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FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

SCHOOL OF POSTGRADUATE STUDIES

FACULTY OF AGRICULTURE AND AGRO-PROCESSING

DEPARTMENT OF FRUIT AND VEGETABLE PROCESSING TECHNOLOGY

AGRONOMIC PERFORMANCE OF FOOD BARLEY (*Hordeum vulgare* L.) VARIETIES AND THEIR RESPONSE TO SEED RATE IN DIGA DISTRICT, EAST WOLLEGA ZONE, ETHIOPIA.

MSc THESIS

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Agronomic Performance of Food Barley (*Hordeum vulgare* L.*)* Varieties and Their Response to Seed Rate in Diga District, East Wollega Zone, Ethiopia.

By

Bekuma Duguma Kumbi

Thesis Submitted to the Technical and Vocational Training Institute, Faculty of Agriculture and Agro-Processing Technology, Department of Fruit and Vegetable Processing Technology, in Partial Fulfillment of the requirements of the Master of Science in Crop Production Technology

Advisor: Waktola Mosisa (PhD)

June, 2026

Addis Ababa, Ethiopia

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DEDICATION

I dedicate this work to my beloved parents, Duguma Kumbi and Ayantu Hirko, for their lifelong sacrifices and for instilling in me the value of education. I also dedicate this work to my sister, Chaliti Duguma Kumbi, whose unwavering support and encouragement have been my greatest strength throughout my academic journey.

STATEMENT OF AUTHOR

By my signature below, I declare and affirm that this thesis is the result of my work. I have followed all ethical principles of scholarship in the preparation, data collection, data analysis, and completion of the thesis. Any scholarly literature that has been referred to in this thesis has been given recognition through citation. I affirm that I have cited and referenced all sources used in this document. Every serious effort has been made to avoid any plagiarism in the preparation of this thesis.

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BIOGRAPHICAL SKETCH

The author was born on January 4, 1984 E.c, to his father, Duguma Kumbi, and his mother, Ayantu Hirko, in Wara Kura Kebele, Sasiga District, East Wollega Zone, Oromia Regional National State, located 328 km west of Addis Ababa. When he reached school age, he attended primary school (Grades 1-8) at Jimata Gumbi Elementary School from 1991 to 1998 E.C, then attended secondary school (Grades 9-10) at Galo from 1999 to 2000 E.C.

He then enrolled Bako TVET College, where he pursued a Diploma in Plant Science from 2001 to 2003 E.C, graduated with Diploma in Plant Science. In 2004 E.C, he was employed by the Oromia Bureau of Agriculture and assigned to the East Wollega Zone, Sasiga District Agriculture and Rural Development, where he served for four years (2004-2007 E.C) as a plant science expert/Development Agent in the Department of Plant Science. He then joined the Haramaya University College of Agriculture and Natural Resource Management, Department of Plant Science, at the Chiro Campus, taking advantage of an opportunity provided by the Oromia Bureau of Agriculture. He graduated with a B.Sc. degree in Plant Science from 2008 to 2010 E.C. He also served at Sasiga District Agriculture and Rural Development, where he served for one year (2011 E.C) as a plant science expert/Development Agent in the Department of Plant Science. He was then employed by the Oromia Bureau of Job Creation and Skills at Wama Hagalo TVET College and served for two years (2012-2014 E.C) as an instructor in the Crop Production Department.

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LISTS OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
ATA	Agricultural Transformation Agency
CSA	Central Statistics Service
DAP	Diammonium Phosphate
EATA	Ethiopian Agricultural Transformation Agency
FAO	Food and Agriculture Organization of the United Nations
HARC	Holeta Agricultural Research Center
HI	Harvest Index
HSD	Honestly Significant Difference
m.a.s.l.	Meter Above Sea Level
MoA	Ministry of Agriculture
RCBD	Randomized Complete Block Design
USDA	United States Department of Agriculture

TABLE OF CONTENTS

APPROVAL SHEET i
CERTIFICATION SHEET ii
STATEMENT OF AUTHOR iv
BIOGRAPHICAL SKETCH v
ACKNOWLEDGEMENT vi
LISTS OF ABBREVIATIONS AND ACRONYMS vii
LIST OF TABLES xi
LIST OF FIGURES xii
LIST OF APPENDIX TABLE xiii
ABSTRACT xiv
1. INTRODUCTION 1
1.1. Background and Justification 1
1.2. Statement of the Problem 2
1.3 Objectives 3
1.3.1 General Objective 3
1.3.2 Specific Objectives 4
2. LITERATURE REVIEW 5
2.1. Overview of Barley Production 5
2.1.1. Origin, Domestication, and Distribution of Barley 5
2.1.2. Global Status of Barley Production 5
2.2. Botanical Description and Agronomic Characteristics of Food Barley 7
2.2.2. Morphological Characteristics of Food Barley 7
2.2.3. Growth and Development of Barley 8
2.3. Production Potential and Constraints of Food Barley in Ethiopia 9
2.3.1. Major Food Barley-Producing Areas 10
2.3.2. Productivity Trends of Food Barley 10
2.3.3. Constraints to Food Barley Production 11
2.4. Effects of Variety on Growth and Yield Performance of Food Barley 12
2.4.1. Concept of Variety Evaluation and Adaptation 14
2.4.2. Phenological Responses of Food Barley Varieties 16
2.4.3. Effects of Variety on Growth Parameters 18
2.4.4. Effects of Variety on Yield Components and Grain Yield 19
2.4.5. Performance of Improved Food Barley Varieties in Ethiopia 20
2.5. Effects of Seed Rate on Growth and Yield of Food Barley 20
2.5.1. Concept and Importance of Seed Rate 21
2.5.2. Influence of Seed Rate on Crop Establishment and Plant Population 22

2.5.3. Effects of Seed Rate on Phenology and Growth Parameters 24
2.5.4. Effects of Seed Rate on Yield Components and Grain Yield 26
2.5.5. Recommended Seed Rates for Food Barley in Ethiopia 27
2.6. Interaction Effects of Variety and Seed Rate on Food Barley Performance 29
2.6.1. Theoretical Basis of Variety and Seed Rate Interaction 29
2.6.3. Effects on Yield Components and Grain Yield 30
2.7. Economic Analysis of Agronomic Practices in Food Barley Production 32
2.7.2. Partial Budget Analysis 33
2.7.3. Marginal Rate of Return Analysis 34
2.7.4. Economic Evaluation of Variety and Seed Rate Technologies 34
3. MATERIALS AND METHODS 36
3.1. Description of the Study Area 36
3.2 Experimental Materials 38
3.2.1. Plant and fertilizer materials 38
3.3. Experimental Treatments and Design 39
3.4. Experimental Procedures and Field Management 39
3.5. Data Collection and Measurements 39
3.4.1. Crop phenology and growth parameters 39
3.4.2. Yield components and yield parameters 40
3.5. Statistical Data Analysis 41
3.6. Partial Budget Analysis 41
4. RESULTS AND DISCUSSION 44
4.1. Phenological and growth parameters 44
4.1.1 Days to 50% emergence 44
4.1.2. Days to 50% heading 45
4.1.3. Days to 90% physiological maturity 46
4.1.4. Plant height (cm) 47
4.1.5. Spike length (cm) 48
4.2. Yield and Yield Components 49
4.2.1. Number of total tillers per plant 49
4.2.2. Number of productive tillers per plant 49
4.2.3. Number of grains per spike 50
4.2.4. Grain yield 52
4.2.5. Biomass yield 52
4.2.6.Straw yield 53
4.4. Harvest Index 54
4.5. Lodging Percentage 54
4.6. Thousand Grain Weight 56

4.7. Correlation Coefficient Analysis 59
4.8. Partial Budget Analysis..... 60
5. CONCLUSION AND RECOMMENDATION..... 63
6. REFERENCE..... 64
7. APPENDIX..... 74

LIST OF TABLES

Table 1. Descriptions of Food barley Varieties used for the experiment**.** ……..38

Table 2. Effect of food barley variety, seed rate, and their interaction on days to emergence in Diga District during the 2025 main cropping season…… 45

Table 3**.** Effect of food barley variety, seed rate, and their interaction on crop phenology and growth parameters of food Barley in Diga district during the 2025 main cropping season ……47

Table 4. Effect of food barley variety, seed rate, and their interaction on yield components and yield of food Barley in Diga District during the 2025 main cropping season. 51

Table 5.Effect of food barley variety, seed rate, and their interaction on straw yield, harvest index, and lodging of food barley in Diga District during the 2025 main cropping season. ……..56

Table 6. Effect of food barley variety, seed rate, and their interaction on thousand-grain weight in Diga District during the 2025 main cropping season. ……..58

Table 7. Correlation coefficients for agronomic traits of food barley in Diga district during the 2025 main cropping season…… 60

Table 8. Partial Budget Analysis of variety and seed rate on food barley (*Hordeum vulgare* L) production in Diga District during the 2025 main cropping season. ……..62

LIST OF FIGURES

Figure 1. Map of the study area. ……37

Figure 2. Monthly rainfall (mm) and monthly mean maximum and minimum temperatures (°C) of the experimental site during the 2025 cropping season…….. 37

Figure 3. Ploughing the land…….. 76

Figure 4.Land Layout…… 76

Figure 5 .Sowing food barley through drilling…… 76

Figure 6. Field management ……77

Figure 7 .Data Recorded At 90% Physiological Maturity…….. 77

Figure 8. Harvesting,Threshing and weighing the grain and above ground dry biomass 77

LIST OF APPENDIX TABLE

Appendix Table 1. Analysis of variance for the effects of food barley varieties, seed rate, and their interaction on the agronomic performance of food barley varieties in Diga District during the 2025main cropping season. 74

Appendix Table 2. Analysis of variance of food barley yield components and yield as influenced by the main effects of variety,seeding rate, and by the interaction of the two factors in Diga District during the 2025 main cropping season. 75

Agronomic Performance of Food Barley (*Hordeum vulgare* L.) Varieties and Their Response to Seed Rate in Diga District, East Wollega Zone, Ethiopia.

ABSTRACT

Food barley is an important crop widely grown in the Diga district, East Wollega Zone of Oromia, Ethiopia. However, the average yield of the crop is low due to the biotic and abiotic production-constraints, among which the use of a local food barley variety and inappropriate seeding rate are the major. Therefore, this experiment was designed to evaluate the responses of four food barley varieties (HB 1307, HB 1966, Jobira, and local check) and four seed rates (75, 100, 125, and 150 kg ha^{-1}) during the 2025 main cropping season in Diga District using a randomized complete block design (RCBD) in factorial arrangement with three replications. Data were collected on phenology, growth, yield components, and yield parameters, and were analyzed using R Studio version 4.3 software. Analysis of variance revealed that, except for days to emergence and 1000-grain weight, all studied variables were significantly ($p \leq 0.05$) *affected by the main effects of barley variety, seed rate, and their interaction. The delayed days to heading (80 days), days to maturity (134 days), and the longest spike length (8.46cm), total tillers per plant (5), productive tillers per plant (4), and number of grains per spike (62) were produced by variety HB1307 planted at a 75 kg ha^{-1} seeding rate. The maximum plant height (109 cm) was obtained from the local variety sown at 150 kg ha^{-1} seeding rate, while the highest grain yield (4, 681.66 kg ha^{-1}) was produced by the variety HB1307 with 125 kg ha^{-1} seed rate. The highest dry biomass yield (14, 288 kg ha^{-1}) was recorded from the variety HB1307 sown at150 kg ha^{-1} seed rate, and the harvest index (42.06%) were recorded from the variety HB1307 sown at125 kg ha^{-1}. The maximum straw yield (10,632 kg ha^{-1}) was recorded for variety HB1307 planted at 150 kg ha^{-1} seed rate, while the maximum lodging percentage was obtained for local varieties sown at 125 and 150 kg ha^{-1} seed rate. The highest grain yield obtained from variety HB1307 planted at 125 kg ha^{-1} exceeded the grain yield of Jobira, HB1966, and local varieties sown at the same seed rate by about 57.4, 67.97, and 106.02%, respectively. Partial budget analysis also revealed that the variety HB1307 at 125 kg seed rate ha^{-1}produced the maximum net profit (*399,932 *Ethiopian birr ha^{-1}), with* 2,008 *% marginal rate of return. Therefore, it is concluded that the HB1307 variety at 125 kg seed ha^{-1} is economically optimal for production in the study area. However, this experiment was done for one season at a single location and needs to be repeated over multiple seasons and locations to reach a conclusive recommendation.*

Keywords: Economic analysis*; Food barley; Grain yield; Productivity; Seed rate; variety*

1. INTRODUCTION

1.1. Background and Justification

Barley (*Hordeum vulgare* L.) is one of the oldest and most important cereal crops cultivated worldwide. It ranks fourth among cereal crops, after maize, wheat, and rice, in terms of production and area coverage, contributing significantly to food security, livestock feed, and industrial uses (Ahmed, 2021; USDA, 2023). Owing to its wide adaptability, barley is grown under diverse environmental conditions, including marginal areas characterized by low soil fertility, drought stress, and high altitudes.

Ethiopia is recognized as both the largest barley producer in Africa and one of the global centers of barley genetic diversity (Daniel *et al.,* 2019; Teklemariam *et al.,* 2022). The crop is predominantly cultivated in the highland and mid-highland agroecologies, where it serves as a major source of food, feed, and household income. Food barley accounts for approximately 90% of the total barley production in the country and is widely used in the preparation of traditional foods and beverages (Ali, 2018). According to the Central Statistical Agency (CSA, 2021), barley is grown on about 926,107 ha of land, producing 2.34 million tons of grain with an average productivity of 2.54 t ha^{-1}.

Despite its economic and nutritional importance, barley productivity in Ethiopia remains low compared with its attainable yield potential. Research findings indicate that yields of 5–6 t ha^{-1} can be achieved under improved management practices; however, the national average remains below 3 t ha^{-1} (Habtamu *et al*., 2014; CSA, 2021). This productivity gap is attributed to several constraints, including limited adoption of improved varieties, inappropriate agronomic practices, declining soil fertility, diseases, moisture stress, and inadequate crop management technologies (Gardi *et al*., 2022).

Among the agronomic factors influencing barley productivity, varietal selection and seed rate management are particularly important. The performance of barley varieties varies considerably due to differences in genetic potential, adaptation, maturity period, tillering capacity, and resistance to biotic and abiotic stresses (Biruk *et al*., 2022; Teklemariam *et al.,* 2024). Consequently, varieties developed for one environment may not perform similarly under different agroecological conditions, necessitating location-specific evaluation and recommendation.

Similarly, seed rate is a critical management practice that determines plant population density, resource-use efficiency, crop growth, and grain yield. Appropriate seed rates promote optimum utilization of light, nutrients, water, and space, thereby enhancing crop productivity. Conversely, excessively high seed rates may increase competition among plants, resulting in poor tillering, lodging, and reduced grain filling, whereas low seed rates often lead to inadequate plant populations, poor canopy development, and reduced yield (Tolesa *et al.*, 2019; Gezahegn *et al.*, 2022). Furthermore, the optimum seed rate varies among barley varieties due to differences in growth habit and tillering ability.

The East Wollega Zone is among the important barley-producing areas of western Ethiopia. In Diga District, barley contributes significantly to household food security and rural livelihoods. However, production remains constrained by the use of low-yielding local cultivars and non-optimal seeding practices. Although several improved food barley varieties have been released in Ethiopia, information regarding their performance and response to different seed rates under the agroecological conditions of Diga District is limited. Therefore, evaluating improved food barley varieties under different seed rates is essential for identifying suitable variety–seed rate combinations that can enhance productivity and improve farmers' livelihoods in the study area.

1.2. Statement of the Problem

Food barley is a vital cereal crop in Ethiopia, significantly contributing to food security, nutrition, income generation, and rural livelihoods. Despite its importance and Ethiopia's status as a center of barley diversity, food barley productivity remains considerably below its potential. The national average productivity is approximately 2.54 t ha^{-1}, which is less than half the yield attainable under improved management practices (CSA, 2021; Habtamu *et al.*, 2014).

Several factors contribute to Ethiopia's low barley productivity, including limited adoption of improved varieties, poor crop management, declining soil fertility, diseases, and inappropriate seed rates (Gardi *et al*., 2022; Jalata, 2023). Among these constraints, selecting suitable varieties and optimizing seed rates are crucial, as they directly influence crop establishment, growth, yield components, and overall grain yield.

Improved barley varieties vary in their adaptation, tillering ability, maturity period, disease resistance, and yield potential. Consequently, their performance differs across locations due

to environmental conditions and genotype-by-environment interactions (Biruk *et al.,* 2022; Teklemariam *et al.,* 2024). Although several improved food barley varieties have been released for the Ethiopian highlands, their adaptability and productivity under the specific conditions of Diga District have not been adequately evaluated. As a result, farmers largely continue to rely on traditional cultivars with relatively low yield potential.

Seed rate is another critical agronomic factor influencing barley productivity. Appropriate seed rates ensure optimal plant population density and efficient resource utilization. However, the optimal seed rate depends on varietal characteristics and environmental conditions. Excessively high seed rates can increase inter-plant competition and reduce yield components, while low seed rates may lead to poor crop establishment and reduced productivity (Gezahegn *et al.,* 2022). Therefore, determining suitable seed rates for specific barley varieties is essential for maximizing grain yield and resource-use efficiency.

Previous studies in Ethiopia have primarily focused on evaluating barley varieties or determining seed rates separately under different environments. However, limited information is available regarding the interactive effects of food barley varieties and seed rates, particularly in the mid-highland agroecologies of western Ethiopia. In Diga District, where barley production is crucial for local livelihoods, scientific recommendations on appropriate variety seed rate combinations are lacking.

Therefore, there is a need to evaluate the agronomic performance of selected food barley varieties under different seed rates to identify the most productive and adaptable variety–seed rate combinations for the study area. The findings of this study are expected to generate location-specific recommendations that will contribute to increased barley productivity, improved resource-use efficiency, enhanced food security, and sustainable agricultural development in Diga District and similar agroecological areas.

1.3 Objectives

1.3.1 General Objective

To increase barley productivity through optimum seeding rate, and the use of responsive varieties in Diga district.

1.3.2 Specific Objectives

- To investigate phenology, growth, and yield performance of improved food barley varieties under different seed rates.
- To identify the best preforming variety to increase barley productivity in the study area
- To evaluate the economic feasibility of food barley varieties in response to different seed rates in the study area.

2. LITERATURE REVIEW

2.1. Overview of Barley Production

2.1.1. Origin, Domestication, and Distribution of Barley

As reported by Wada *et al*. (2022), barley (Hordeum vulgare L.) is one of the oldest crops cultivated by humans and is native to the Fertile Crescent, with domestication dating to 8,000–10,000 years ago. The cultivation of barley, as with all other crops, originated in the Fertile Crescent, which included areas such as Jordan, Lebanon, Palestine, Syria, southeastern Turkey, Iraq, and western Iran (Gadissa *et al*., 2021).

After domestication, barley spread to Europe, North Africa, and Asia due to its adaptability. The crop grows across varied elevations and prefers highland ecosystems, particularly above 2,000 m a.s.l. This means that Ethiopia is considered a center of origin for barley and other cultivated crops.

Ethiopia is the first country to have grown barley, and barley has been cultivated there since before 3, 000 BC (Wada *et al.*, 2022). Barley has been used to prepare various dishes whose recipes are deeply embedded in the nation's traditional culture. The greatest diversity in morphology, genetic races, disease-resistant lines, and endemic morphotypes is found in Ethiopia. Although Ethiopia is widely recognized for its diverse native barley species, it is accepted as one of the centers of diversity for crops (Daniel, 2019).

The study by Teklemariam *et al.* (2022) on barley landraces between different seasons and at different elevations revealed low genetic divergence between seasons and geographical areas but high genetic divergence between elevation groups. This suggests that altitude adaptation contributed greatly to the diversification of the barley populations studied. There are some regions in Ethiopia where there has been reported to be a great genetic diversity among barley landraces, namely Tigray, Shewa, Arsi, and Bale (Teklemariam *et al*., 2022; Gadissa *et al.,* 2021).

2.1.2. Global Status of Barley Production

Barley is the fourth most produced cereal crop globally and the top five countries in the world for its production of point of view are the European Union, Russia, Australia, Canada, and Turkey. Russia and the European Union are the world's two largest producers of barley and also they produce over 51.45 million tons (Jalata 2023). Australia, Canada, and Turkey are

the third, fourth, and fifth greatest producers of barley, with respective production amounts of 13.7, 9.99, and 7.40 million tons, from a total worldwide production of 147.06 million metric tons (Beyene, 2024). The top five countries have respective shares of 55.28%, 20.63%, 13%, 10.74%, and 8.1%, on the world.

2.1.3. Barley Production and Importance in Ethiopia

Barley is one of Ethiopia's five most important cereal crops, and a significant amount of arable land may be used to grow barley (CSA, 2018; Habtamu, 2025). Among the eleven nations that produce the most barley worldwide, Ethiopia is the largest producer in Africa (Statista, 2021). The country's main producers of barley are Oromia, Amhara, Tigray, and the Southern Nations, Nationalities, and Peoples ' Regions; the northern and central regions cultivate the grain for food. Barley accounts for roughly 53% and 30% of the nation's total output, respectively, and is mostly grown in the Oromia and Amhara regions (Dagnew *et al.,* 2024).

The crop has been grown on 811,782.08 hectares of land in the nation, yielding an annual production of about 1,767,518.447 tons and a productivity of 2.3 tons per hectare (CSA, 2019). According to CSA (2020/21), the crop is grown on approximately 926,106.90 hectares of land annually, yielding 2,339,109.9 tons at a productivity of 2.53 tons per hectare. Because barley is planted during both the major and short rainy seasons in Ethiopia, combined with residual moisture, it ensures food security for farmers in highland areas (Chala *et al.*, 2020).

Furthermore, barley is an important crop in Ethiopia since it is a component of the sociocultural and livelihood systems of the highland communities (Wada *et al.*, 2022). Basso (finely ground roasted barley combined with water, butter, or oil) and Chuiko (prepared by soaking Basso in pure butter) are two examples of barley-based dishes. Other foods, including Genfo, Kolo, Kinche, Dabbo, Kitta, and Atmit, are also consumed by people. For many Ethiopian small-scale farmers, barley can be utilized as animal feed, thatch roofing, and a source of revenue (Wada *et al*., 2022).

2.2. Botanical Description and Agronomic Characteristics of Food Barley

Food barley (*Hordeum vulgare* L.*)* is an annual grain crop that belongs to the family of Poaceae. It is among the most adaptable cereal crops cultivated across different agro-ecological zones. This grain crop can adapt to difficult conditions such as high altitude, low soil fertility, drought, and cold climatic conditions, making it an important food security crop in the highlands of Ethiopia (Jalata, 2023). Its importance is attributed to its short life cycle, adaptability, and the fact that it can produce economic quantities of yield even under difficult growth conditions.

2.2.1. Taxonomy and Classification of Barley

Barley is one of a diploid cereal with 14 chromosomes (2n=14 and it is also one of the oldest cereal crops. Taxonomic classification of the domesticated barley is Kingdom: *Plantae;* Division: *Magnoliophyta*; Class: *Liliopsida*; Order: *Poales;* Family: *Poaceae*; Genus: *Hordeum*; Species: *Hordeum vulgare L*.

There are two main classes to which the domesticated barleys may be divided based on the morphology of the spikes. These are: (1) two-rowed barley (*Hordeum vulgare var. distichon*) and (2) six-rowed barley (*Hordeum vulgare var. hexastichon*). These two types of barley differ in that the former has only fertile central spikelets, whereas the latter has fertile spikelets at all three rachis nodes of the spike.

Food barley production in Ethiopia is mostly characterized by six-row genotypes due to their wide adaptability, high numbers of grains per spike, and suitability for the traditional preparation of foods. There are enormous genetic resources available for barley in Ethiopia that comprise of numerous landraces as well as improved varieties for different agro-climatic zones. The molecular characterization has proved the presence of enormous genetic diversity in the barley germplasm of Ethiopia, thus providing enormous genetic resources for the development of crops in climate-resilient breeding (Yirgu *et al*., 2023).

2.2.2. Morphological Characteristics of Food Barley

Food barley also possesses morphological characteristics that enable the plant to survive and thrive in different environments. Food barley has fibrous roots, which include the seminal roots and nodal roots. The seminal roots develop after the germination stage in order to stabilize and take nutrients from the soil, while the nodal roots, which grow late, help in taking up water and nutrients throughout the remaining growth period (Gadissa, 2023).

The stem is cylindrical in shape and has hollow internodes and solid nodes. The height of the plant varies significantly depending on the genotype and the environment, ranging between 60 cm and 120 cm for food barley varieties grown in Ethiopia. Tall varieties are vulnerable to lodging; however, the semi-dwarf varieties are advantageous due to their high harvest index and yield (Abebe *et al.*, 2023).

The leaves are long and narrow. Every leaf is composed of a sheath, blade, ligule, and auricle. In the case of the food crop barley, what is unique about the morphology of the plant is that the auricles of the barley are large and clasp the stem. The development of the leaf surface influences the efficiency of the photosynthesis process, and consequently, biomass production, and finally, grain yield. The inflorescence of barley is the spike, containing the rachis, which supports the spikelets at each node. The features of the grain, in terms of size, shape, color, and number of grains per unit weight, vary from one genotype to another.

2.2.3. Growth and Development of Barley

There are various physiological and morphological stages involved in the growth and development process of barley, resulting in the eventual yield formation. These processes can be said to include germination, emergence, tillering, growth of the shoot, booting, heading, flowering, filling of the grains, and physiological maturity. The stages are associated with distinct periods of time depending on various conditions such as the genetic makeup of the barley plant, temperature, photoperiodism, soil fertility, soil moisture, and management techniques (Derbew *et al*., 2023). Germination entails water absorption, enzyme activity, and, lastly, the sprouting of the radicle and the coleoptile.

Crop establishment is particularly significant in the cultivation of barley because it affects the population of plants and, hence, the production of yield. The reproductive phase starts with stem elongation and ends with heading and flowering. The heading period is an advantageous adaptive trait that controls the adaptability of the crop to avoid terminal drought and other stresses.

Early maturing crops are preferred in drought-affected areas, whereas late maturing ones produce a high yield in good growing conditions (Abebe *et al*., 2023). Following the pollen transfer, the grains start filling due to assimilate translocation from the leaves and stem into the grains. The process of grain filling determines grain weight and, thus, production. Environmental stress factors at this growth stage include the presence of drought and

nutritional stress, resulting in lower yields. Physiological maturity of grains is defined through the desiccation of grains and cessation of dry matter accumulation. The growth characteristics of food barleys vary because of differences in the genetic predisposition of these cereals concerning thermoregulation, photoperiodism, and adaptation.

2.3. Production Potential and Constraints of Food Barley in Ethiopia

Ethiopia is the first country in Africa that grows the largest amounts of barley, and it is also one of the centers of barley diversity (Jalata, 2023; Yirgu *et al*., 2023). The favorable environment for growing this crop ranges from cool sub-humid areas to higher altitudes, while the presence of various indigenous germplasms provides many opportunities for variety improvement.

Nevertheless, although there exists a high productivity potential for this crop, its yield is lower than the yield capacity shown by the improved varieties of barley under investigation. It is necessary to note that the average productivity of the country is much lower than the yield capacity due to various constraints, such as biophysical, technological, socioeconomic, and institutional. These include lack of improved varieties, poor use of seeds, limited use of fertilizers, decline in soil fertility, moisture stress, poor crop management practices, and inadequacy in extension services (Shiferaw, 2022; Tadesse *et al.,* 2021).

Moreover, there are diseases like scald, leaf blotch, rust, and smut, along with insect pests that affect the grain production and reduce grain quality. Such factors have a significant impact on the production of barley (Jalata, 2023). Environmental factors like cold, acidic soil, waterlogging, and unpredictable rainfalls further limit productivity in Ethiopia's highland areas, where barley cultivation occurs.

The efficiency of barley cultivation is also highly dependent on the complex interactions between the genetic makeup, environmental conditions, and cultivation practices. Because of differences in altitude, soil fertility, precipitation levels, and climatic conditions, most high-yielding barley varieties released in Ethiopia have shown variable performance across locations. This indicates that inadequate agronomic information and lack of site-specific variety selection remain major constraints to sustainable barley production (Molla *et al.,* 2020; Assefa *et al.,* 2021). Scientific studies in several regions of Ethiopia have revealed that the output and yield components of barley are remarkably enhanced through a combination of

improved varieties, proper seeding rates, fertilization, timing, and disease-weed management (Tadesse *et al.*, 2021).

2.3.1. Major Food Barley-Producing Areas

Barley grains are mainly cultivated in the highlands of Ethiopia at elevations ranging from 1,800 meters to 3,400 meters above sea level. The crops are grown in the Oromia, Amhara, Central Ethiopia, Southern Ethiopia, and Tigray areas, where the climatic conditions are relatively cool and rainfall is favorable (CSA, 2024). The first and second regions in terms of barley cultivation in Ethiopia are Oromia and Amhara, respectively.

The major zones in the Oromia region where there is high production of barley include the West Shewa, Arsi, Bale, West Arsi, Horo Guduru Wollega, North Shewa, and East Wollega zones. Other zones where barley is produced include the South Wollo, North Wollo, South Gondar, and East Gojjam zones in the Amhara region (Jalata, 2023). The existence of several landraces that have been adapted to various environments constitutes important genetic material for breeding purposes.

2.3.2. Productivity Trends of Food Barley

Barley continues to be one of the important cereal crops grown in Ethiopia, both in acreage and production. There has been a gradual increase in production levels during the past decade, resulting from improvements in cultivars, an increase in the use of farm inputs, and better extension service delivery.

According to current agricultural data, barley is cultivated in about one million hectares every year and makes an important contribution to the nation's cerealeconomy(CSA200024). There has been a positive trend in national average productivity, with productivity increasing from less than 2.0 t ha^{-1} in past decades to about 2.3-2.5 t ha^{-1} in the current years. However, this productivity level is much lower than the potential productivity of improved food barley cultivars, which is often higher than 4.0-5.0 t ha^{-1} (Derbew *et al.*, 2023).Various reasons account for this gain in productivity, such as the availability of high-yielding and disease-resistant varieties, increased use of fertilizers, and better agronomic practices.

The national barley breeding programs have developed many varieties of food barleys that have outstanding agronomic characteristics and suitability for various conditions. The adoption of these varieties has not been uniform across different regions due to variations in access to the improved seeds and marketing opportunities (Lakew *et al*., 2020).

Recent research has indicated wide variations in productivity between barley-growing regions and systems. Productivity is relatively higher in areas where improved varieties and good agronomic practices are widely adopted compared to those that adopt traditional varieties and low-input systems (Abebe *et al.,* 2023). This implies that a further increase in yields would depend on technology transfer and appropriate location-specific practices.

2.3.3. Constraints to Food Barley Production

Though being of high significance and having high productivity potential, food barley production in Ethiopia faces various challenges that adversely influence its efficiency. These challenges can consist of biotic, abiotic, technological, and socio-economic problems. Diseases can be referred to as one of the main biotic factors. Such diseases as scald (*Rhynchosporium commune*), net blotch (*Pyrenophora teres*), leaf rust (*Puccinia hordei*), and powdery mildew (*Blumeria graminis f. sp. hordei*) cause great yield losses in the most important zones where barley is cultivated.

Although resistant varieties have been created, the appearance of new pathogen strains is a potential threat to sustainable production (Jalata, 2023). Abiotic stresses are among the important causes that reduce yields. Poor soil fertility, moisture stress, uneven precipitation distribution, frosts, and climate variability are phenomena that occur in barley cultivation zones. Due to continuous cultivation and low fertilization, soil fertility and barley yields decrease in the most highland areas.

Climate change has also added another threat to production through temperature and precipitation variability (Beyene, 2024). Technical limitations are associated with the poor availability of improved seeds, non-adoption of recommended agronomic practices, inefficient use of fertilizers, and low mechanization levels. Smallholder farmers still grow their local landraces following traditional practices, which results in poor productivity. In addition, unsuitable seed rates, late planting dates, and improper crop management practices negatively influence the yield potential of the crops (Derbew *et al.,* 2023).

Socioeconomic and institutional factors limit barley production. Poor credit services, a poor seed delivery system, weak market linkage, and weak extension services limit farmers' ability to adopt better technology. Poor input costs and market price variations demotivate farmers from investing in barley production (Lakew *et al.,* 2020).

2.4. Effects of Variety on Growth and Yield Performance of Food Barley

The genetic differences among varieties of barley are very important in affecting growth characteristics, phenology, yield components, yield level, and adaptation of the crop. In this respect, the development and use of good varieties are the most significant ways to improve barley production and food security in the country. Varietal differences in crop growth are associated with the genetic ability to utilize resources, photosynthesis processes, nutrient uptake, tillering ability, and resistance to biotic and abiotic factors.

Improved food barley varieties demonstrate a better growth capacity than local varieties because of their genetic structure and environmental adaptability. Important varietal differences have been found in characteristics such as days to heading, days to maturity, plant height, spike length, productive tiller number, thousand-kernel weight, biomass productivity, and grain yield in various barley-growing regions of Ethiopia (Birhanu *et al*., 2020; Derbew, 2023). Varietal effects on crop phenology are especially critical, as the periods of heading and maturity influence the capacity of the genotype to avoid terminal moisture stress and make full use of the growing season's resources.

Genotypes that mature early have an advantage in dry areas, while late-maturing genotypes tend to take advantage of the longer growing season to achieve a greater amount of biomass and yield. Research carried out in Ethiopian highland environments revealed significant differences in the number of days to heading and maturity between different food barley genotypes (Birhanu *et al*., 2020; Belete, 2024).

Plant height is another critical growth factor affected by the genotype. Differentiation in plant heights is attributed to genetic variations in stem extension and dry matter accumulation. Higher plants generally possess high biomass, but increased height renders them vulnerable to lodging and hence low grain yield. It was revealed in Ethiopian research that there were significant varietal differences in the plant height of food barley genotypes (Derbew, 2023; Biramo *et al*., 2023).

Tillering capacity is one of the vital attributes for predicting the eventual grain yield since productive tillers contribute to the spike number per unit area. Genotypes with higher tillering capacity tend to bear more spikes and consequently high grain yield under favorable growing conditions. Studies conducted in Ethiopia reported variations among food barley genotypes in terms of the number of productive tillers, highlighting the significance of genetics in

determining yield performance (Derbew, 2023; Birhanu *et al.,* 2020). Yield attributes such as spike length, kernels per spike, spikes per square meter, and thousand-kernel weight are strongly influenced by genotypic differences. The combination of the above attributes determines the ultimate grain yield of the barley crop.

Improved varieties tend to perform better than local checks due to their capacity for developing larger spikes, higher kernel counts, and heavier grains. Assessment of food barley genotypes in the highlands of North Gondar showed that improved genotypes performed significantly better than local genotypes in grain yield and other yield-contributing attributes (Birhanu *et al.,* 2020).

Yield production is the best reflection of genotypic performance in given environmental settings. Several studies conducted in Ethiopia have indicated substantial differences in grain yield between varieties of food barley. For example, variety evaluation in the highlands of southern Ethiopia has revealed the presence of improved varieties with superior agronomic performances and higher grain yields compared to standard and local checks, owing to improved adaptation and the expression of yield components (Derbew, 2023). Likewise, evaluations at several locations in southwestern Ethiopia have indicated substantial genotype effects on grain yields, thus highlighting the significance of choosing varieties with broad adaptations and high yields (Belete, 2024).

Varietal effects on yield performance can be explained in terms of genotype-environment interaction. This means that there are substantial differences between the responses of different varieties to changes in soil fertility, rainfall distribution, altitude, temperature, and management practices. Thus, a variety that performs well in a particular environment is not necessarily expected to perform in the same way elsewhere. Stability analyses carried out in several Ethiopian environments have shown significant genotype-environment interaction effects (Assefa *et al*., 2021; Belete, 2024).

The presence of large genetic diversity makes it possible to implement breeding programs intended to create productive and adaptable barley varieties resistant to stress factors. Agronomic and morphological analyses of Ethiopian barley showed considerable variability in agronomic traits connected with yield, which indicates the possibility of future productivity improvements (Habtegebriel *et al*., 2024). Moreover, the responses of different genotypes to agricultural inputs such as fertilization and seeding rates are significantly

different. There are genotypes with higher resource utilization capability characterized by higher productivity.

2.4.1. Concept of Variety Evaluation and Adaptation

Variety evaluation and adaptation trials form integral elements of crop improvement and technology transfer programs. Variety evaluation in barley (*Hordeum vulgare* L.) involves the systematic evaluation of genotypes in a given environment to assess their agronomic performance, stability, adaptability, and suitability for cultivation. On the other hand, adaptation refers to the ability of a given variety to survive, grow, develop, and produce economically acceptable yields under certain environmental conditions and management systems.

The main purpose of variety evaluation is the identification of the best genotypes with good yield potential, stability, stress tolerance, and agronomic characteristics for promotion in target environments (Assefa *et al.,* 2021; Belete, 2023).The environmental heterogeneity prevailing in Ethiopia due to differences in altitude, precipitation, temperature, soil fertility, and agricultural practices results in substantial differences in the performance of a barley variety. In other words, a genotype with exceptional performance in a certain environment might not perform well in a different environment. Hence, adaptation trials are carried out in order to evaluate the response of the varieties in different environments (Assefa *et al*., 2021).

The theory behind variety evaluation is rooted in the notion of G (genotype), E (environment), and G x E (interaction of genotype and environment). Genotype effects denote the genetic ability of the varieties, whereas environmental effects denote the impact of environmental factors on varieties such as climate, soil, and management practices. The occurrence of G x E interaction is when there is a differential response of varieties to environmental shifts. The presence of G x E interaction makes it difficult to choose among varieties since excellent performance in one environment may not necessarily be sustained in other environments.

Adaptation can be categorized into broad adaptation and specific adaptation. Broadly adapted varieties exhibit relatively stable performance across diverse environments and are less sensitive to environmental fluctuations. These types of varieties are desirable for widespread distribution since they provide stable yields under different conditions. However, varieties that are specifically adapted achieve very high performance in specific environments but are

less productive outside the target environment. The decision on whether to select a variety that is broadly adapted or specifically adapted is based on the production goals, variation in the environment, and cultivation practices in the target area (Belete, 2023).

The testing of barley varieties includes assessing traits that determine the productivity and adaptability of the varieties. The traits include days to emergence, days to heading, days to maturity, plant height, spike length, number of productive tillers, biomass yield, thousand-kernel weight, grain yield, and harvest index. Differences among varieties for these traits indicate the existence of genetic variability, which serves as the basis for varietal selection and improvement (Biramo *et al*., 2023; Fesseha *et al.*, 2023).

Yield emerges as the main consideration in evaluating barley breeding varieties with respect to adaptability. But it is not always enough since yield is a complex trait affected by many environmental and genetic factors. This is why researchers use stability analysis in combination with agronomic assessments to select varieties that are productive and stable in performance.

Statistical approaches like AMMI and GGE biplot analysis are used to evaluate the stability and adaptability of barley varieties (Belete, 2023). Another aspect of adaptation is related to tolerance to stress. The major limitations in barley cultivation in Ethiopia are associated with moisture stress, soil acidity, nutritional deficiencies, disease, insect pest damage, and temperature stress. Adapted varieties should have tolerance mechanisms that allow them to withstand stresses and maintain good productivity at the same time. For this reason, variety evaluation programs increasingly consider resistance/resilience to stresses in addition to yield performance while recommending varieties for particular agro-ecologies (Biramo *et al.*, 2023; Fesseha *et al*., 2023).

The recent trials carried out in Ethiopia have given a lot of emphasis on multi-location and multi-year assessments to ensure reliability in recommending new varieties. This is because of seasonal variation and fluctuations in environments and thus helps in determining the actual performances and stability of varietal traits. For example, different grain yields and adaptations have been observed among food barley varieties assessed in the southwestern Ethiopian highlands (Belete, 2023). The method of participatory variety selection combines the farmers' needs and preferences with traditional agronomic evaluations to determine the best-performing varieties that suit both scientific and farmers' needs. The characteristics that farmers look at while selecting new varieties include grain yield, duration, resistance to

diseases, straw yield, grain quality, and marketability, among others. Adaptation studies for food barley in Ethiopia have shown the effectiveness of this method (Fesseha *et al*., 2023).

Diversity is also important in the development of adaptation of varieties. Germplasms of barley in Ethiopia have high agro-morphological and genetic diversity, offering opportunities for breeding new varieties suitable for different production zones. Research studies have been conducted on barley landraces in Ethiopia, revealing significant variation in phenology, morphology, and yield traits, thus implying the presence of important genetic materials to develop breeding programs that enhance adaptation and productivity amid climate change (Gadissa *et al.*, 2021; Dido *et al*., 2021).

2.4.2. Phenological Responses of Food Barley Varieties

Phenology can be defined as the process of development and growth of a plant from emergence to flowering and grain filling up to physiological maturity. In the instance of food barley (*Hordeum vulgare* L.), phenological traits are among the most adaptive traits because they dictate the timing of growth and development stages, efficiency in the utilization of resources, adaptation to the environment, and, ultimately, grain yield. The phenological traits of plants are mostly genetically influenced; however, they can also be affected by environmental conditions such as temperature, rainfall, photoperiodism, soil fertility, and farming practices.

Phenological characteristics commonly employed in the evaluation of barley varieties include days to emergence, days to heading, days to flowering, grain fill period, and days to physiological maturity (Fantahun *et* al., 2023; Teklemariam *et* al., 2024). These are very important factors for indicating adaptation because they reflect the ability of the genotype to synchronize its phenology with the environment. Varieties that have favorable phenologies will be able to escape from terminal drought and heat stress during the grain fill stage and fully exploit the available water and nutrients.

Days to heading is one of the crucial phenological traits in barley due to its ability to indicate the transition from the vegetative to reproductive phase. Large varietal differences in days to heading in food barleys have been documented in different Ethiopian highland agro-ecologies. This difference is based on the variations in the growth rate of the variety and the response to the environment (Fantahun *et* al., 2023). Early heading varieties usually perform well in moisture-stressed environments as they can complete their reproductive phase before

terminal drought. Conversely, late heading varieties take advantage of vegetative growth phases; therefore, more biomass and possibly higher grain yields accumulate in favorable environments.

Another important phenological trait that significantly affects grain development and yield formation is the number of days required to attain physiological maturity. The maturity period determines the duration of the grain filling stage and the extent to which the crops can use their environment for biomass accumulation and assimilation. Early maturing types are crucial for areas where the rainfall pattern is erratic because they minimize terminal drought stress. Late maturing types usually have a larger biomass accumulation capacity and, therefore, are likely to yield high grain under rainy and long growing season environments. The longer the grain-filling stage, the more assimilate is accumulated , resulting in larger grains and higher yield capacity. However, overly long grain-filling periods can make crops susceptible to unfavorable environmental factors, such as water scarcity and diseases (Fantahun *et al.*, 2023). Thus, the perfect compromise between earliness and a sufficiently long grain filling period is needed to achieve maximum productivity.

The response of barley phenology is strongly affected by genotype × environment interactions. The environment plays a critical role in the phenotypic manifestation of traits such as altitude, temperature, rainfall distribution, and photoperiod. There are significant variations in environments in different parts where barley cultivation occurs in Ethiopia, ranging from cooler highlands to warmer mid-altitudes. Thus, there are differential phenological reactions of varieties in different environments. Multi-environment trials conducted in Southwestern, Southern, and Central Ethiopia have demonstrated significant genotype × environment interactions for phenological traits, particularly days to heading and days to physiological maturity, indicating that varietal adaptation and performance vary across agro-ecologies (Belete, 2023; Fekadu *et al*., 2023; Derbew *et al*., 2024).

One of the most significant environmental factors that impacts the phenology of barley is temperature. Generally, crop development accelerates when temperature levels rise, leading to early heading and maturity. Conversely, cooler temperature levels are known to promote vegetative development while delaying the reproductive stage. In the Ethiopian Highlands, different altitudes create temperature gradients that influence phenological manifestations in different barley varieties. As a result, barley varieties suitable for certain altitude levels are usually selected based on their maturity behavior and reaction to local temperature levels.

The sensitivity of barley varieties to photoperiodic conditions is another factor that significantly impacts phenological development. Since there is variability in barley genotypes regarding photoperiod sensitivity, different varieties initiate flowering and transition to reproductive development at different day lengths. The right photoperiod sensitivity is usually preferred since it helps varieties adjust their flowering and grain development to favorable environmental periods. Nutrient availability might also affect the phenological behavior of barley. Nutrient adequacy leads to good vegetative development, which, in turn, tends to extend the development period of the plant by increasing biomass production.

2.4.3. Effects of Variety on Growth Parameters

For instance, in the case of barley (*Hordeum vulgare* L.*)*, the aforementioned traits are primarily determined by genetics and plant architecture, vegetative growth, photosynthetic activity, nutrient uptake efficiency, and dry matter accumulation. This is proven in studies of barley germplasm from Ethiopia, where considerable genetic variation in agronomic and physiological traits of Ethiopian barley germplasm was revealed (Fantahun *et al*., 2023; Caproni *et al*., 2023; Habtegebriel *et al.,* 2024). Thus, there is considerable variation between genotypes in traits such as plant height, tillering, leaf area development, biomass accumulation, and crop growth rate.

Plant height can be used as one of the growth indices for barley, since it is the product of genotype and environmental interaction. There are considerable variations in plant height due to differences in internode length, growth period, and dry matter accumulation. Tall genotypes have larger vegetative biomass and straw content, while shorter ones demonstrate higher lodging resistance and more efficient allocation of assimilates into the grain (Derbew, 2023; Belete, 2023; Fantahun *et al*., 2023).

Another important growth characteristic that influences the development of the canopy and grain production is tillering capability. Tillering involves the formation of shoots from basal nodes. The leaf area determines the photosynthetically active leaf area for carbon fixation. An increased leaf area index will lead to higher rates of photosynthesis, increased dry matter, and grain yield production. The number, orientation, and longevity of leaves affect canopy architecture, crop growth rate, and resource use efficiency. Dry matter production is influenced by photosynthesis, nutrient absorption, and assimilate partitioning. The variation in these features in Ethiopian barleys has been documented (Caproni *et al*., 2023). Biomass production in barley varieties is quite variable because of differences in growth period, canopy structure, photosynthesis efficiency, and stress resistance. Increased biomass generally corresponds to increased grain yield according to the harvest index and efficiency of assimilate allocation.

While some genotypes tend to grow vegetatively, other genotypes effectively allocate assimilates to the grain; thus, there is variability in growth and yield traits. Environmental conditions such as rainfall, temperature, soil fertility, and agricultural practices also affect

growth variability. Hence, assessing the growth traits in specific environments is important. Different levels of efficiency in nutrient utilization also cause variations in growth performance. Superior genotypes exhibit better root architecture and greater efficiency in nutrient utilization. Lastly, growth characters are closely linked to grain yield. Traits such as early vigor, plant height, tillering ability, and biomass impact photosynthesis, assimilate accumulation, flower formation, and grain filling. Therefore, better growth performance results in higher grain yields in barley varieties.

2.4.4. Effects of Variety on Yield Components and Grain Yield

Varietal effects constitute important sources affecting yield components and grain yield of food barley (*Hordeum vulgare* L.*).* The performance of a variety depends on its genetics, which control its agronomic traits such as productive tillers, spike length, kernels per spike, thousand kernel weight, biomass production, harvest index, and grain yield. Improved varieties vary from one another in terms of resource utilization and response to management operations, which causes differences in yield depending on location and season.

According to Derbew (2023), improved barley varieties vary significantly in terms of plant height, productive tillers, spike length, kernels per spike, thousand grain weight, biomass, and grain yield in southern Ethiopia. Superior varieties have greater assimilate production and distribution to the reproductive parts of plants, which leads to yield increases. Likewise, Biramo *et al*. (2023) revealed a lot of variability among the cultivars in terms of effective tiller count, spike characteristics, seed weight, harvest index, and seed yield due to various NPSB fertilization levels in southern Ethiopia. Cultivars with higher tiller fertility and grain weights yielded more grain, indicating the importance of varietal choice in low soil fertility situations.

In southwestern Ethiopia, Belete (2023) found very significant variations among barley varieties with regard to grain yield and associated traits in different environments. It was evident that the study established stable, high-yielding varieties with good adaptability, indicating the importance of genetic variability in variety choice. Variations in spike characteristics, kernel number, kernel weight, and biomass were the main determinants of grain yield variability. The factors that influence yield include productive tiller number, kernels per spike, and thousand kernel weight, as these improve sink strength and assimilate translocation during the grain filling period. Selecting varieties based on these traits is therefore very important.

2.4.5. Performance of Improved Food Barley Varieties in Ethiopia

The improved varieties developed by the national research organization have high potential for greater yield and better resistance to various diseases and stresses, as well as adaptation to different agro-climatic environments. The performance of the varieties differs from location to location, which requires constant evaluation in a particular environment. In the last ten years, more than forty-seven barley varieties were released in Ethiopia (Derbew, 2023). These varieties outperform the local cultivars in terms of yield, biomass, resistance to diseases, and other factors, although there is a low adoption rate of these varieties in many regions. Several studies have identified important differences between varieties in their agronomic characteristics and yield.

In Southern Ethiopia, Derbew (2023) established significant variability between improved varieties in days to heading, maturity, plant height, spike length, thousand-kernel weight, biomass production, and grain yield. The superior varieties were well adapted and had good productivity due to effective assimilate transformation into grain yield. Also, in Southern Ethiopia, Biramo *et al.* (2023) identified significant variations between varieties in productive tillering ability, spike characteristics, grain weight, harvest index, and grain yield. High-yielding varieties were more efficient and had better reproductive performance.

Belete (2023) in Southwestern Ethiopia indicated significant genotype and genotype-by-environment interaction for yield and its related characters. Some varieties were characterized by stable and high- yield performance. Field trials conducted in the Buno Bedele Zone also supported the superiority of improved varieties over the local checks. Significant differences were recorded in relation to yield, biomass, and other agronomic characteristics, where the improved varieties scored higher due to their superior tillering capacity and grain filling. In the North Shewa Zone, Geleta (2022) selected genotypes with yield potential and environmental adaptability as well. In addition, the results indicated the existence of variety adaptation specificity and wide adaptability, which further proved genotype-by-environment interaction

2.5. Effects of Seed Rate on Growth and Yield of Food Barley

The amount of seeds planted (seed rate) is one of the key factors in agricultural practice that dictates plant population, inter-plant competition, canopy development, and ultimately grain yield of food barley (*Hordeum vulgare* L.). In the Ethiopian highland agro-ecosystems, where

precipitation levels are erratic and soil fertility is poor, the optimum seed rate is essential for ensuring proper tillering and resource use. In many empirical studies conducted , it has been found that seed rate significantly influences the growth and yield of barley crops. For example, according to Biruk *et al.* (2022), increasing the seed rate from 80 kg ha^{-1} to 120 kg ha^{-1} significantly improved the yield and biomass of food barley in South Ethiopia, where the highest grain yield (4481 kg ha^{-1}) was recorded at 120 kg ha^{-1} due to increased spike density per unit area, even with fewer tillers per plant.

From a physiological perspective, a higher seeding rate would mean faster canopy cover and increased LAI, resulting in better radiation capture and weed competitiveness. However, excessive plant density beyond the optimum value leads to competition among plants for nutrients, water, and radiation; as a result, lower tillering capacity, spike fertility, and grain size will be achieved (Biruk *et al.*, 2022).This observation corresponds with the widespread quadratic response of barley grain yield to seeding rate, characterized by increasing yields within an optimum density range, followed by a decrease due to lack of assimilates during grain filling.

The genotypes of barley characterized by high tillering capacity usually respond well to lower levels of seeding density due to compensating tillering capacity, while the weak-tillering types require higher seeding rates to obtain the optimum number of spikes per square meter (Tolesa *et al.*, 2019).In the case of improved soil fertility levels, reduced seed rates can suffice because of better productivity of the tillers. However, when dealing with marginal soil or water-stressed environments, increased seed rates are needed for plant stand establishment (Ayalew *et al.*, 2020; Biruk *et al*., 2022). Altogether, literature reveals that intermediate seed rates (100-120 Kg ha^{1} in rainfed Ethiopian highlands) optimize the ratio between plant density and the productivity of plants and lead to maximum grain yield (Biruk *et al*., 2022)

2.5.1. Concept and Importance of Seed Rate

Seed rate is an important agronomic input since it influences plant stand density, plant spatial arrangement, and early canopy development, which ultimately affect the growth, development, and yield of barley. In the Ethiopian Highlands, the seed rate is one of the most important variables due to the variability of rainfall, the limitation of soil fertility, and the dominance of rainfed production systems.

The reason behind the significance of seed rate is that it regulates competition and tillering. An adequate seed rate will lead to early canopy cover that improves radiation interception and eliminates weed competition, hence crop vigor and establishment. However, higher seed rates can increase intra-specific competition, which reduces tiller survival, spike fertility, and grain size, while lower seed rates lead to poor stand density and spike count per unit area. This trade-off of yield is based on the general notion that barley yield in the field is more closely correlated with plant population effectiveness rather than individual plant performance (Biruk *et al.,* 2022).

Physiologically the optimal seed rate promotes early leaf area index growth, thereby facilitating a more efficient use of light energy and faster establishment of ground cover. This can lead to better water-use efficiency by minimizing soil evaporation losses. However, exceeding the optimal limit, a too-high plant density results in stress due to competition, reduced assimilate availability during the grain-filling stage, and finally, a poor harvest index. This underlies the commonly found quadratic relationship between seed rate and grain yield in barley production in Ethiopia (Tolesa *et al.,* 2019).

Highly tillering barley varieties require lower seed rates due to their compensatory tillering capability, while low-tillering varieties need higher seed rates to ensure proper spike density (Ayalew *et al*., 2020; Biruk *et al.,* 2022). Thus, seed rate is one of the important biological and managerial factors that play a major role in interaction with genotype and environment, becoming an integral part of site-specific agronomic practices for sustainable barley production in Ethiopia.

2.5.2. Influence of Seed Rate on Crop Establishment and Plant Population

Seed rate plays a crucial role in establishing a proper plant stand, determining plant population density in barley-growing systems. It affects the number of seedlings established in the area, as well as early plant stands and the nature of plant competition in the fields. The process of establishment depends on achieving the required plant population density necessary for the effective acquisition of resources during the initial growing period. An adequate seed rate increases the chances of obtaining even germination and faster coverage of the area, which promotes better light interception at the initial stage and reduces soil moisture evaporation (Biruk *et al.,* 2022).

Experiments carried out in the Ethiopian highlands have shown that seed rate positively affects field emergence and plant stand up to a certain point (Biruk *et al.*, 2022). This is attributed to the fact that there is always a biological balance between securing enough seedlings and ensuring that intra-specific competition is not too high among the growing plants. The density of plants is a direct function of seed rate, germination rate, and seedling survival rate. High seed rates tend to produce high plant density per square meter; however, the relationship is not necessarily linear, as it is subject to the density dependence of death.

With high seed rates, the struggle for limited resources such as water and nutrients becomes more intense, and seedlings become less vigorous, resulting in the early deaths of plants. Alternatively, low seed rates give rise to poor plant densities, leaving some soil resources unused, thus exposing the fields to weed invasion and consequently lower yields. The empirical studies on Ethiopian barley confirm this (Tolesa *et al*., 2019).

Physiologically, the optimal plant population obtained using an appropriate seeding rate promotes good canopy structure and leaf area development earlier, thus improving radiation efficiency at the crucial vegetative stage. High density, which is obtained through high seed rates, adversely affects the survival rate of tillers and causes inter-crop shading, thus affecting the structural strength of the stem and spike production per plant (Ayalew *et al*., 2020). This shows how important the plant population is to yield more than the plant.

The condition of soil fertility, the availability of moisture , and the condition of the seedbed are important factors that affect establishment. Under conditions of poor soil fertility and moisture content, a higher seed rate may be needed to offset expected establishment losses, while a lower seed rate is sufficient to obtain an optimal plant population in well-fertilized soil with adequate moisture (Biruk *et al.*, 2022; Ayalew *et al*., 2020).

In general, the seed rate is one of the major agronomic inputs influencing the efficiency of crop establishment and the resultant plant population structure in barley. The optimization of this parameter allows for ensuring good plant stand density, preventing yield losses associated with poor crop establishment, and enhancing the efficient use of available resources. The seed rate is the main parameter determining the initial plant population density and crop stand homogeneity. The higher seed rate usually increases the number of emerged plants per unit area, thus ensuring better ground coverage and less weed competition.

However, besides the seed rate itself, germination and emergence are affected by such factors as seed quality, soil moisture content, and seeding depth. It is worth noting that Ethiopian barley cultivation systems demonstrate the positive impact of optimum seed rate on the percentage of field emergence and the number of plants necessary to reach maximum yield (Abebe *et al.,* 2023). Lower seed rates usually cause poor stands, more weed infestations, and inefficient resource capture. Empirical evidence shows that plant population density strongly correlates with final spike density, which is a major determinant of grain yield in barley-based systems (Derbew *et al.,* 2023)

2.5.3. Effects of Seed Rate on Phenology and Growth Parameters

The right seed rate leads to proper plant population and utilization of available environmental resources. An increased seed rate usually causes higher inter-plant competition, resulting in early heading and maturity. A lower seed rate causes an extension in the vegetative phase because of the reduced inter-plant competition (Bekele *et al*., 2020). In southeastern Ethiopia, Bekele *et al.* (2020) found that increased seeding rates led to decreased days to heading and physiological maturity of malt barley varieties. These changes were attributed to heightened plant competition and resultant reproductive development acceleration. Similarly, Bayisa *et al.* (2024) observed the strong dependence of crop density and phenological characteristics on each other, implying that higher plant populations contributed to accelerated heading and maturity because of the increased competition.

The variety used also plays an important role in the effect of the seed rate on phenology. Specifically, Tolesa *et al.* (2019) indicated that barley varieties vary in their responsiveness to plant population density because of differences in growth habit, tillering ability, and resource use efficiency. Therefore, the optimal seed rate should be established depending on varietal traits and the local agro-ecological environment.

Plant height depends greatly on the seed rate due to the effect of the latter on light interception and canopy structure. With the increase in seed rate, competition for light becomes more intense, thus contributing to stem elongation and height increment (Bekele *et al*., 2020). From the studies carried out by Bekele *et al*. (2020), it is clear that there is an increase in the height of malt barley as the seed rates increase. The increase in the height of the plants resulted from the shade avoidance reactions caused by competition for sunlight. The same results were reported by Kebede (2024), who stated that increasing the density of plants increases the stem elongation of barley in Ethiopia's highlands.

However, very high seed rates may increase the risk of lodging because of excessive stem elongation and weakness of stems (Bayisa *et al.*, 2024). Hence, it is important to determine the optimal seed rates that provide desirable plant heights without causing the risk of lodging.Tillering is among the most important yield components in barley because productive tillers play a role in spike formation. Tillering is highly influenced by seed rates through the effect of plant density. The number of tillers per plant is higher at low seed rates compared to high seed rates due to the availability of growth resources to each plant (Tolesa *et al*., 2019).

According to Bekele *et al.* (2020), the number of productive tillers per plant decreased significantly with increasing seed rate from low to high values. Likewise, Tolesa *et al*. (2019) observed that the barley plants cultivated with low seed rates recorded more tillers per plant compared to those with high seed rates. Even though the number of tillers per plant may be reduced, the total tillers per unit area might increase at high seed rates due to high plant establishment (Bayisa *et al*., 2024). The effects of seed rates include canopy development, leaf area index (LAI), and dry matter production. High seed rates improve canopy closure and leaf area index, resulting in light interception and reduced weed growth (Assefa *et al*., 2021).

Increased canopy development helps enhance the total dry matter production in the vegetative growth phase. However, excessive plant numbers might lead to mutual shading within the canopy and decrease the photosynthesis process as well as dry matter accumulation per plant (Bayisa *et al.,* 2024). As explained by Tolesa *et al.* (2019), optimal seed rates ensure good canopy formation and biomass production while minimizing the negative impacts of inter-plant competition.

Overall, barley seed responses to seed rate can differ significantly among various varieties because of the varying genetics of each variety. High-tillering barley varieties usually respond positively to low seed rates, whereas barley varieties with poor tillering capacities need relatively high seed rates to reach an optimum plant number (Tolesa *et al*., 2019). Significant variety by seed rate interactions have been found in some of the growth parameters of barley, such as plant height, tiller formation, biomass production, and grain yield, in studies conducted in western Ethiopia (Tolesa *et al.,* 2019). Likewise, Bekele *et al.* (2020) observed significant variety × seed rate interactions in the growth parameters of malt barley. The seed rate has a substantial impact on phenology and growth characteristics of food barley.

2.5.4. Effects of Seed Rate on Yield Components and Grain Yield

Productive tillers are one of the main yield components in barley because each productive tiller produces a spike. The number of productive tillers per plant is highly influenced by the seed rate because seed rate determines the density of the plants. Lower seed rates are favorable for tillering due to less competition for light, moisture, nutrients, and space. On the other hand, higher seed rates inhibit tiller development due to competition (Gezahegn *et al.*, 2022). According to Tolesa *et al.* (2019), significant interaction effects of barley variety and seeding rates were found on total tiller numbers and effective tiller numbers.

While the tiller number per plant declined as the seeding rate increased, the total number of productive tillers per hectare would increase to a maximum population density, after which the competition becomes too high for productive tillers. It follows that the optimum seed rate ensures proper production of tillers and proper population of plants to obtain optimum spike density.

Spike length is a key yield component, as long spikes contain a large number of florets and grains. The seed rate affects spike length through competition for assimilates and nutrients. At low plant density, barley plants have plenty of space to grow and develop, and the spike lengths become longer. On the other hand, higher seed rates cause spikes to shorten (Mekonnen, 2018). Field experiments in western Ethiopia have shown that spike length is greatly influenced by seed rate, whereby a reduction in seed rate results in longer spike lengths when compared with very high planting rates (Tolesa *et al*., 2019). Shortened spike lengths at high seed rates are usually caused by a lack of sufficient assimilate.

Grain numbers per spike play an important role in determining grain yield and are highly influenced by environmental factors and management strategies. Seed rate influences grain numbers via its effects on spike formation and assimilate partitioning. Low seed rates usually promote grain production due to increased nutrient availability and more exposure to photosynthetic light. On the other hand, higher plant populations promote competition and decrease the survival of flowers, thus decreasing grains per spike (Gezahegn *et al.*, 2022).

Significant interactions have been identified by Tolesa *et al.* (2019) between barley varieties and seed rates on grains per spike. The thousand-kernel weight (TKW) determines the size of the grain and the efficiency of grain filling and is regarded as one of the most stable yield components. However, seed rate can affect TKW due to competition-related consequences of

assimilate supply during grain filling. High seed rates tend to reduce grain weight due to increased competition for nutrients, water, and assimilates during the reproductive stage (Mekonnen, 2018).

According to Tolesa *et al.* (2019), who conducted research in the Elfeta District, the thousand-seed weight was considerably reduced at high seed rates. The reduction in grain weight was attributed to the increase in plant density that led to a reduction in the assimilate supply and its translocation to the grains. Likewise, Gezahegn *et al*. (2022) found that grain weight was higher at moderate seed rates compared to high plant density.

The biomass yield of plants depends on the density of plants per unit area and the development of the canopy. An increase in the seed rate increases the biomass accumulation until the optimal stage since the increased plants add to dry matter production. Beyond the optimal point, competition negatively affects growth and reduces biomass accumulation (Assefa *et al.,* 2021). Similarly, the harvest index, which refers to the fraction of total biomass that goes to grains, is dependent on seed rate. An intermediate value of seed rate improves the harvest index through a balance of vegetative and reproductive growth. An excessive value of seed rate may decrease the harvest index since increased competition favors vegetative growth at the expense of grain filling (Tolesa *et al.,* 2019).

The grain yield of crops is the net result of the interactions of yield components and the environment. Barley grain yield as a function of seed rate is mostly in quadratic form, whereby an increase in seed rate increases grain yield until the optimal value and then decreases thereafter due to excessive competition (Gezahegn *et al*., 2022). According to Tolesa *et al.* (2019), there was a significant interaction between variety and seed rate in relation to the grain yield of food barley. The treatment that gave the highest grain yield among those assessed was the use of variety HB 19/66 and a seed rate of 125 kg ha^{-1}, which yielded 6.23 t ha^{-1}. The authors suggested that the optimum seed rate increases yield by enhancing spike density, the number of productive tillers, and efficient utilization of resources.

2.5.5. Recommended Seed Rates for Food Barley in Ethiopia

The determination of the optimal seed rate is important since a low plant population hampers the efficient use of available resources, while high plant densities lead to increased competition among plants for water, nutrients, sunlight, and growth. However, based on

recent scientific studies carried out over the last decade, optimal seed rates are usually lower than those used by farmers and need to be adjusted depending on varietal characteristics and environment (Gezahegn *et al*., 2022).

According to Tolesa *et al.* (2019), who conducted the study in West Shoa of the Oromia Region, found that the highest grain yield (6.23 t ha^{-1}) and economic return were attained at a seeding rate of 125 kg ha^{-1} by variety HB-19/66. According to the research, 125 kg ha^{-1} was found to be the most economical and agronomically efficient seeding rate for the area. Similarly, Gezahegn *et al*. (2022), in their study in Semen Ari Woreda of Southern Ethiopia, assessed the effects of seeding rates of 80, 100, and 120 kg ha^{-1} on the production of food barley and found that the best grain and biomass yields were realized at a seeding rate of 120 kg ha^{-1} with proper row spacing. Similarly, a study carried out by Bereket Tagesse (2022) on the effect of seed rate on yield and yield components of food barley varieties in the Duna District of Southern Ethiopia demonstrated that moderate seed rates between 100 and 125 kg ha^{-1} resulted in better grain yields than low or high plant population densities.

From the study, it is evident that the optimum seed rates increase resource use and reduce competition among the crops. Finally, the national recommendations for the production of barley varieties have been encouraging the use of moderate seed rates for barley production. According to the Ethiopian national seed database, various released food barley varieties, including EH 1493/F6.32H.3, are recommended at 125 kg ha^{-1} under highland production systems. However, although general guidelines are available, seed rates are dependent on varieties owing to variations in tillering ability, plant type, seed size, and adaptation. As such, generalized guidelines may not fit all production systems (Tolesa *et al*., 2019). Additionally, environmental conditions have a significant impact on seed rate requirements. In areas with sufficient rainfall and fertile soils, relatively high plant populations can be sustained; otherwise, where moisture is limiting, reduced seed rates would be considered to reduce competition for water and other essential nutrients.

Location-specific and variety-specific guidelines are therefore gaining importance in Ethiopian barley breeding programs (Gezahegn *et al.,* 2022). In summary, the results of recent studies carried out in Ethiopia show that seed rates recommended for food barley are between 100 and 125 kg ha^{-1}, where 125 kg ha^{-1} appears to be the most common optimum rate under many highland production areas. Nonetheless, the true optimum seed rate will

depend on the variety, agroecological conditions, soil fertility levels, and cultivation practices.

2.6. Interaction Effects of Variety and Seed Rate on Food Barley Performance

From an agronomic perspective, seed rate influences plant density, resource-use efficiency, and yield formation. However, barley genotypes respond differently to seed rate because they vary in tillering ability, growth habit, nutrient-use efficiency, canopy structure, and environmental adaptation. Consequently, strong genotype × seed rate interactions commonly occur for growth, phenology, yield components, and grain yield (Tolesa *et al.,* 2019). This interaction is important for determining the optimal plant population per unit area, since high-tillering genotypes compensate for low plant populations by forming additional productive tillers, whereas low-tillering genotypes require relatively higher seed rates to achieve the optimal number of spikes per unit area. Thus, it is important to identify the most suitable genotype × seed rate combinations to optimize productivity and resource-use efficiency (Gezahegn *et al.,* 2022). Accordingly, variety-specific seed rates have been identified as an important approach to boost food barley production in Ethiopia's highlands (Tolesa *et al.,* 2019; Shimelis *et al.,* 2022).

2.6.1. Theoretical Basis of Variety and Seed Rate Interaction

The theory underlying the variety-by-seed-rate interaction is based on the concept that crop production is due to genotype-by-management interaction. There are differences in the genotypes of barley varieties in terms of growth rate, tillering ability, leaf angle, biomass production, maturation time, and assimilate allocation. The genotype of the varieties determines their responsiveness to changes in plant population density (Tolesa *et al.,* 2019). Plant population density is one of the factors that affect competition for light, water, nutrients, and space availability. As the plant population increases, there is increased competition, and this will change how the plants grow and develop.

Plants respond differently to competition; genotypes that have high tillering ability can maintain optimal spike density at lower seed rates than those with poor tillering ability (Gezahegn *et al.,* 2022). Variety × seed rate interaction is associated with physiological factors such as the efficiency of photosynthesis, canopy formation, uptake of nutrients, and partitioning of dry matter. This interaction arises due to differences among the varieties in terms of their ability to utilize resources depending on the degree of competition. As such, the

optimal seed rate of any variety will depend on the genetic capability of the variety in terms of vegetative and reproductive growth within certain environmental conditions (Shimelis *et al.*, 2022). **2.6.2. 2.6.2 Effects on Phenological and Growth Traits**

Interactions between variety and seed rate affect phenological attributes like days to heading, flowering, grain filling period, and physiological maturity of the crop. There are genetic differences in growth rates within barley varieties. The response of barley to different seed rates is modified by the growth rates of the genotypes (Tolesa *et al*., 2019). The barley genotypes that exhibit vigorous early growth and efficient resource use show a low response to different seed rates regarding heading and maturity dates. On the other hand, the genotypes that are not as vigorous can show high variations in their phenology according to increases in plant density. This indicates that the effects of seed rates on barley must be considered based on genotype and density.

There are interactions between variety and seed rate on growth characteristics as well. The growth of barley, such as height, tillering, leaf area expansion, and dry matter accumulation, depends on genotype and plant density. High seed rates cause increased height due to competition for light, which results in the elongation of the stem. However, the extent of stem elongation differs between barley genotypes (Gezahegn *et al*., 2022). The variety × seeding rate interaction is especially notable in tillering. High tillering varieties have enough productive tillers even at lower densities, while low tillering varieties need higher densities to compensate for low tiller production. As a result, high interactions are often noted in tiller number, biomass production, and canopy development in Ethiopian barley cultivation systems (Tolesa *et al*., 2019). In general, the variety × seeding rate interaction impacts crop growth through its effect on resource capture, canopy architecture, and dry matter production.

2.6.3. Effects on Yield Components and Grain Yield

Yield components are the key factors that determine the yield of grains and are affected by variety and seed rate interaction to a large extent. Productive tillers per plant, spike length, grain number per spike, thousand-kernel weight, biomass yield, and harvest index may show variable responses for different varieties depending upon plant populations (Tolesa *et al.*, 2019). Productive tiller number plays a pivotal role because it serves as a compensation strategy in barley. Varieties with a high tiller number compensate for the effect of lower plant populations with their higher tiller count, while low tiller varieties require a higher seed rate

to achieve optimum spike density. Thus, the response of productive tillers to seed rate is quite variable among barley varieties (Gezahegn *et al*., 2022).

Similarly, grain number per spike and thousand-kernel weight depend on competition for assimilation during the reproductive phase. A high plant population tends to decrease grain-filling efficiency and kernel weight due to the competition for nutrients and water. However, some varieties exhibit high tolerance to competition and demonstrate better grain-filling capacity at high plant populations. Therefore, significant variety × seed rate interactions exist for yield-related traits (Shimelis *et al.*, 2022). Grain yield is the outcome of these yield components acting together. The seed rate increases up to its optimal point, grain yield tends to increase. After this optimal point, it begins to decrease because competition becomes greater than the crop's compensatory capability. Since each genotype has different capabilities for utilizing resources and compensating for population changes, the optimal seed rate varies from one variety to another (Tolesa *et al*., 2019). Thus, achieving high grain yields necessitates determining the appropriate variety and seed rate combination for productive tillers, grains per plant, and weight of the grains.

2.6.4. Previous Studies on Variety × Seed Rate Interaction in Ethiopia

There are not many studies conducted on variety and seed rate interaction in Ethiopia, but all the studies done in the past have proven the significance of variety × seed rate interaction in food barley production. One of the most extensive studies conducted so far is the study by Tolesa *et al*. (2019) in the Elfeta District of the West Shoa Zone in the Oromia Region. The field experiment involved testing four food barley varieties at four seed rates (75, 100, 125, and 150 kg ha^{-1}). The significant interaction effects were observed for productive tillers, grains per spike, biomass yield, straw yield, and grain yield. The highest grain yield (6.23 t ha^{-1}) was recorded for variety HB-19/66 at a seed rate of 125 kg ha^{-1}, proving that the performance of the variety depends significantly on the plant population density.

Gezahegn *et al*. (2022) studied the effects of seed rate and row spacing on food barley production in southern Ethiopia and found that different varieties of food barley respond differently to plant population. It is therefore important to determine the optimum seed rates depending on the variety. In a similar vein, Shimelis *et al*. (2022) found considerable variations among food barley genotypes for growth characters, yield attributes, and grain yield under various agronomic management practices.

Even though the study was conducted on levels of fertilization, the results clearly emphasized the idea of genotype × management interaction and showed that varietal behavior is heavily affected by agronomic practices. Recent investigations conducted on barley improvement in Ethiopia have shown considerable genotypic variability for phenology, growth, and yield attributes of released food barley genotypes (Nbiret *et al*., 2024). This shows that different varieties need specific agronomic management practices, including seed rate recommendations. Altogether, studies conducted in Ethiopia reveal that the interaction between variety and seed rate plays an important role in phenology, growth and development, yield components, and grain yield. The results suggest the necessity for site and variety-specific seed rate recommendations to improve productivity and efficiency in the production process.

2.7. Economic Analysis of Agronomic Practices in Food Barley Production

The study of economics is crucial in agronomy since the main aim of agronomic technologies is not just to increase biological yield but also to enhance the profitability of farms. In the cultivation of food barley (*Hordeum vulgare* L.*)*, farmers decide their management strategies based on the economic returns that can be gained from the use of improved varieties, planting densities, fertilizer application rates, and other agronomic technologies. Hence, the recommendations from agronomic studies must be supplemented with evidence of economic returns indicating that more investments bring adequate returns to farmers (Assefa *et al.,* 2021; Biramo *et al*., 2023).

Various agronomic and economic studies conducted in Ethiopia to improve barley cultivars have revealed considerable differences among cultivars and agronomic technologies in terms of yield and economic returns. However, the agronomic treatment with the highest yield does not necessarily generate the highest profit since the cost of production differs among the different treatments. Hence, economic analysis is necessary to select agronomic technologies that maximize net benefits while reducing risks of production (Tolesa *et al*., 2019).

Economic assessment helps in making a decision on whether the additional return from a particular treatment makes sense economically (Biramo *et al.,* 2023). The economic evaluation techniques designed by the CIMMYT are frequently applied in Ethiopian agricultural experiments. These methods, especially partial budgeting and marginal rate of

return analysis, offer useful instruments for the examination of the profitability of different agricultural techniques (CIMMYT, 1988).

2.7.1. Concepts of Economic Feasibility Analysis

Feasibility analysis in terms of economics means the analysis of the profitability and sustainability of a technology from an economic perspective under the conditions of farmers. The key goal is to find out whether the gains are higher than the costs and to motivate the adoption of the technology (CIMMYT, 1988).In agronomic research, feasibility is usually analyzed in relation to gross field benefit, total variable cost, net benefit, and benefit-cost relationship. Gross field benefit is the monetary value of the yield from a treatment, whereas the total variable cost entails the costs of items that vary between treatments. These include seed cost, fertilizer cost, labor cost, and agro-chemical cost. Net benefit equals the difference between gross field benefit and total variable cost (CIMMYT, 1988).It is worth noting that economic feasibility analysis plays a vital role in the analysis of varieties and seed rates, considering that various types of crops have different capacities in terms of yielding and response to plant population densities. Similarly, an increase in seed rates may help in increasing yields; however, such actions would entail increases in the cost of production. Technologies must thus be assessed both in terms of their effectiveness and profitability (Tolesa *et al.*, 2019). According to Biramo *et al*. (2023), economically viable technologies are those that provide better net gains in relation to the costs involved.

2.7.2. Partial Budget Analysis

Partial budgeting is a type of economic assessment tool that can be applied to determine the financial impacts of adopting a new agricultural technology or altering a farming practice. This method is concerned solely with the differential costs and benefits between treatment alternatives and ignores fixed costs that do not vary from one treatment alternative to another (CIMMYT, 1988). The technique is widely adopted in agricultural research due to its simple approach to comparing different technologies. According to CIMMYT (1988), partial budgeting entails estimating adjusted yield, gross field benefit, total variable cost, and net benefit. Yield obtained through experimentation is usually adjusted by about 10%. Calculation of gross field benefit entails the multiplication of adjusted grain yield and the prevailing market price of grains. On the other hand, total variable cost includes all expenses for each treatment, including seed expense based on various seed rates and labor cost of crop management. The formula for calculating net benefit is:

NB=GFB−TVC

Where:

NB = Net Benefit;

GFB = Gross Field Benefit; and

TVC = Total Variable Cost.

Partial budget analysis thus offers a better ground for technology recommendations compared to agronomic performance alone. The current studies of barley in Ethiopia have highlighted the significance of economic evaluation in addition to agronomic assessment (Biramo *et al*., 2023).

2.7.3. Marginal Rate of Return Analysis

Marginal Rate of Return (MMR) indicates the percentage rate of return gained from each extra investment in going from a low-cost to a high-cost treatment (CIMMYT, 1988). The treatments should be sorted in ascending order with respect to the total variable cost before the calculation of MRR; dominance analysis is performed to discard the economically non-preferable treatments. A treatment will be dominated by another treatment if it gains less net benefit than another treatment with a lower cost (CIMMYT, 1988). The marginal rate of return is calculated using the following formula: MRR(%) = Δ NB / ΔTVC × 100, where: ΔNB = Change in Net Benefit; and ΔTVC = Change in Total Variable Cost. This percentage represents the return obtained per unit increase in spending. For instance, an MRR of 100 percent means that every extra Birr of spending brings one more Birr in addition to compensating for the initial spending. As suggested by CIMMYT (1988), technologies that are recommended for farmers need to attain at least an MRR of 50-100 percent to account for the risks and uncertainties of production. For barley-based production systems, the MRR assessment is important to see if additional seed rates or variety improvements bring enough additional advantages to offset additional costs.

2.7.4. Economic Evaluation of Variety and Seed Rate Technologies

Economic assessment of variety and seed rate technology includes the analysis of the economic viability and efficiency of different combinations of genotypes and management. As the variety and seed rate have a significant impact on yield, production costs, and resource use efficiency, their economic performance needs to be assessed simultaneously (Tolesa *et*

al., 2019). Although a high seed rate increases yield and plant establishment, the high seed cost reduces its economic efficiency (Dobocha *et al*., 2020). Economic assessment includes both agronomic and economic factors to identify treatments that can bring about maximum profits. In factorial experiments with varieties and seeding rates, the treatment that results in maximum grain yields does not always yield maximum profit. Studies carried out in different barley-producing regions in Ethiopia have shown significant differences in economics between varieties and management practices; thus, there is a need for the integration of agronomic and economic assessments when recommending technologies (Assefa *et al*., 2021; Biramo *et al.*, 2023).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

The experiment was carried out at the experimental site in the Diga district, which is found in the East Wollega Zone of the western part of Ethiopia, at the end of July of the main cropping season of 2025. This site is located 343 kilometres away from Addis Ababa, which is 12 kilometres away from Nekemte Town, and has an elevation of 2190 meters to 2390 meters above sea level. Based on geographical location, the research was carried out geographically between latitude 8^0 56′-$9^0$10′ N and longitude 36°30′-37°04′E . The mean annual temperature was 19.1°C and the mean annual rainfall was 1357.1 mm. Diga District comprises lowland and midland (60% each) agro-ecologies (Sori & Wana, 2019). This area receives rainfall through a bimodal rainfall system, which means that there are two rainy seasons : the Belg, which is the short rainy season between February and May, and Meher, which is the long rainy season between June and September. The soils available within this region include Vertisols and Nitosols. In terms of crop production, cultivation is largely done using rainwater, with the main cereal crops being Tef, wheat, maize, and barley. Other common crops produced in this area include cash crops such as sesame and groundnut (Moisa *et al*., 2022).

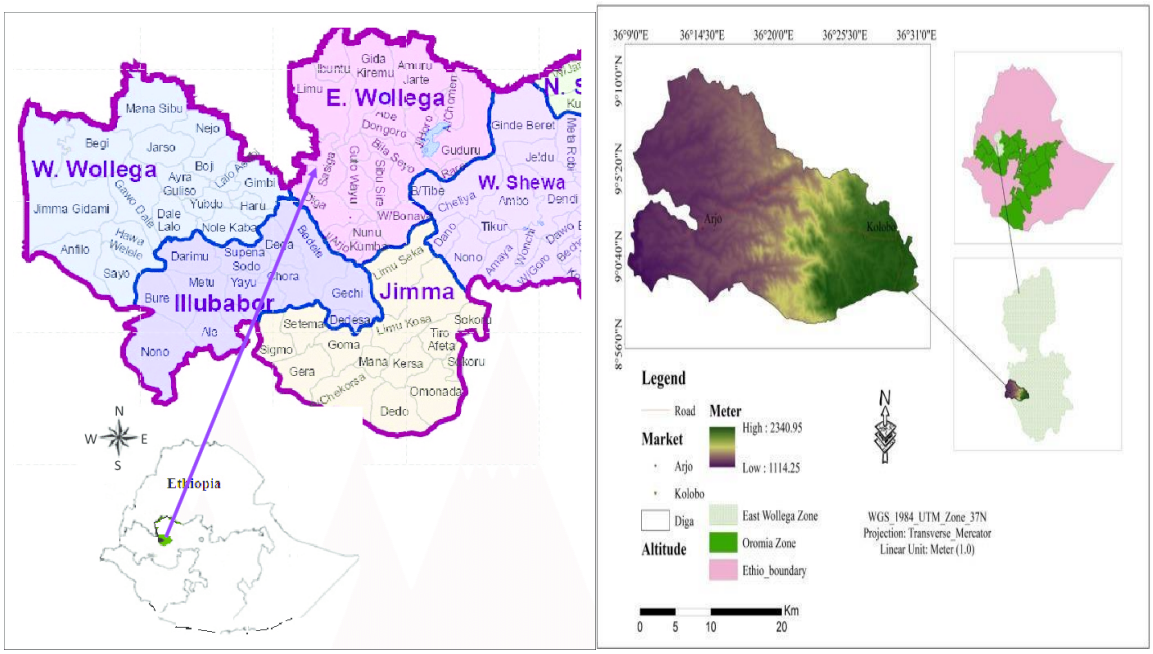


Figure 1. Map of the study area.

Source: (Tafese *et al.*, 2012)

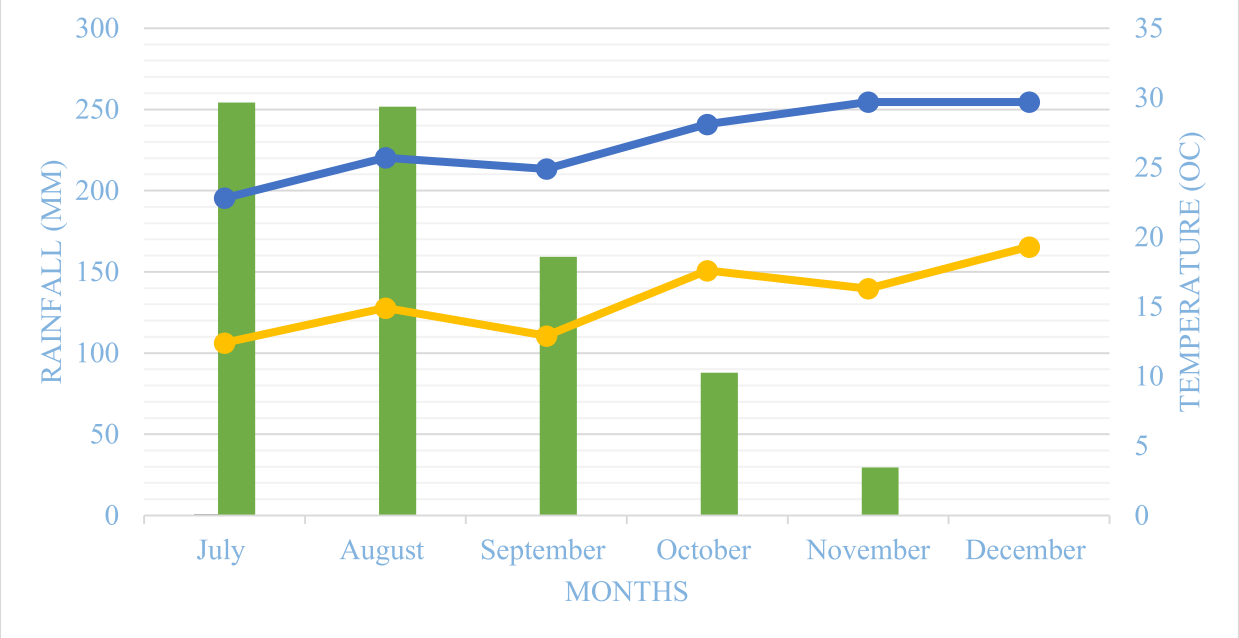


Figure 2. Monthly rainfall (mm) and monthly mean maximum and minimum temperatures (°C) of the experimental site during the 2025 cropping season

Source: Nekemte Meteorological Observatory through Ethiopian National Meteorology Agency

3.2 Experimental Materials

3.2.1. Plant and fertilizer materials

Improved food barley varieties, namely, HB 1307, HB 1966, and Jobira, obtained from the Holota Agricultural Research Center (HARC), and one local variety. A detailed description of the food barley varieties used in this research is presented in Table 1. Blended NPS and urea fertilizer were obtained from the Diga Agriculture and Rural Development office and applied uniformly to the experiment.

Table 1. Descriptions of Food barley Varieties used for the experiment**.**

Varieties	Breeder	Released year	Adaption area Altitude (m)	Rainfall (mm)	Maturity Date	Yield in tons/ha	
						RC	FF
HB 1307	HARC	2006	2000-3000	700–1000	119–145	3.5-5.0	2.5–3.5
HB 1966	HARC	2017	2300–3000	750–1500	130–140	3.6	2.5–3.5
Jobira	HARC	2024	2300–3000	750–1500	131	3.3-7.4	2.5-3.3
Local	Farmers selection	–	2000–3000	700–1000	110–130	25–32	1.5–2.0

Source: (Ethiopian crop variety register book 2006, 2017, and 2024); HARC = Holota Agricultural Research Center; RC = Research center; FF = Farmers' fields.

The same fertilizer management approach was followed in all experiments with the application of 100 kg NPS fertilizer (18-38-7.5) per hectare and 75 kg nitrogen per hectare from urea, following fertilizer management strategies commonly used for barley growing in Ethiopia (Habte *et al*., 2021). All NPS fertilizer and one-third of the nitrogen from urea were placed in the same row as the seeds at planting, while the other two-thirds were top-dressed at the tillering stage to increase the efficiency of nitrogen utilization and yield (Habte *et al.,* 2021; Chemeda *et al.,* 2024).

3.3. Experimental Treatments and Design

The treatments comprised four food barleyvarieties (HB1307, HB1966, Jobira, and Local variety), and four seed rates (75, 100, 125, and 150 kg/ha) with a total of sixteen treatment combinations. The experiment was laid out as a randomized complete block design with a factorial arrangement with three replications. Individual plots were prepared with a size of 3m long and a width of 2 m (6 m^2) by keeping 0.5 m and 1.5 m paths between plots and blocks, respectively. The total gross area required was 55.5 m x 9 m (499.5 m2), and treatments were assigned to each plot randomly. The outer row from each side and the plant at 20 cm of each row were considered a border row with edge effects and not considered for collecting data. Food barley was sown at 20 cm between rows using a hand drill, and each plot consisted of 10 rows. The yield data were collected from the eight central rows with a net plot size of 1.6m x 2.6m (4.16 m^2).

3.4. Experimental Procedures and Field Management

The experimental field was ploughed using the plough drawn by oxen into a fine tilth state thrice and allowed to rest for three weeks. The experimental field layout was designed and leveled along the gradient. In the last week of July 2025, seeds of food barley were hand drilled based on the prescribed rates indicated in the treatments and experimental design above. In order to minimize nitrogen losses, urea at 75 kg/ha was uniformly applied to all plots in two splits of $1/3^{rd}$ at sowing and the remaining $2/3^{rd}$ at full tillering, while the full dose of NPS at 100 kg/ha was applied at sowing and was then covered with soil. All the cultural practices, including weeding and other management, were done uniformly in all plots as per the recommendations.

3.5. Data Collection and Measurements

3.4.1. Crop phenology and growth parameters

Days to 50% emergence : - It was visually recorded as the number of days from the date of sowing to date when 50% of the plant in each plot emerged.

Days to 50% heading: - It was visually recorded as the number of days from the date of planting to the date when 50% of the plant population in each plot produced flowers.

Days to 90% physiological maturity: It was visually determined as the number of days from the time of sowing to the time when 90% of the plants in each of the plots turned yellow and

no green color remained on the glumes, and grains became hard and difficult to break with a thumbnail.

Plant height: It was measured from 10 randomly selected plants of each net plot area at physiological maturity from the ground level at the base of the stem to the tip of spikes (awns excluded) with the aid of a handheld meter and was expressed on a per-plant basis.

Total number of tillers per plant: It was determined by counting the number of tillers from the main stem of 10 randomly selected plants of each net plot area at the full tillering stage, and then the mean was determined per plant.

3.4.2. Yield components and yield parameters

Number of productive tillers per plant: It was determined by counting all spike-bearing tillers from 10 randomly selected main stems of each net plot area at physiological maturity, and then the mean was calculated per plant.

Spike length : It was measured from 10 randomly selected plants of each net plot area at physiological maturity from the bottom of the spike to the tip of the spike, excluding the awns, with the aid of a handheld meter, and the average was calculated as spike length per plant.

Number of grains per pikes: At harvest, 10 spikes were randomly taken from the main stem of each net plot, and separately threshed carefully, and the number of grains per spike was manually counted, and the average grains per spike was calculated.

Lodging percentage :- Before harvesting, the percent of lodging was evaluated visually with respect to a 1 to 5 score, where 1 (0-15^{o}) equals to no lodging; 2 (15-30^{o}) equals 25% lodging; 3 (30-45^{o}) equals 50% lodging; 4 (45-60^{o}) equals 75% lodging; and 5 (60-90^{o}) equals 100% lodging (Tesfayehu, *et al*., 2020).

Aboveground dry biomass yield: At harvesting maturity, using a hand sickle, plants in each net plot area were harvested at ground level, tied in a bundle, sun-dried for one week in a stand position until a constant weight was achieved, and then weighed using a portable digital electronic weighing balance and finally converted to kg ha^{-1} following the formula used by Alemayehu (2024).

$$\text{Biomass yield kg/ha} = \text{Biomass yield kg/net plot} \times \frac{10000\ (\text{m}^2)}{\text{Net plot size}\ (\text{m}^2)}$$

Grain yield: The dried biomass yield of each net plot was manually threshed using a hand stick, and then grain moisture content was determined immediately using a grain moisture meter. The values of each net plot moisture content were adjusted at 12.5%, standard grain moisture content, and multiplied by field weight to determine the adjusted yield of each net plot in kg ha^{-1}, following the formula used by Alemayehu (2024).

$$\text{Adjusted Yield} = \frac{\text{(Actual yield weight) x 100-measured moisture content}}{\text{100-12.5(standard grain moisture content)}}$$

$$\text{Grain yield (kg/ha)} = \text{Grain yield (kg/net plot)} \times \frac{10000\ (m^2)}{\text{Net plot size } (m^2)}$$

Straw yield: After biomass yield of each net plot was separately thrashed, the straw yield of each net plot was obtained by subtracting the grain yield from each biomass and expressed in kg ha^{-1}

Thousand-grain weight : was determined by counting 1000 grains from a bulk of thrashed grains of each net plot using a grain counter, weighing with an electric balance at 12.5% standard grain moisture content, and then the average 1000-grain weight was expressed as 1000-grain weight in grams.

Harvest index: It was computed as the ratio of grain yield to the aboveground dry biomass yield of each net plot and expressed as a percentage.

$$\text{HI (\%)} = \frac{\text{Grain yield (kg/ha)}}{\text{biomass yield (kg/ha)}} \text{x } 100$$

3.5. Statistical Data Analysis

All collected data were subjected to analysis of variance (ANOVA) using R Studio version 4.3 statistical software program. Whenever treatment effects were significant, mean comparison was done using LSD at the 5% probability level.

3.6. Partial Budget Analysis

The partial budget analysis was conducted using a partial budget approach following the procedures described by CIMMYT (1988). Prevailing market prices for inputs at planting and outputs at harvesting were used. Some necessary costs and benefits were calculated on a hectare basis and expressed in Ethiopian Birr per hectare (ETB ha^{-1}). The economic advantage of varieties and seed rate was evaluated using this partial budget framework. Only

costs that varied among treatments were considered as total variable costs (TVC). Total variable costs included seed rates cost and although the barley varieties were obtained free of charge from the research center for experimental purposes, their economic value was included to reflect realistic farmer conditions. The seed cost per hectare was calculated using a recommended seed rate of 125 kg ha^{-1} and a market price of 80 ETB/kg for each variety, indicating that 10000 ETB/125 kg, 6000 ETB/75 kg, 8000 ETB/100 kg, and 12,000 ETB/150 kg seed rates at the time of sowing. Labor costs for sowing were estimated at 50 ETB/kg seed rate, and the total labor costs for sowing were calculated according to the rates of seeds/ha, indicating that 3,750 ETB/75 kg, 5,000 ETB/100 kg, 6, 250 ETB/125 kg, and 7,500 ETB/150 kg seed rate. The market prices of food barley grain at harvesting were 85 ETB/ kg for HB1307, 78 ETB/kg for HB1966, 78 ETB/ kg for Jobira, and 75ETB/ kg for the local variety, while the straw price was 2 ETB/kg for all varieties. The total variable cost (TVC) for each treatment was computed as the sum of the costs of seeding rate and labor cost for sowing. Any treatment that has a higher TVC but a lower net benefit (NB) that is less than or equal to the preceding treatment is a dominant treatment and marked as "D". The dominance analysis illustrates that to improve farmers' income, it is important to pay attention to net benefits rather than yields because higher yields do not necessarily mean higher net benefit. Other management and fixed costs were assumed to be uniform across treatments and were therefore excluded from the analysis.

Adjusted yield (AjY): To account for the discrepancy between experimental and farmer-obtained yields under field circumstances, the average straw and grain yields (kg/ha) were lowered by 10%.

AjY = AvY– (AvY*0.1).

Gross field benefit (GFB) was computed by multiplying the farm sale price that farmers receive for straw and grain yield when they sell it as the adjusted yield.

GFB = AjY*farm sale price for straw and grain yield at harvest.

Total variable costs (TVC): The purchase cost of food barley seed rates, and labor cost of seed sowing were established by negotiation and considered to estimate total variable costs for this experiment.

Gross field benefit (GFB) (ETB ha^{-1}) was calculated by multiplying the adjusted grain and straw yield by the corresponding farm-gate price received by farmers, as follows: GFB = AGY × farm-gate price + ASY× farm-gate price.

Net benefit (NB): was calculated by subtracting the total variable costs from the gross field benefit for each treatment. NB = GFB-TVC.

The marginal rate of return (MRR %) was calculated by dividing the change in net benefit by the change in total variable costs and times by100.

$MRR(\%) = \frac{\Delta NB}{\Delta TVC} X100$, where MRR = marginal rate of return in percent, ΔNB and ΔTVC = change in net benefit and change in total variable costs, respectively, with a minimum acceptable MRR of 100% adopted for Ethiopia.

4. RESULTS AND DISCUSSION

4.1. Phenological and growth parameters

4.1.1 Days to 50% emergence

The analysis of variance showed that days to emergence did not significantly ($P \geq 0.05$) affect either by the main effects of food barley variety and seed rates (Appendix Table 1). The consistent emergence of both the local and the improved genotypes could indicate the same metabolic threshold for emergence in the absence of stress.The insignificant effect of varieties of food barley, seed rate, and their interaction on seedling emergence implies that the process of emergence depends more on factors such as seed viability, seed vigor, soil moisture, temperature, and seedbed conditions rather than genetic variation or recommended seed-rate levels. In the case of uniform conditions in the field and correct crop management practices, the improved varieties of barley have the same potential for germination and, thus, equal emergence. Thus, the interaction between variety and seed rate is not an influential factor since favorable environmental conditions contribute to the uniformity of germination in all treatments. Similar results were observed by (Tagesse 2022). Tadesse *et al*. (2022) also align the data based recommended, says that emergence had a non-significant influence on the food barley variety as well as seed rate.

Table 2. Effect of food barley variety, seed rate, and their interaction on days to emergence in Diga District during the 2025 main cropping season

Food Barley Varieties	**Days to emergence (%)**
Local	5
HB1307	5
HB1966	5
Jobira	5
LSD (0.05)	NS
Seed rate (kg/ha)	
75	5
100	5
125	5
150	5
LSD(0.05)	NS
CV (%)	18.46

LSD= list significant differences; CV= coefficient of variation; NS= non-significant

4.1.2. Days to 50% heading

Analysis of variance showed that days to heading were highly significantly affected ($P \leq 0.01$) by barley variety and seed rate, while the interaction between these factors exerted a significant influence ($P \leq 0.05$) on the trait (Appendix Table 1). Days to heading were maximum (80 days) for HB1307 at a seed rate of 75 kg ha^{-1} and minimum (66 days) for the local variety at a seed rate of 150 kg ha^{-1} (Table 3). Early heading of the local variety could have been due to the adaptation of barley landraces in Ethiopia, which head early as an

escape mechanism from terminal water stress and other adverse environmental conditions. However, the delayed heading of HB1307 indicates late maturity. Transition from the vegetative to the reproductive phase occurred rapidly with an increase in seeding rates, possibly due to increased competition for light, nutrition, moisture, and space among plants. Lower seed rates reduced such competition, thereby delaying heading. Teklemariam *et al*.(2024) observed the same trend in relation to the genetic variability as well as the ability of the genotype to adapt to the environment. Mohammed *et al.* (2024) found early heading of plants under high seed density because of increased plant competition.

4.1.3. Days to 90% physiological maturity

The analysis of variance indicated that the main effects of barley variety and seed rate, as well as their interaction, had a highly significant effect ($P \leq 0.01$) on days to maturity (Appendix Table 1).Days to physiological maturity ranged from 111 to 134 days (Table 3). Although planting HB1307 at 75 and 100kg ha^{-1} required 134 days to physiologically mature, while the local variety planted at 125 and 150kg ha^{-1} matured early (111 days) (Table 3). The local variety is an early-maturing one suitable for areas with a short rainy season; however, the high number of days to maturity in the HB1307 variety indicates its late-maturing nature. Lower inter-plant competition could be a reason for delayed maturity at lower seed rates due to the ability of plants to photosynthesize and fill their grains for a longer time. According to Tizazu (2025) on barley seed varieties and seeding rates in Central Ethiopia, where he showed varietal differences for phenological characteristics, such as days to maturity, with the variety HB1307 having a longer maturity period than the rest of the varieties that support the recorded result.

On the contrary, higher seed rates caused faster maturity due to the intense competition for light, moisture, nutrients, and space, causing leaf senescence and rapid depletion of resources. Similar findings were observed by Mohammed *et al.* (2024), who observed that low seed rates caused late maturity, whereas high seed rates caused early maturity because of more efficient use of resources. According to Bayisa *et al.* (2024), prolonged photosynthesis and grain filling could cause late physiological maturity of Ethiopian barley.

Table 3**.** Effect of food barley variety, seed rate, and their interaction on crop phenology and growth parameters of food Barley in Diga district during the 2025 main cropping season

Food Barley Varieties	**Seed rate (kg/ha)**	**Days to 50% heading**	**Days to 90%physiological maturity**	**Plant height (cm)**	**Spike length (cm)**
Local	75	68.00^{k}	112^{h}	106^{bcd}	5.40^{h}
	100	66.66^{l}	112^{g}	107^{abc}	5.36^{h}
	125	66.66^{l}	111^{g}	108^{ab}	5.06^{i}
	150	66.33^{l}	111^{g}	109^{a}	4.94^{i}
HB1307	75	80.00^{a}	134^{a}	100^{e}	8.46^{a}
	100	79.33^{b}	134^{a}	100^{e}	8.43^{a}
	125	78..66^{c}	133^{b}	101^{e}	8.40^{a}
	150	78.00^{d}	133^{b}	101^{e}	7.93^{b}
HB1966	75	75.66^{e}	132^{d}	105^{cd}	7.3^{ef}
	100	75.33^{ef}	132^{d}	106^{bcd}	7.18^{fg}
	125	75.00^{fg}	131^{c}	106^{bcd}	7.11^{g}
	150	74.66^{g}	131^{c}	107^{abc}	7.06^{g}
Jobira	75	73.00^{h}	129^{e}	89^{g}	7.64^{bc}
	100	72.33^{i}	129^{e}	90^{fg}	7.53^{cd}
	125	71.33^{j}	128^{f}	92^{f}	7.44^{cde}
	150	71.33^{j}	128^{f}	97^{ef}	7.35^{def}
LSD(0.05)		0.79	0.53	0.96	0.18
CV(%)		**0.97**	**0.38**	**0.85**	**2.32**

Means with a column followed by the same letter(s) are not significantly different at a 5% level of significance; LSD=Least Significant Difference at a 5% level; CV = Coefficient of variation.

4.1.4. Plant height (cm)

The analysis of variance indicated that plant height was highly significantly influenced ($P \leq 0.01$) by the main effects of barley variety and seed rate, as well as by their interaction, highlighting the combined contribution of genetic and management factors to variation in plant height (Appendix Table 1).

The highest plant height was recorded by the local variety at 150 kg ha^{-1}, but the shortest plant was produced when HB1307 was planted at 75 and 100 kg ha^{-1} (Table 3). Higher seed rates increase the competitive ability of the crop for sunlight, leading to greater stem elongation as a mechanism to avoid shade (Bayisa *et al*., 2024). Lower seed rates decrease competition, making stem elongation minimal and assimilation for structural development such as root and stem thickening (Mohammed *et al*., 2024). Improved varieties with shorter heights are selected to reduce lodging potential under improved agronomic practices; however, the tall stature of the local variety is a trait of Ethiopian cultivars because these usually produce long straws at very low yields (Teklemariam *et al*., 2024). Tolesa *et al*. (2019) reported a similar variation in plant height based on variety and seed rate effects.

4.1.5. Spike length (cm)

The analysis of variance indicated that the main effects of barley variety and seed rate, as well as their interaction, exerted a highly significant influence ($P \leq 0.01$) on spike length, underscoring the importance of both genetic and management factors in determining this trait (Appendix Table 1).

At 75 ,100,125,and150 kg per hectare, variety HB1307 which was longest had recorded spike lengths of 8.46 ,8.43,8.40 and 7.93 ,cm respectively. Conversely, the local variety's spikes were the shortest at 150 kg per hectare as recorded at the seed rate of 75,100,125,and 150 kg per hectare 5.40,5.36,5.06 and 4.94 cm, respectively. Spike length dropped across all varieties as the seed rate rose (Table 3). This could be because plants had to compete more for light, water, and nutrients like nitrogen and phosphorus as their numbers grew. This competition cuts down on food for spike growth during the plant's reproductive phase, making the spikes shorter. Still, HB1307 kept its spikes longer than the local variety at different seed rates, showing its better genetic ability to grow spikes. Tizazu (2025) noticed that similar higher seed rates stepped up plant rivalry and messed with growth and yield parts in food barley. Likewise, Gezahegn *et* al. (2022) and Tolesa *et* al. (2019) reported that greater plant competition reduced spike length and grain number per spike, thereby affecting overall yield performance.

The low values of the coefficient of variation (CV) found for days to 50% heading (0.97%), days to 90% physiological maturity (0.38%), plant height (0.85%), and spike length (2.32%) indicate that the experiment was conducted with high accuracy and low variation of the environment between experimental units. The low values of CV suggest that there is good

uniformity in the field, crop management, and data collection. This ensures low experimental error. As a result, the differences found between the treatment combinations are caused not by environmental variation but by the effect of food barley varieties, seed rates, and their interaction.

4.2. Yield and Yield Components

4.2.1. Number of total tillers per plant.

The analysis of variance indicated that the number of total tillers per plant was highly significantly influenced ($P \leq 0.01$) by the main effects of barley variety and seed rate, as well as by their interaction, highlighting the combined contribution of genetic and agronomic factors to variation in tillering capacity (Appendix Table 1).

The maximum number of tillers per plant was obtained from the HB1307 variety at seed rates of 75 and 100 kg ha^{-1}. This finding is consistent with the results of Tolesa *et al.* (2019), who reported a significant interaction effect ($P < 0.05$) between variety and seed rate on tiller production, and a highly significant effect ($P < 0.01$) on grain yield, straw yield, and biomass yield. In contrast, Gezahegn *et al.* (2022) observed that increased intra-specific competition under higher plant densities may reduce spike length and the number of grains per spike, thereby adversely affecting grain yield.

4.2.2. Number of productive tillers per plant

The analysis of variance indicated that the number of productive tillers per plant was highly significantly influenced ($P \leq 0.01$) by the main effects of barley variety and seed rate, as well as by their interaction, highlighting the combined influence of genetic and agronomic factors on productive tiller formation (Appendix Table 1).

The highest number of productive tillers was observed in HB1307 when the seed rate was 75 kg ha^{-1} (Table 4). In contrast, the lowest count of tiller was seen with the local variety at a higher seed rate of 150 kg ha^{-1}. As the seed rate increased to 150 kg ha^{-1}, there was a drop in the total and productive tillers for all treatments. For instance, HB1307's tillers went down from five to three. Likewise, HB1966 and the local variety each ended up with only two tillers. Productive tillers declined as seed rate increased across all varieties because higher plant density intensified competition for light, moisture, nutrients, and growing space, thereby reducing tiller initiation and survival. In contrast, lower seed rates provided favorable growing conditions that enhanced tiller development, particularly in the improved variety

HB1307, which possesses superior genetic tillering ability compared with the local variety (Gezahegn et al., 2022; Tagesse, 2022). Tizazu (2025) found that higher seed rates decrease tiller numbers in food barley. Alemayehu (2024) agreed, noting big differences in tillering between varieties and also said that more plant competition at higher densities reduces both number of the total and productive tillers.

4.2.3. Number of grains per spike

The analysis of variance indicated that the number of grains per spike was highly significantly influenced ($P \leq 0.01$) by the main effects of barley variety and seed rate, as well as by their interaction, underscoring the combined contribution of genetic and agronomic factors to variation in this trait (Appendix Table 1).The average values for the number of grains per spike exhibited a declining trend as seed rates increased across all varieties and also significantly impacted by the main effects of both varieties and seed rates (Table 4). Variety HB1307 had the highest grains per spike (62) at a rate of 75 kg ha^{-1}. On the other hand, the local cultivar showed the least number grain per spike (16) at 150 kg ha^{-1}.

Using highest high seed rate in the cultivation resulting, each plant produces fewer grains per spike due to their competition for light, water, and nutrients.

This happens during pre-anthesis and the reproductive stage, leading to less fertile spikelets. Similar studies in Ethiopian highlands (Derbew, 2023; Tadesse *et al*., 2020) showed that rising the planting density meant there wasn't enough food for proper spike development, reducing grains per spike. Across all the seed rates, HB1307 produced the highest number of grains per spike compared to the rest of the varieties, suggesting a more efficient use of available resources such as light, water, and nutrients. The superiority of HB1307 implies that this variety is able to produce and translocate a higher quantity of photosynthates from the source to the sink organ and therefore form a greater amount of grain. Even under the highest seed rate of 150 kg ha^{-1}, which implied increased competition for resources between plants, HB1307 formed a higher number of grains per spike compared to the rest of the varieties (48 grains per spike).

Table 4. Effect of food barley variety, seed rate, and their interaction on yield components and yield of food Barley in Diga District during the 2025 main cropping season.

Food Barley Varieties	Seed rate (kg/ha)	Number of Total tillers per plant	Number of Productive tillers per plant	Number of Grains per spike	Grain yield (kg/ha)	Biomass yield (kg/ha)
Local	75	3^{c}	2^{c}	19^{l}	1060^{j}	5283^{m}
	100	3^{c}	2^{c}	19^{l}	1898^{i}	7943^{l}
	125	3^{c}	2^{c}	18^{l}	2275^{h}	9270^{j}
	150	2^{d}	1^{d}	16^{m}	1873^{i}	10007^{fgh}
HB1307	75	5^{a}	4^{a}	62^{a}	2853^{d}	9595^{i}
	100	5^{a}	3^{b}	60^{b}	3810^{b}	10057^{fg}
	125	4^{b}	3^{b}	59^{c}	4687^{a}	11130^{d}
	150	3^{c}	2^{c}	48^{f}	$3657b^{c}$	14288^{a}
HB1966	75	4^{b}	3^{b}	44^{gh}	2027^{hi}	7917^{l}
	100	4^{b}	2^{c}	41^{i}	2605^{g}	9823^{h}
	125	3^{c}	2^{c}	38^{jk}	2807^{ef}	10217^{f}
	150	2^{d}	2^{c}	36^{k}	2556^{g}	12570^{c}
Jobira	75	4^{b}	3^{b}	53^{d}	2243^{h}	8396^{k}
	100	4^{b}	3^{b}	50^{e}	2702^{g}	9933^{gh}
	125	4^{b}	2^{c}	45^{g}	2977^{e}	10602^{e}
	150	3^{c}	2^{c}	40^{ij}	2684^{g}	12738^{b}
LSD (0.05)		0.25	0.22	1.69	211.4	222.0
CV (%)		6.37	4.47	7.03	1.836	1.012

Means with a column followed by the same letter(s) are not significantly different at a 5% level of significance; LSD=Least Significant Difference at a 5% level; CV = Coefficient of variation.

4.2.4. Grain yield

The analysis of variance indicated that grain yield was highly significantly influenced ($P \leq 0.01$) by the main effects of barley variety and seed rate, as well as by their interaction, highlighting the combined contribution of genetic and agronomic factors to variation in grain yield (Appendix Table 2).The highest grain yield 4681.66 kg ha^{-1} was recorded from the HB1307 variety planted at a seed rate of 125 kg ha^{-1}, while the lowest yield of 1060 kg ha^{-1} was noted by the local variety grown at a seed rate of 75 kg ha^{-1} (Table 4). This interaction indicates that the HB1307 variety at a seed rate of 125 kg ha^{-1} represents the optimal combination, achieving the maximum yield of 4681.66 kg $ha^{-1.}$ However, the local variety had a low grain yield since its genetic potential was relatively lower compared to HB1307 and due to inefficient resource use . In addition, the low seed rate led to a low plant population, whereas high seed rates resulted in intra-specific competition for growth resources, thereby lowering yield components and ultimately grain yield. Thus, the optimal seed rate of 125 kg ha^{-1} enabled a good balance between plant population and resource use efficiency, thereby achieving the highest grain yield of HB1307. Similar results have been obtained by Ethiopian researchers, who found that the grain yield of food barley is highly affected by the interaction of varieties and seed rates on plant population, resource use efficiency, and yield components (Gezahegn *et al*., 2022; Bayisa *et al.,* 2024).

4.2.5. Biomass yield

The analysis of variance indicated that biomass yield was highly significantly influenced ($P \leq 0.01$) by the main effects of barley variety and seed rate, as well as by their interaction, highlighting the combined contribution of genetic and agronomic factors to variation in biomass production (Appendix Table 2).When the seed rate increased from 75 to 150 kg ha^{-1}, biomass output increased steadily across all cultivars (Table 4). The local variety produced the lowest biomass output at 75 kg ha^{-1} (5,283.33 kg ha^{-1}), while HB1307 produced the maximum biomass yield at 150 kg ha^{-1} (14,288.33 kg ha^{-1}). The increased plant population per unit area, which promotes canopy formation, light interception, and total dry matter accumulation, could be the reason for the steady rise in biomass yield with increasing seed rate. Similar results were reported by Tolesa *et* al. (2019), who found that the interaction between variety and seed rate had a substantial impact on food barley biomass output, with

higher seed rates typically resulting in larger biomass yields because of increased plant density. Similarly, Gezahegn *et* al. (2022) found that raising the seed rate considerably boosted the total biomass output in food barley, suggesting that larger plant populations improve vegetative development and dry matter production. Even when grain yield does not increase proportionately, HB1307's increased biomass output at 150 kg ha^{-1} indicates that this variety has a superior capacity to convert available resources into vegetative development under dense plant populations.

4.2.6.Straw yield

The analysis of variance indicated that straw yield was highly significantly influenced ($P \leq 0.01$) by the main effects of barley variety and seed rate, as well as by their interaction, highlighting the combined contribution of genetic and agronomic factors to variation in straw yield (Appendix Table 2). Variety HB1307 planted at a seeding rate of 150 produced the highest straw yield (10,631.67 kg ha^{-1}). This yield advantage was more than 2,498 kg ha^{-1}, greater than that of the local variety, demonstrating the enhanced variety's superior capacity to produce biomass at higher plant population densities. The higher number of plants per unit area, which improved vegetative growth and total above-ground biomass accumulation through increased stem and leaf production, may be the reason for the higher straw yield seen at higher seed rates. Biruk *et* al. (2022) observed similar results, noting that raising the seed rate enhanced barley's biomass production and yield performance. HB1307's improved genetic composition, better adaptation to the highlands, and increased effectiveness in making use of available growth resources under dense plant stands may also contribute to its superior performance. Additionally, greater canopy development and effective solar radiation interception are known to sustain larger biomass accumulation in enhanced barley types, leading to increased straw output. Zenebe *et* al. (2023), also stated that HB1307 demonstrated improved above-ground biomass yield compared with native cultivars under favorable management conditions in Southern Ethiopia, corroborate the current finding. The higher straw yield from HB1307 at 150 kg ha^{-1} indicates its potential contribution to both grain production and livestock feed security, since barley straw is a valuable livestock feed resource in the mixed crop–livestock farming systems of the Ethiopian highlands. As a result, the variety might be regarded as a useful dual-purpose cultivar for raising smallholder farming systems' sustainability and productivity.

4.4. Harvest Index

Statistical data analysis indicated that harvest index was highly significantly ($p \leq 0.01$) influenced by barley variety, seed rate, and their interaction (Appendix Table 2). An essential physiological measure that shows how well a crop transforms its total accumulated biomass into economic yield (grain) is the harvest index (HI). At a seed rate of 125 kg ha^{-1}, the food barley variety HB1307 achieved the greatest harvest index (42.06%) in the current investigation, demonstrating its superior capacity to partition assimilates toward grain production under ideal plant population density (Table 5). The harvest index dropped to 25.59% when the seed rate was increased to 150 kg ha^{-1}, indicating that the balance between vegetative growth and reproductive development was negatively impacted by high plant density. Increased competition among plants for light, moisture, nutrients, and growing space may have contributed to the decrease in HI at higher seed rates by promoting vegetative biomass buildup while restricting assimilate transfer to developing grains. Biruk *et* al. (2022) reported similar results, noting that increasing the seed rate above the optimal level enhanced biomass production but decreased yield efficiency because of increased intra-specific competition among barley plants. In comparison to the local variety, which had the lowest harvest index (18.73%), HB1307's superior harvest index further demonstrates its enhanced genetic potential for effective resource utilization and assimilate partitioning. This outcome is consistent with the findings of Zenebe *et al.* (2023), who found that improved food barley varieties, especially HB1307,outperformed local cultivars in Southern Ethiopia in terms of yield performance and biomass use efficiency. The lower harvest index suggests that this density might not be ideal for maximum grain yield, even though the greater seed rate of 150 kg ha^{-1} increased straw and overall biomass production. However, in mixed crop-livestock farming systems, where barley straw is a valuable source of animal feed, such increased biomass production might still be beneficial. In order to achieve an ideal balance between grain yield and biomass production while improving overall production efficiency, the results emphasize the significance of choosing suitable seed rates for particular cultivars.

4.5. Lodging Percentage

ANOVA indicated that lodging percentage was highly significantly ($p \leq 0.01$) affected by barley variety, seed rate, and their interaction (Appendix Table 1).In comparison to the local variety and HB1966, the enhanced variety HB1307 consistently showed reduced lodging percentages (9-12%) across all seed rates, demonstrating its superior lodging resistance

(Table 5). Stronger stem strength, improved plant architecture, and improved adaptation to highland production settings are some of the genetic traits that may be responsible for HB1307's comparatively low lodging incidence. On the other hand, at a seed rate of 150 kg ha^{-1}, the local variety had the highest lodging percentage (40%), indicating greater vulnerability to stem bending and plant displacement under dense plant populations. Increased competition among plants for light, which encourages stem elongation and decreases stem strength, may be linked to the rise in lodging with increasing seed rate. The result align with Tadesse *et al*. (2022) that found changes in canopy structure and increased competition for growth resources led to an increase in lodging incidence at higher plant densities. Because keeping an erect crop canopy enhances light interception, photosynthetic efficiency, grain filling, and harvesting efficiency, HB1307's higher lodging resistance is significant from an agronomic standpoint. Thus, HB1307's appropriateness for intensive barley production systems in this area, where seasonal rainfall and strong winds commonly contribute to lodging-related yield losses, is demonstrated by its capacity to maintain low lodging levels even at increased seed rates.

Table 5.Effect of food barley variety, seed rate, and their interaction on straw yield, harvest index, and lodging of food barley in Diga District during the 2025 main cropping season.

Food Barley Variety	**Seed rate (kg/ha)**	**Straw yield (kg/ha)**	**Harvest index (%)**	**Lodging (%)**
Local	75	4223^{m}	20.05^{lm}	30^{c}
	100	6045^{jk}	23.89^{j}	33^{bc}
	125	6995^{g}	24.54^{i}	35^{ab}
	150	8133^{c}	18.73^{n}	40^{a}
HB1307	75	5797^{l}	36.45^{c}	9^{f}
	100	6247^{i}	37.88^{b}	10^{f}
	125	6448^{h}	42.06^{a}	11^{f}
	150	10632^{a}	25.59^{h}	12^{ef}
HB1966	75	5890^{kl}	25.60^{h}	20^{d}
	100	7218^{ef}	26.50^{g}	22^{d}
	125	7410^{e}	27.47^{e}	23^{d}
	150	10014^{b}	20.33^{l}	25^{d}
Jobira	75	6153^{ij}	26.71^{fg}	13^{ef}
	100	7231^{ef}	27.20^{ef}	14^{ef}
	125	7625^{d}	28.06^{d}	15^{e}
	150	10055^{b}	21.06^{k}	16^{e}
LSD (0.05)		**121.57**	**0.58**	**5.86**
CV(%)		**1.514**	**1.957**	**0.18**

Means with a column followed by the same letter(s) are not significantly different at a 5% level of significance; LSD=Least Significant Difference at a 5% level; CV = Coefficient of variation.

4.6. Thousand Grain Weight

Analysis of variance revealed that thousand-grain weight was highly significantly ($p \leq 0.01$) influenced by barley variety, while neither seed rate nor its interaction with barley variety exerted a significant effect on this trait (Appendix Table 2). HB1307 produced the highest thousand seed weight (43.15 g), followed by HB1966 (41.25 g) and Jobira (41.00 g), while the local cultivar recorded the lowest value (38.50 g) (Table 6). In contrast to other yield components like productive tillers and grains per spike, the lack of a substantial seed-rate

effect indicates that thousand seed weight is primarily controlled by genetic determinants and is less susceptible to plant population density. The results were aligned with rsearch reported by Biruk *et* al. (2022), who found significant varietal differences in grain weight across food barley cultivars but limited impacts of seed rate. HB1307's improved thousand seed weight suggests that it has a higher capacity for assimilate accumulation and grain filling, which allows it to maintain consistent grain size at different seed rates.

Table 6. Effect of food barley variety, seed rate, and their interaction on thousand-grain weight in Diga District during the 2025 main cropping season.

Food Barley Variety	**Thousand grain weight (g)**
Local	38.5[d]
HB1307	43.15[a]
HB1966	41.25[b]
Jobira	41.00[c]
LSD (%)	0.18
Seed rate (kg/ha)	
75	40.96
100	40.98
125	40.98
150	40.98
LSD (0.05)	NS
CV(%)	0.4

Means with a column followed by the same letter(s) are not significantly different at a 5% level of significance; LSD=Least Significant Difference at a 5% level; CV= Coefficient of variation; NS= non-significant

4.7. Correlation Coefficient Analysis

Based on the results of correlation analysis, it becomes clear that there is a significant association between grain yield and several other agronomic traits (Table 7). The grain yield was significantly ($P<0.01$) and positively associated with biological yield (r=0.763**), spike length (r=0.661**), straw yield (r=0.635**), number of kernels per spike (r=0.613**), harvest index (r=0.524**), and total tillers per plant (r=0.514**), Biological yield has been observed to exhibit the highest significance among all the traits stated above with respect to grain yield. Biological yield is known to contribute largely to grain yield. Highly positive correlations exist in yield-contributing traits. Total tillers per plant have shown a highly positive correlation with productive tillers per plant (r=0.972**). Spike length has been observed to have a positive correlation with kernels per spike (r=0.976**). All these traits show a positive correlation with grain yield and thousand-kernel weight, thus contributing to improving grain yield. Biological yield shows a highly positive correlation with straw yield (r=0.942**) but has a significantly negative correlation with the harvest index (r=-0.301*). However, straw yield shows a significantly negative correlation with the harvest index (r=-0.603**). Harvest index showed a high positive correlation with thousand-kernel weight (r=0.730**), which indicates that proper allocation of assimilates is important in grain formation and development. In general, through correlation analysis, it was noted that biological yield, spike length, kernels per spike, tillers, harvest index, and thousand-kernel weight were the major characteristics for grain yield improvement. Consequently, these traits need to be considered when developing food barley cultivars through breeding and crop management under the prevailing conditions of the current study. The results of the study are in agreement with recent studies, which stated that fertile tillers, thousand-kernel weight, kernels per spike, and their respective yield components have positive relationships with grain yields.The results were aligned with several recent studies, which have stated that fertile tillers, grain weight, grain number per spike, and related yield parameters have significant associations with grain yield and are important traits for selection in barley breeding programs (Tadesse *et al.*, 2025; Wondimu *et al.*, 2017).

Table 7. Correlation coefficients for agronomic traits of food barley in Diga district during the 2025 main cropping season.

Trait	TT	PT	SPL	KN	BY	GY	SY	HI	TKW
TT	1.000								
PT	0.972**	1.000							
SPL	0.756**	0.744**	1.000						
KN	0.842**	0.831**	0.976**	1.000					
BY	0.462**	0.451**	0.432**	0.312*	1.000				
GY	0.514**	0.502**	0.661**	0.613**	0.763**	1.000			
SY	0.438**	0.426**	0.394**	0.354*	0.942**	0.635**	1.000		
HI	0.371*	0.365*	0.503**	0.462**	-0.301*	0.524**	-0.603**	1.000	
TKW	0.529**	0.516**	0.648**	0.598**	0.281*	0.486**	0.327*	0.73**	1.000

TT = Total Tillers per Plant; PT = Productive Tillers per; Plant SPL = Spike Length; KN = Kernels per Spike; BY = Biomass Yield; GY = Grain Yield; SY = Straw Yield; HI = Harvest Index; TKW = Thousand Kernel Weight

4.8. Partial Budget Analysis

The seed cost per hectare was calculated using a recommended seed rate of 125 kg ha^{-1} and a market price of 80 ETB/kg for each variety, indicating that 10000 ETB/125 kg, 6000 ETB/75 kg, 8000 ETB/100 kg, and 12,000 ETB/150 kg seed rates at the time of sowing. Labor costs for sowing were estimated at 50 ETB/kg seed rate, and the total labor costs for sowing were calculated according to the rates of seeds/ha, indicating that 3,750 ETB/75 kg, 5,000 ETB/100 kg, 6, 250 ETB/125 kg, and 7,500 ETB/150 kg seed rate. The market prices of food barley grain at harvesting were 85 ETB/ kg for HB1307, 78 ETB/kg for HB1966, 78 ETB/ kg for Jobira, and 75ETB/ kg for the local variety, while the straw price was 2 ETB/kg for all varieties. The total variable cost (TVC) for each treatment was computed as the sum of the costs of seeding rate and labor cost for sowing.

The total variable cost ranged from 9750 to 19500 Ethiopian Birr (ETB/ha), which differed due to the differences in costs, seed rates, and labor cost for seed rate (Table 8). The partial budget analysis showed that net benefits ranged from 99,810 to 399,932 ETB/ha, with seed rates of 100 and 125 kg ha^{-1} consistently producing greater net benefits across all barley

varieties compared with seed rates of 75 and 150 kg ha^{-1}. Furthermore, increasing the seed rate to 150 kg ha^{-1} for all varieties decreased the relative net benefit, demonstrating that higher plant population density increased competition among plants and consequently reduced grain yield. At a seed rate of 125 kg ha^{-1}, the barley variety HB1307 produced the highest net benefit of Birr 399,932 ha^{-1} with an MRR of 2,008%, while at 100 kg/ha the same variety generated a net benefit of Birr 334,685/ha and a higher MRR of 2,276%. The combinations of HB1307 variety with seed rates of 100 and 125 kg ha^{-1} increased the average net economic benefit by approximately 235% and 301%, respectively, compared with the local variety planted at 75 kg ha^{-1}.

On the other hand, the lowest net benefits, 99,810 and 169,542 ETB/ha, were obtained from the local barley variety planted at seed rates of 75 and 100 kg ha^{-1}, respectively. These low returns were attributed to reduced productivity, as reflected by fewer productive tillers, poorer yield components, and lower grain yield under the relatively sparse plant population. The highest net income was obtained from the HB1307 variety at seed rates of 100, 125, and 150 kg ha^{-1}, demonstrating its superior adaptability and productivity under both moderate and high plant population densities. Furthermore, the adoption of improved barley varieties and appropriate seed rates is driven not only by their potential to increase yield but also by their ability to enhance profitability. Seed rate, varietal choice, and their associated production costs are critical factors influencing economic returns. In the study area, both barley grain and straw have substantial economic value, with grain used for human consumption and straw serving multiple purposes, including animal feed, house plastering (when mixed with mud), and as filling material for traditional pillows and bedding mattresses used for household comfort. Therefore, the combination of the HB1307 variety and a seed rate of 125 kg ha^{-1} was identified as the most economically viable option for barley production in the study area.

Table 8*. Partial Budget Analysis of variety and seed rate on food barley (*Hordeum vulgare L*) production in Diga District during the 2025 main cropping season.*

Food barley varieties	**Seed rate (kg/ha)**	**AGY (kg/ha)**	**ASY (kg/ha)**	**GR (ETB/ha)**	**TVC (ETB/ha)**	**NB (ETB/ha)**	**MRR (%)**
local	75	954	3,801	109560	9,750	99,810	–
local	100	1,708	5,441	182542	13,000	169,542	2,146
local	125	2,048	6,296	216518	16,250	200,268	945
local	150	1,686	7,320	199,650	19,500	180,150	D
HB1307	75	2,568	5,217	270,450	9,750	260,700	–
HB1307	100	3,429	5,622	347,685	13,000	334,685	2,276
HB1307	125	4,213	5,803	416,182	16,250	399,932	2,008
HB1307	150	3,291	9,568	375,419	19,500	355,919	D
HB1966	75	1,824	5,301	195,282	9,750	185,532	–
HB1966	100	2,345	6,496	247,836	13,000	234,836	1,517
HB1966	125	2,526	6,669	263,718	16,250	247,468	3,89
HB1966	150	2,301	9,012	269,577	19,500	250,077	80
Jobira	75	2,019	5,537	212,855	9,750	203,105	–
Jobira	100	2,432	6508	254,783	13,000	241,783	1,190
Jobira	125	2,682	6,863	277,797	16,250	261,547	608
Jobira	150	2,415	9,,049	278,885	19,500	259,385	D

AGY = Adjusted grain yield; Adjusted straw yield; GR = Gross return; TVC = Total variable cost; NB = Net benefit; MRR = Marginal rate of return; ETB = Ethiopian Birr; ha = hectare.

5. CONCLUSION AND RECOMMENDATION

The results of this study have demonstrated that the use of improved varieties planted at an appropriate seeding rate significantly increased phenology, growth, yield components, and yield of barley. The maximum grain yield of barley (4,681.66 kg ha^{-1}) was obtained from the variety HB1307 planted at a seed rate of 125 kg ha^{-1}, whereas the highest biomass yield (14,288 kg ha^{-1}) and straw yield (10,632 kg ha^{-1}) were recorded from the same variety at a seed rate of 150 kg ha^{-1}. The grain yield produced by HB1307 planted at a seed rate of 125 kg ha^{-1} exceeded by about 106%, 67%, and 57% the yields obtained from the local variety, HB1966, and Jobira, respectively, at the same seed rate. In contrast, the local variety sown at a seed rate of 75 kg ha^{-1} produced the lowest grain yield (1,060 kg ha^{-1}). Similarly, the lowest biomass yield (5,283 kg ha^{-1}) and straw yield (4,223 kg ha^{-1}) were also recorded at the same seed rate, indicating that inadequate plant population adversely affected overall crop productivity. Based on partial budget analysis, cultivating HB1307 at a 125 seeding rate yielded a maximal net benefit of 399,932 ETB/ha with an acceptable marginal rate of return of 2,008%. These results indicate that barley productivity can be increased by more than 100% through the use of improved varieties combined with an optimum seeding rate. Therefore, the combination of the HB1307 variety and a seed rate of 125 kg ha^{-1} is recommended for farmers in the Diga District to enhance barley productivity, improve farm profitability, and strengthen household food security. Thus, for further verification, it needs to be wider promotion and adoption of improved barley varieties, together with appropriate seeding rates, could substantially contribute to increased barley production and food security in the investigated area and similar agro-eclogical region.

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7. APPENDIX

Appendix Table 1. Analysis of variance for the effects of food barley varieties, seed rate, and their interaction on the agronomic performance of food barley varieties in Diga District during the 2025main cropping season.

Source of variation	**DF**	**Mean square**								
		DE	DH	DM	PH	LOG	TT	PT	SPL	KN
Block	2	0.187^{ns}	0.021^{ns}	0.062^{ns}	0.487^{ns}	0.001**	0.011^{ns}	0.028^{ns}	0.002	0.910^{ns}
V	3	0.139^{ns}	313.632**	1200.46**	577.095**	1344.0**	5.524**	3.772**	20.913**	3303.070**
SR	3	0.028^{ns}	4.243**	1.021**	32.671**	58.50**	4.661**	3.065**	0.332**	209.319**
VXR	9	0.231^{ns}	0.724*	0.354**	4.634**	5.833**	0.166**	0.118**	0.029**	18.154**
Error	30	0.583	0.354	0.146	0.263	0.012	0.033	0.011	0.001	2.337
CV		**18.51**	**0.81**	**0.30**	**0.51**	**0.18**	**5.15**	**4.47**	**0.35**	**0.99**

DF = Degrees of Freedom; V = Variety; SR = Seed Rate; V × SR = Interaction of Variety and Seed Rate; DE = Days to Emergence; DH = Days to Heading; DM = Days to Physiological Maturity; PH = Plant Height; LOG = Lodging; TT = Total Tiller pre plant; PT = Productive Tillers per Plant; SPL = Spike length; KN = Kernels per Spike. ns = non-significant; * and ** indicate significance at the 5% and 1% probability levels, respectively.

Appendix Table 2. Analysis of variance of food barley yield components and yield as influenced by the main effects of variety,seeding rate, and by the interaction of the two factors in Diga District during the 2025 main cropping season.

Source of variation	**DF**	**Mean square**				
		BY	GY	SY	HI	TKW
Block	2	4404.25^{ns}	538.19^{ns}	8013.56^{ns}	0.158^{ns}	0.0001**
V	3	20055448.8**	9037817.02**	4899910.9**	419.225**	10.932**
SR	3	46217445.5**	2104769.91**	37559844.8**	188.190**	0.003^{ns}
VXR	9	872237.5**	98765.95**	976577.1**	14.911**	0.0001^{ns}
Error	30	10142.7	2454.81	12079.6	0.279	0.007
CV		**1.012**	**1.836**	**1.514**	**1.957**	**0.4**

DF = Degrees of Freedom; V = Variety; SR = Seed Rate; V × SR = Interaction of Variety and Seed Rate; BY = Biological Yield; GY = Grain Yield; SY = Straw Yield; HI = Harvest Index; TKW = Thousand Kernel Weight; CV = Coefficient of Variation; ns = Non-significant; * = Significant at $P \leq 0.05$; ** = Highly significant at $P \leq 0.01$. ns = non-significant; * and ** indicate significance at the 5% and 1% probability levels, respectively.



Figure 3. Ploughing the land



Figure 4.Land Layout



Figure 5 .Sowing food barley through drilling



Figure 6. Field management



Figure 7 .Data Recorded At 90% Physiological Maturity



Figure 8. Harvesting,Threshing and weighing the grain and above ground dry biomass