Drought stress effects in different growth stages on potato cultivars. *Potato Res*. *53*: 383-392.

Chapter 8. General Summary, Conclusion, Recommendations and Future Work

Potato is a crucial crop for food security, yielding high-quality produce with minimal inputs and a short growing season. In Ethiopia, the conditions are favorable for potato production, and the crop plays an important role in enhancing food security, and increasing cash income for smallholder farmers. Potatoes provide affordable, nutritious food, rich in vitamins, minerals, and trace elements, and they are one of the most economical sources of energy, producing more protein per unit area compared to rice, maize, and wheat. Despite its potential, potato cultivation remains underutilized, particularly in combating hunger and malnutrition. Tigray is one of the regions where potato production has been practiced for several years. The agro-climatic conditions, especially in the eastern, southern, and central zones, are ideally suited for potato cultivation. However, regional productivity is lower than the national average due to various challenges, including moisture stress, climatic variability, traditional agronomic practices, low-yielding varieties, and limited access to quality seed. Moreover, information on potato production practices, constraints, and potentials is inadequate. Currently, no potato varieties have been released for moisture-stressed areas, and research on water and nutrient management in relation to potato cultivation in Tigray is limited. Studies were conducted to identify opportunities and constraints in potato production, and to determine the water and nutrient use efficiency of potato genotypes in semi-arid areas of Tigray, Ethiopia through the following research activities.

A survey conducted in the major potato-growing zones of Tigray provided insights into farm-level production practices, constraints, and opportunities, as well as farmers' perceptions of climate variability. The assessment confirmed that potato is the main horticultural crop in the study areas, serving as a source of cash, food, and seed under both irrigation and rainfall conditions. In Tigray, potato is typically planted between December and January, as well as May and June, under irrigation and rainfall conditions, respectively. Most farmers use a combination of inorganic and organic fertilizers for potato production at rates below the recommended level. The average tuber yield under irrigation ranges from 15.0 to 12.6 t ha^{-1}, while it ranges from 14.6 to 12.4 t ha^{-1} under rainfall conditions. The study findings reveal that the availability of suitable agroecology, good soil type, access to irrigation water, and labor are the key opportunities for potato production. However, challenges, including diseases and pests, a lack of improved varieties, drought, and limited access to markets, hindered the productivity of this crop in Tigray. Key opportunities for potato production in the study areas include suitable agro-ecological conditions, good soil types, access to irrigation water, and a readily available labor force. However, challenges such as diseases and pests, lack of improved varieties, drought, and limited market access. Rainfall patterns in the study areas are erratic, showing decreasing trends in both annual and seasonal rainfall, alongside rising temperatures. This variability negatively impacts the kiremt season, characterized by late-onset and early cessation of rainfall, ultimately shortening the growing period. In Agreement with these underlying facts, farmers have perceived these changes, noting reduced rainfall and increased temperatures that adversely affected crop production.

The field experiment concluded that the interaction between irrigation and potato genotypes significantly affects the growth, yield, and yield components of potato. The highest marketable yield, total tuber yields and water use efficiency along with shorter days to flowering and maturity, were obtained from the genotypes CIP-394611.112 and CIP-3960478.90 under both rainfall and irrigation condition. Applying supplemental irrigation improved total tuber yield, ranging from 5540.0 to 781.7 kg per hectare, depending on the genotype, the highest total water and irrigation water productivity was achieved with the genotype CIP-394611.112 in both irrigated and non-irrigated conditions. It was also concluded that effective rainfall was insufficient to meet crop evapotranspiration needs in September and early October, highlighting that rainfall alone is inadequate for potato production in semi-arid areas of Tigray. The application of full irrigation levels positively influenced the marketable and total tuber yields of all genotypes, whereas reducing irrigation water by 50% significantly decreased yield and yield components. Genotypes CIP-394611.112 and CIP-3960478.90 demonstrated significantly higher marketable and total tuber yields compared to other genotypes, with their responses improving with increased irrigation levels. However, higher irrigation levels reduced the water use efficiency of all genotypes.

The study in a pot experiment concluded that genotype, irrigation levels, and zinc fertilizer rates significantly influenced potato growth, yield, and quality of potato under a screen house. The highest marketable and total yields were recorded due to the interaction of genotype

CIP-394611.112 with both full irrigation and a 2.5 kg Zn rate per hectare. Genotype, irrigation level, and Zn fertilizer influenced the dry matter content of potato. Furthermore, specific gravity was influenced by the interactions of genotype with both irrigation levels and Zn fertilizer rate (kg ha^{-1}).

To sum up, this study clearly showed that, if proper focus is given to genotype and water management activities, along with good agronomic practices, potato can significantly contribute to the challenging task to ensuring food and nutrition security and delivering economic benefits to the poor people dwelling in the semiarid areas of Tigray, Ethiopia. Based on the present research result, the following recommendations and associated future works are suggested.

Recommendations

- Develop and implement farmer-based seed tuber production systems for sustainable potato production
- Enhance technical knowledge and skills in potato production (through training) programs for farmers and development agents on potato crop production, disease and pest protection measures, and agronomic practices.
- Strengthen partnerships with international organizations, such as the International Potato Center -CIP, to improve seed quality and productivity in potato production.
- Develop drought-tolerant potato varieties to address the challenges of climate change.
- Optimize agronomic and water management practices to mitigate the effect of climate variability on potato production, particularly from September to early October, to ensure adequate water availability when rainfall is insufficient.
- Implement rainwater-harvesting systems to capture runoff during the rainy season. This water can be stored for later use for supplemental irrigation during the months.

- Enhance soil structure and water retention by incorporating organic matter, such as compost or manure.
- Preliminary data from our evaluations indicate that genotypes CIP-394611.112 and CIP-390478.90 demonstrated promising traits for semi-arid regions, including high yield potential and improved water use efficiency under both rain-fed and irrigated conditions.

- Genotype CIP-390478.90 is recommended to produce under irrigation condition, and genotype CIP-394611.112 under rain-fed condition.

- Further field verification of these genotypes in relation to irrigation level and Zn fertilizer rate is recommended for their potential release as high-yield varieties in Tigray and similar regions.

- Employ climate data analytics to predict weather patterns and adjust irrigation plans accordingly.

- At last, irrigation level, fertilizer rate, water, and fertilizer use efficiency were interrelated to each other and variety development program should consider these parameters to gather with the yield and yield component of the potato for sustainable production with maintained safe environment sufficient benefit.

Future Work

- Initiate farmer training programs and establish partnerships with international organizations

- A follow-up study using crop simulation models (e.g., DSSAT) to precisely quantify the impact of observed climate trends on potato yield

- Evaluate the performance of recommended genotypes across different irrigation and fertilization conditions.

- Future research could focus on multi-year field trials to assess the long-term performance of the recommended genotype under varying climatic conditions

- Investigating deeper physiological mechanisms (e.g., root architecture, osmolyte production) behind the drought tolerance of genotypes

- Further studies could investigate the economic feasibility and adoption potential of the recommended irrigation practices among smallholder farmers in the Tigray region.

- Continuously update training programs based on the latest research and field data to ensure relevance and effectiveness.

BIOGRAPHICAL SKETCH

The author was born on October 14, 1977, in Mekelle City, Tigray Regional State, to his father, Abebe Misgina, and mother, Fitsum Ebuy. He attended his elementary, junior, and secondary school education at Adiss Alem, Elalla Junior Secondary School, and Atse-Yohannes Comprehensive Secondary School in Mekelle, respectively. In 1997, he joined the then Ambo Agricultural College, now known as Ambo University, and graduated with a Diploma in General Agriculture. He worked at the Tigray Agricultural Research Institute (TARI), Mekelle Agricultural Research Center, as a Technical Assistant in the horticulture department until in 2004, he rejoined Ambo University to pursue his first degree, graduating in 2007 with a BSc in Crop Production and Protection, After graduation, he was assigned as a Junior Researcher and served until 2012, when he joined Mekelle University for postgraduate studies. In 2013, he obtained his MSc in Dry land Agronomy and continued his work as a Researcher II in Horticultural Crops at the Mekelle Agricultural Research Center until he joined the School of Graduate Studies at Hawassa University in 2017 to pursue his PhD studies. The author has published four journal articles and contributed 12 research outputs to conference proceedings as a first author and co-author in the last ten years. He also released two spice varieties (Black and White cumin), two wheat and one-faba bean crop varieties for Tigray, as well as for Ethiopian farmers.

Appendices

Chapter 3 and 4.

Appendix 1:- Survey Questionnaire on Opportunities, Constraints, and Climate Variability in Potato Production

Respondent No.________

Date _______________

Part I. Farmers general information

1. Zone--------------------------------District------------------------------ Kebele--------------Specific name of the place---------------------------------

2. Name of household head --

2.1 Sex: A) Male--------------- B) Female----------------Age---------- family size (number) -------------- A) Male--------------- B) Female----------------

2.2 Marital status: A) Single -------- B) Married ----------- C) Divorced--------- D) Widowed----------- E) Others (Specify) ----------------------

2.3 Education level of the household head A) No Education------- B) Grade 1-5 ---------- C) Grade 6-8 --- D) Grade 9-10--------- E) Diploma and above-------

2.4 Economic group of the household A) Rich ___ B) Middle __C) Poor

II. Farming practice information

3. Total land holding? -----------ha

3.1 Land acquisition

Type of acquisition	*Area in hectare*	*Remarks*
a)Inherit from parents/family		
b) Obtained from government		
c)Sharecropping/contract/renting		
d)Others (specify)		

3.2 Land allocate to potato   A) Under irrigation (ha) _____ B) Rainfed (ha) _____

4. Type of farming activities carried out by the household

4.1 Crop farming (rainfed) specify : A) Cereals ----------- B) Pluses -------- C) Vegetables ------- D) Root and tuber crops E/ Perennial fruits   ----------- C) Others (specify) ----------

4.2 Crop farming (irrigated) : A) Vegetables ------- B) Root and Tuber crops-------- C) crops ------- D) Perennial fruits ----------- E) Others (specify) --------------

4.3 Animal farming: A) Dairy ------- B) Beef -------- C) small ruminant farm------- D) Poultry ----------- E/ Others (specify) --------------

4.3 Off-farm activity A/ Daily labor B/Builder C/ others specify ----------------------------

5. What are the major types of Horticultural crops cultivate/produce/ in your area in order of priority?

Type major of Horticulture crop	Area (ha)	Rank	Remark
A. Potato			
B. Sweet potato			
C. Onion			
D.Tomato			
E. Garlic			
F. Lettuce			
G. Others (Specify)------------			

6. Potato Production purpose and Practice

6.1 For what purpose do you produce potato? A) Food _____B) Seed _______

6. 2. For how long have you been growing Irish potato? A) Less than 1 year ----- B)1-5 years ----- C) more than 5 years -----

6.3 Under what Season /Condition do you produce potato? A) Rainfall ----------B) Irrigation ----- C) both ---------------D) others specify

6.4 When do you plant potato during main season A) May -------B) June -----------C)July ------ D) Others (specify) -----------------

6.5 When do you plant potato during irrigation? A) November --------B) December --------- C) January-------------D) others (specify) ---------------------

7. Potato production inputs and management practices in the study areas

7.1 What are the inputs used in potato production with their source? A) Fertilizer ------B) Improved tuber/seed -----C) Chemicals -----------D) others (Specify)---------

Type of input	Source	Accessibility	
A) Fertilizer ;Inorganic -Organic B) Seed/tuber : Improved : Local C) Chemicals 12.4 others (Specify)			

Source : A) Government B) Non-government agency C) Private Seed producer cooperatives D) local market E) Others (Specify)------

Accessibility: A) High, B) Medium C) poor

7.2 What kinds of Inorganic fertilizer type, rate, method of application and frequency do you use for potato production?

Type	Rate (Kg ha -1)	Method of application	Frequency(1,2,3)
A) Urea only			
B)DAP (TSP) only			
Urea & DAP (TSP)			
Blended fertilizer depend on the area			
others (Specify)_____			

Rate: 100, 200, 150, 200, others specify

7.3 What kinds of Organic fertilizer type, rate, and method of application do you use for potato production?

Type	Rate (Kg ha -1)	Method of application	Frequency
A) Compost			
B) Manure			
C) Manure and Compost			
others (Specify)_________			

7.4 What are the major potato varieties produced in your area? A) Gudanie ___B) Belete ___C) Awash ____D) Gera ___E) Jaleni_____ others (Specify)___________

7 .5 which potato variety more preferable in the market by consumers and have attractive prices? A) Gudane ____B) Belete___ C) Awash ___D) Gera __E) others (Specify) -------

7.6 What is the source of water for potato production A) rainfall -------------- B) Irrigation /river groundwater/shallow well/ pond ---------- c) Others (specify) --------------------

8. In average how much quintal per hectare of potato do you produce last three years?

8.1 Under irrigation condition ____

8.2 Under rainfed condition __________

11. What is your observation is potato production and productivity increase or decrease from year to year? A) Increase B) Decrease C) No change D) Others (Specify) -------------------

III. Potato production opportunities and constrain ties

1. What are the main opportunities to produce potato in your area?

No	Main opportunities	Rank	Remark

2. What are the major constraints did you face during potato production in your area and their solution?

No	Major Constraints	Rank	Possible Solutions

IV.Qustioners for Focus Group Discussion

1. What are the major horticultural crops produce in your area?
2. What are the opportunities for potato production in your area? List them-
3. What inputs are you use for potato production and where is the source of your input?
4. What type of cropping system do you implemented during potato production?
5. When do you produce potato?
6. What are the major problems to produce potato and their possible solution?
7. Suggestions to strengthen potato production

V. Qustioners for Farmers Percepation to Climate variability

1. Do you know/hear about climate variability? A) Yes B) No

2. If your answer is yes, which challenge of climate variability have been facing for potato production in your district?

3. Rainfall amount

3.1 what is you Percepation on the trend of annual rainfall from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

3.2 what is you Percepation on the trend of kiremt season rainfall from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

3.3 what is you Percepation on the trend of belg season rainfall from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

3.4 what is you Percepation on the trend of bega season rainfall from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

4. Temperature

4.1 what is you Percepation on annual temperature from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

4.2 what is you Percepation on the trend of kiremt season temperature from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

4.3 what is you Percepation on the trend of belg temperature from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

4.4 what is you Percepation on the trend of bega rainfall from to year A) Increase _______B) Decrease ______ D) No change _____ E) others specify _______

5 .Kiremt season rainfall characteristics

5.1 What is you Percepation on onset date of kiremt rainfall from to year A) early set _______B) late set ______ D) No change _____ E) others specify _______

5.2 What is you Percepation on Cessation date of kiremt rainfall from to year A) early set _______B) late set ______ D) No change _____ E) others specify _______

5.3 What is you Percepation on the length-growing period of kiremt rainfall from to year A) short _______B) long ______ D) No change _____ E) others specify _______

6 .Farmers Percepation on the impact of climate variability on potato production

No	Perceived impact	Respondents		
		N	%	Rank
1				
2				
3				
4				
5				

7. What Adaption measures do you take during climate variability to produce potato?

Climate variability	Adaptation measures taken	
	Increase	Decrease
Rainfall		
Temperature		
Frost		

IV. Questioner for group discussion related to climate variability

1. Do you know about Climate variability? Yes /NO

2 .What did the situation/climate look like when you were young, and how has it changed over time in your lifetime?’

3. Which challenge of climate variability have been facing for potato production in your district? Rank it by their influence for the crop

Climate change	Rank	Possible measures taken

4. Which are the indigenous methods of farming you are employing in your farm to cop the challenge?

5. What measures do you implemented/take during water stress during Rainy season and irrigation?

6. What is the trend of rainfall look like when you were young, and how has it changed over time in your life time?’

7. What do you need/expect/from research Centre, government NGOs and other responsible bodies in order to improve potato production in this area?---
-

Appendix 2: Major potentials to produce potato in the study area ranked by farmers

Zone	List of major potentials	Number of respondents ranked								Result			
		1st	2nd	3rd	4th	5th	6th	7th	8th	Sum	Index	Index (%)	Rank
East	Suitable agro ecology	169	18							1478	0.22	21.96	1
	Good soil type	18	145	24						1303	0.19	19.36	2
	Availability to improved seed		7	61	2		1	89	27	633	0.09	9.40	6
	Access to irrigation		10	87	29	61				981	0.15	14.57	3
	Access to rainfall			1	87	86	11		2	820	0.12	12.18	4
	Access to labour			24	70	34	13	34	12	749	0.11	11.13	5
	Access to market					1	150	21	15	511	0.08	7.59	7
	Access to transport						11	47	129	256	0.04	3.80	8
South east	Suitable agro ecology	88	14							802	0.22	21.73	1
	Good soil type	14	88							728	0.20	19.72	2
	Availability to improved seed			14	3			52	33	236	0.06	6.39	7
	Access to irrigation			64	25	13				561	0.15	15.20	3
	Access to rainfall			8	15	65	11		3	419	0.11	11.35	5
	Access to labour			13	55	15	16	3	0	467	0.13	12.65	4
	Access to market			3	4	9	67	6	13	300	0.08	8.13	6
	Access to transport						3	70	29	178	0.05	4.82	8
South	Suitable agro ecology	93	4	0						772	0.22	22.08	1
	Good soil type	4	93	0						683	0.20	19.53	2
	Availability to improved seed							69	28	166	0.05	4.75	8
	Access to irrigation			79	18	0				564	0.16	16.13	3
	Access to rainfall			6	23	62	6			417	0.12	11.92	5

	Access to labour			12	56	23	6			462	0.13	13.21	4
	Access to market					12	62		23	257	0.07	7.35	7
	Access to transport						23	33	41	176	0.05	5.03	6
Over all the study area	Suitable agro ecology	350	36							3052	0.22	21.93	1
	Good soil type	36	326	24						2714	0.19	19.50	2
	Availability to improved seed		7	75	5		1	210	88	1035	0.07	7.44	7
	Access to irrigation		10	230	72	74				2106	0.15	15.13	3
	Access to rainfall			15	125	213	28		5	1656	0.12	11.90	5
	Access to labour			49	181	72	35	37	12	1678	0.12	12.06	4
	Access to market			3	4	22	279	27	51	1068	0.08	7.67	6
	Access to transport						37	150	199	610	0.04	4.38	8

Appendix 3: Major Constraints in potato production in the study area ranked by farmers

		Number of Respondents ranked								Results			
Zone	List of major problems	1st	2nd	3rd	4th	5th	6th	7th	8th	Sum	Index	Index (%)	Rank
East	lack of improved seed	8	20	117	7	27	3	5		1068	0.16	15.92	3
	Disease and pest	80	104			3				1380	0.21	20.57	1
	Access to market		23	30	122	11	1			998	0.15	14.87	4
	Water stress	99	32	14	23	18	1			1290	0.19	19.23	2
	Frost			4	30	77	76			710	0.11	10.58	5
	Input			26	8	50	101	2		703	0.10	10.48	6
	Poor soil fertility							115	72	302	0.05	4.50	7
	lack of extension service							72	115	259	0.04	3.86	8
South east	lack of improved seed	43	18	32	2	7				700	0.19	19.40	2
	Disease and pest	15	78	1	-	8				704	0.20	19.51	1
	Access to market	1	4	28	58	11				538	0.15	14.91	4
	Water stress	20	1	27	13	41				558	0.15	15.46	3
	Frost			11	24	33	34			420	0.12	11.64	5
	Input			24	5	3	63	6	1	383	0.11	10.61	6
	Poor soil fertility							63	39	165	0.05	4.57	7
	lack of extension service							39	63	141	0.04	3.91	8
South	lack of improved seed	1	45	22	9	18		2		576	0.17	16.59	3
	Disease and pest	59	24			14				696	0.20	20.04	1
	Access to market		17	39	33	8				550	0.16	15.84	4
	Water stress	36	10	9	9	26	7			582	0.17	16.76	2
	Frost		1	16	36	24	19	1		438	0.13	12.61	5
	Input			10	10	0	76	1		340	0.10	9.79	6

	Poor soil fertility							82	15	179	0.05	5.15	7
	lack of extension service							15	82	112	0.03	3.22	8
Over all the study area	lack of improved seed	52	83	171	18	52	3	7		2344	0.17	17.00	3
	Disease and pest	154	206	1		25				2780	0.20	20.16	1
	Access to market	1	44	97	213	30	1			2086	0.15	15.12	4
	Water stress	155	43	50	45	85	8			2430	0.18	17.62	2
	Frost		1	31	90	134	129	1		1568	0.11	11.37	5
	Input			60	23	53	240	9	1	1426	0.10	10.34	6
	Poor soil fertility							260	126	646	0.05	4.68	7
	lack of extension service							126	260	512	0.04	3.71	8

Chapter 5.

Annex 4.ANOVA of potato yield under rainfall condition

Variable	Source of variation	DF	SS	MS	F Value	Pr>f
Marketable tuber yield (MTY)	Location (Loc)	1	2275.92	2275.92	509.86	0.0601
	Year (Y)	1	0.560	0.560	0.13	0.7241
	Loc*Y	1	17.633	17.633	3.95	0.0507
	Genotype (Ge)	4	2598.458	649.615	145.53	<.0001
	Ge*Loc	4	53.839	13.460	3.02	0.0534
	Ge*Y	4	86.891	21.723	4.87	0.0016
	Ge*Loc*Y	4	7.723	1.931	0.43	0.7847
	Irrigation (Irr)	1	231.852	231.852	51.94	<.0001
	Irr*Loc	1	3.008	3.008	0.67	0.4144
	Irr*Y	1	4.107	4.107	0.92	0.3407
	Irr*Loc*Y	1	0.432	0.432	0.10	0.7566
	Ge*Irr	4	90.968	22.742	5.09	0.0011
	Ge*loc*Irr	4	26.410	6.603	1.48	0.2175
	Ge*Irr*Y	4	24.715	6.179	1.38	0.2480
	Loc*Y*Ge*Irr	4	0.648	0.162	0.04	0.9974
	Rep(Loc*Y)	8	310.554	38.819	8.70	<.0001
Total tuber yield (TTY)	Location (Loc)	1	2046.085	2046.085	431.22	<.0701
	Year (Y)	1	6.215	6.215	1.31	0.2562
	Loc*Y	1	37.420	37.420	7.89	0.0064
	Genotype (Ge)	4	2487.457	621.864	131.06	<.0001
	Ge*Loc	4	108.620	27.155	5.72	0.0705
	Ge*Y	4	131.842	32.960	6.95	<.0001
	Ge*Loc*Y	4	9.641	2.410	0.51	0.7300
	Irrigation (Irr)	1	287.587	287.587	60.61	<.0001
	Irr*Loc	1	6.557	6.557	1.38	0.2437
	Irr*Y	1	1.242	1.242	0.26	0.610
	Irr*Loc*Y	1	0.869	0.869	0.18	0.670
	Ge*Irr	4	94.368	23.592	4.97	0.0014
	Ge*loc*Irr	4	25.960	6.490	1.37	0.2536
	Ge*Irr*Y	4	33.048	8.262	1.74	0.1503
	Loc*Y*Ge*Irr	4	2.257	0.564	0.12	0.9754
	Rep(Loc*Y)	8	348.215	43.527	9.17	<.0001
Biomass yield	Location (Loc)	1	2988.811	2988.811	266.83	<.0001
	Year (Y)	1	1329.869	1329.869	118.73	<.0001
	Loc*Y	1	0.224	0.224	0.02	0.888
	Genotype (Ge)	4	3734.164	933.541	83.34	<.0001
	Ge*Loc	4	253.901	63.475	5.67	0.0005
	Ge*Y	4	265.169	66.292	5.92	0.0004

	Ge*Loc*Y	4	65.549	16.387	1.46	0.222
	Irrigation (Irr)	1	259.838	259.838	23.20	<.0001
	Irr*Loc	1	19.748	19.748	1.76	0.1884
	Irr*Y	1	0.265	0.265	0.02	0.878
	Irr*Loc*Y	1	5.018	5.018	0.45	0.505
	Ge*Irr	4	189.964	47.491	4.24	0.0039
	Ge*loc*Irr	4	47.893	11.973	1.07	0.3782
	Ge*Irr*Y	4	107.656	26.914	2.40	0.0576
	Loc*Y*Ge*Irr	4	6.404	1.601	0.14	0.9655
	Rep(Loc*Y)	8	357.982	44.748	3.99	0.0006

Appendix 5 .Long run Monthly Min Temp, Max Temp, Relative Humidity, Wind Speed, and Sunshine hours of Mekelle, Elalla site

Month	Min Temp(°C)	Max Temp(°C)	Humidity (%)	Wind(Km/day)	Sun (hours)
January	8.7	25.6	51	198	9.7
February	10.0	26.8	47	229	9.8
March	12.3	27.6	47	240	8.8
April	14.3	28.0	46	234	9.1
May	14.2	29.1	43	172	9.4
June	13.2	29.3	48	106	7.1
July	13.7	25.7	67	73	4.9
August	13.6	24.7	75	61	4.9
September	11.6	27.5	55	99	6.8
October	11.3	25.8	48	184	9.5
November	10.2	25.1	49	213	9.8
December	8.8	24.9	49	211	9.8
Average	11.8	26.7	52	168	8.3

Appendix 6 .Long run Monthly Min Temp, Max Temp, Relative Humidity, Wind Speed, and Sunshine hours of K/Awlaelo, Aynalem site

Month	Min Temp(°C)	Max Temp(°C)	Humidity (%)	Wind(km/day)	Sun (hours)
January	8.1	26.9	70	130	9.6
February	9.2	28	68	138	9.6
March	11.6	28.7	65	147	9.5
April	13.5	29.3	60	147	9.3
May	13.6	29.9	55	173	10.1

June	12.9	30.3	58	156	9
July	13	26.6	86	147	6.8
August	13.3	26	89	147	6.3
September	11.5	27.9	73	147	9.3
October	10.5	27.1	61	173	9.6
November	9.1	25.6	64	112	9.3
December	7.6	25.7	70	104	9.6
Average	11.2	27.7	68	143	9

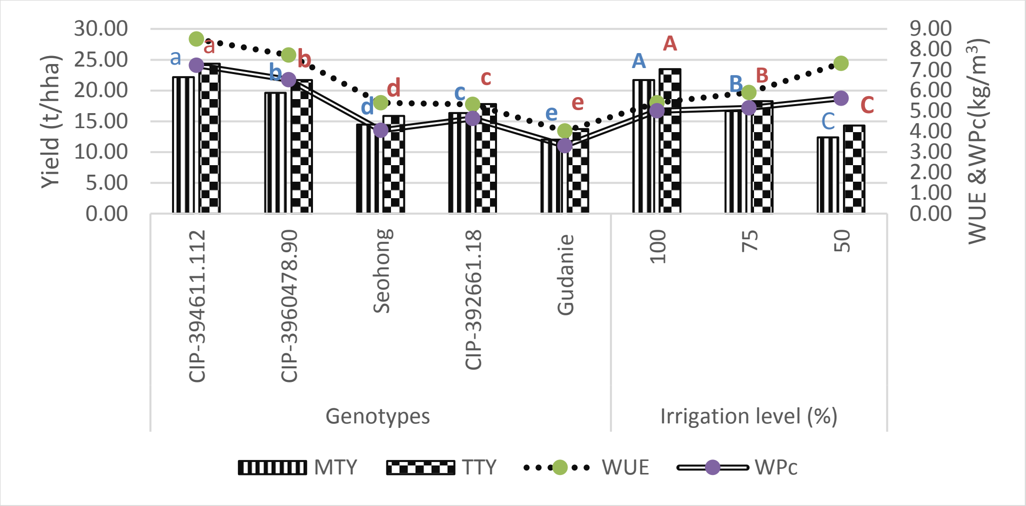
Chapter 6.

Appendix 7. ANOVA of Yield and Water Productivity under irrigation condition

Variable	Source of variation	DF	SS	MS	F -Value	Pr>f
Marketable tuber yield (MTY)	Replication	2	30.60	15.30	2.40	
	Genotype (Ge)	4	1160.90	290.23	43.45	<.0001
	Irrigation (Ir)	2	1218.36	609.18	91.20	<.0001
	Location (loc)	1	146.48	146.48	21.93	0. 0615
	Ge*Ir	8	182.01	22.75	3.41	0.0027
	Ge*loc	4	150.48	37.62	5.63	0.066
	Ir*loc	2	4.00	2.00	0.30	0.7423
	Ge*Ir*Loc	8	123.91	15.49	2.03	0.0307
	Residual	58	370.16	6.38		
	Total	89	3386.97			
Total tuber yield (TTY)	Replication	2	15.92	7.96	1.22	
	Genotype (Ge)	4	1311.60	327.90	49.96	<.0001
	Irrigation (Ir)	2	1201.75	600.87	91.55	<.0001
	Location (loc)	1	264.68	264.68	40.33	0.0650
	Ge*Ir	8	178.70	22.34	3.40	0.0028
	Ge*loc	4	160.21	40.05	6.10	0.053
	Ir*loc	2	4.90	2.45	0.37	0.6899
	Ge*Ir*Loc	8	139.40	17.42	2.66	0.0546

	Residual	58	377.93	6.516		
	Total	89	3655.67			

Appendix 8. The main effect of genotype and irrigation level (%) on yield and water use efficiency (WUE)



Graphs and lines with similar color have different letters showed significant different among variables but similar letter not significant deference among the variables at (P <0.05) due to the main effect of genotype and irrigation level

Chapter 7.

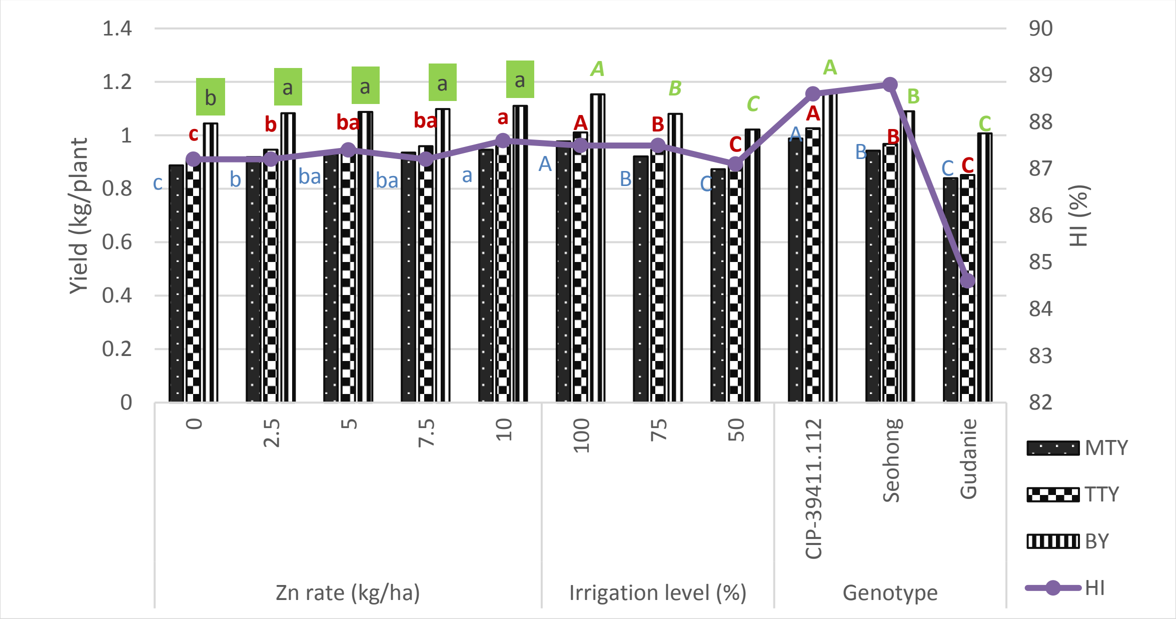
Appendix 9.ANOVA of potato on yield and quality o under screen house

Variable	Source of variation	DF	SS	MS	F Value	Pr>f
Marketable tuber yield	Genotype (Ge)	2	0.5139	0.2569	198.11	<.0001
	Irrigation (Ir)	2	0.2451	0.1225	94.49	<.0001
	Zinc rate (Zn)	4	0.0541	0.0135	10.43	<.0001
	Ge*Ir	4	0.1095	0.0274	21.10	<.0001
	Ge*Zn	8	0.0358	0.0045	3.45	0.0017
	Ir*Zn	8	0.0143	0.0018	1.38	0.2172
	Ge*Ir*Zn	16	0.0242	0.0015	1.17	0.3098
Unmarketable	Replication	2	0.0024	0.0012	5.15	0.0077
	Genotype (Ge)	2	0.0166	0.0083	36.38	<.0001
	Irrigation (Ir)	2	0.0059	0.0029	12.84	<.0001
	Zinc rate (Zn)	4	0.0006	0.0001	0.62	0.6482

	Ge*Ir	4	0.0020	0.0005	2.15	0.0815
	Ge*Zn	8	0.0012	0.0002	0.67	0.7123
	Ir*Zn	8	0.0014	0.0002	0.78	0.6213
	Ge*Ir*Zn	16	0.0071	0.0004	1.94	0.0266
Total tuber yield (TTY)	Replication	2	0.0092	0.0046	3.81	0.0250
	Genotype (Ge)	2	0.7090	0.3545	293.96	<.0001
	Irrigation (Ir)	2	0.3266	0.1633	135.42	<.0001
	Zinc rate (Zn)	4	0.0576	0.0144	11.93	<.0001
	Ge*Ir	4	0.1307	0.0327	27.09	<.0001
	Ge*Zn	8	0.0400	0.0050	4.14	0.0003
	Ir*Zn	8	0.0228	0.0028	2.36	0.0236
	Ge*Ir*Zn	16	0.0306	0.0019	1.59	0.0889
Total Biomass yield (TBY)	Replication	2	0.0318	0.0159	11.30	<.0001
	Genotype (Ge)	2	0.50722	0.2536	180.56	<.0001
	Irrigation (Ir)	2	0.3855	0.1928	137.23	<.0001
	Zinc rate (Zn)	4	0.0665	0.01662	11.83	<.0001
	Ge*Ir	4	0.1408	0.0352	25.07	<.0001
	Ge*Zn	8	0.0410	0.0051	3.64	<.0001
	Ir*Zn	8	0.0281	0.0035	2.50	0.0169
	Ge*Ir*Zn	16	0.0356	0.0022	1.59	0.0893
Harvest index (HI)	Replication	2	0.0040	0.0020	12.53	<.0001
	Genotype (Ge)	2	0.0506	0.0253	158.67	<.0001
	Irrigation (Ir)	2	0.0005	0.0003	1.67	0.2058
	Zinc rate (Zn)	4	0.0003	0.0001	0.41	0.7991
	Ge*Ir	4	0.0013	0.0003	2.07	0.0920
	Ge*Zn	8	0.0006	0.0001	0.50	0.8565
	Ir*Zn	8	0.0008	0.0001	0.65	0.7307
	Ge*Ir*Zn	16	0.0017	0.0001	0.65	0.8307
Dry matter content	Genotype (Ge)	2	194.5449	97.2724	14.60	<.0001
	Irrigation (Ir)	2	93.7894	46.8947	7.04	0.0014
	Zinc rate (Zn)	4	30.3407	7.5852	1.14	0.3437
	Ge*Ir	4	52.0398	13.0010	1.95	0.1086
	Ge*Zn	8	49.4887	6.1861	0.93	0.4973
	Ir*Zn	8	35.4364	4.4296	0.66	0.7211
	Ge*Ir*Zn	16	64.4281	4.0268	0.60	0.8728
Specific gravity	Genotype (Ge)	2	0.0008	0.0004	2.75	0.0696
	Irrigation (Ir)	2	0.0093	0.0047	31.38	<.0001
	Zinc rate (Zn)	4	0.0017	0.0004	2.85	0.0281
	Ge*Ir	4	0.0059	0.0015	9.96	<.0001
	Ge*Zn	8	0.0058	0.0007	4.93	<.0001
	Ir*Zn	8	0.0046	0.0006	3.89	0.0006
	Ge*Ir*Zn	16	0.0051	0.0003	2.14	0.0126
Starch content	Genotype (Ge)	2	18.1781	9.0891	1.53	0.2232
	Irrigation (Ir)	2	399.8674	199.9337	33.55	<.0001
	Zinc rate (Zn)	4	70.9617	17.7404	2.98	0.0233

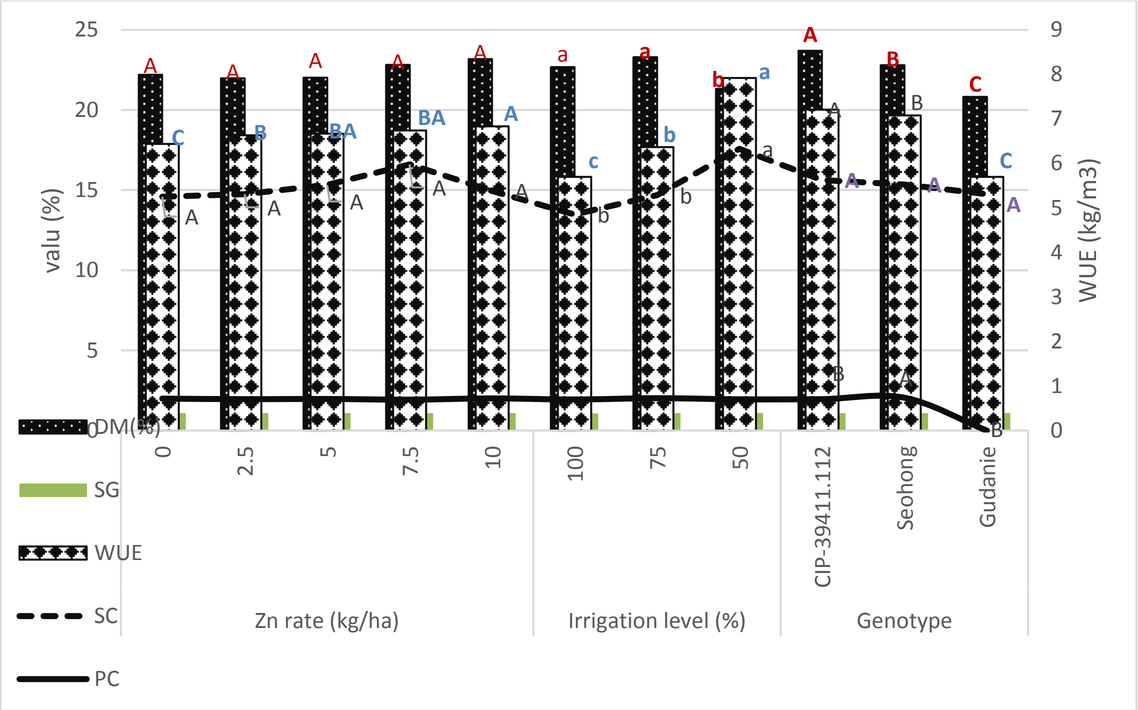
	Ge*Ir	4	215.5974	53.8993	9.04	<.0001
	Ge*Zn	8	237.4745	29.6843	4.98	<.0001
	Ir*Zn	8	191.9167	23.9896	4.03	0.0004
	Ge*Ir*Zn	16	204.1309	12.7582	2.14	0.0127
Protein content	Genotype (Ge)	2	0.4944	0.2472	5.66	0.0049
	Irrigation (Ir)	2	0.1616	0.0808	1.85	0.1633
	Zinc rate (Zn)	4	0.1008	0.02519	0.58	0.6804
	Ge*Ir	4	0.0855	0.0214	0.49	0.7437
	Ge*Zn	8	0.6290	0.0786	1.80	0.0875
	Ir*Zn	8	0.1950	0.0244	0.56	0.8097
	Ge*Ir*Zn	16	0.4518	0.0282	0.65	0.8377

Appendix 10. The main effect of genotype, irrigation level and Zn fertilizer rate on the yield of potato



Graphs and lines with similar color have different letters showed significant different among variables such as MTY, TTY, BY and HI but similar letter (no letters) not significant deference among the variables at (P <0.05) due to the main effect of Zn rate, irrigation level and genotype

Appendix 11. The main effect of Zn fertilizer rate, irrigation level and genotype on quality parameters of potato



Graphs and lines with similar color have different letters showed significant different among water use efficiency (WUE) and quality parameters of potato such as dry matter content (DM), specific gravity (SG) and starch content of potato but similar letter (no letters) not significant deference among the variables at (P <0.05) due to the main effect of Zn rate, irrigation level and genotype

Appendix 12 . Field experiment pictures

Evaluation by the Tigray Agricultural research Institute director

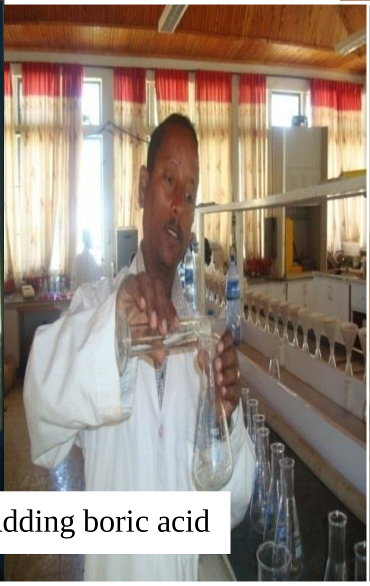
Evaluation and Monitored by my Adviser Dr Gebre Hadgu

Appendix 14. Selected Pictures in Laboratory work

Oven

Plant sample at Furness

N preparation



Adding boric acid

Distillation process

N at digestion block

Appendix 15. Weighting of potato in water to determine Specific gravity