MEKELLE UNIVERSITY

College of Dryland Agriculture and Natural Resources

Department of Plant and Horticultural Sciences

Inter- and Intra-Row Spacing Effect on Growth, yield and economic Benefit of Garlic (Allium sativum L.) Under Furrow Irrigation in Central and North Western Zones of Tigray, Northern Ethiopia

A Thesis Submitted

By

Gebregiorgis Berhe

In Partial Fulfillment of the Requirements for the Master of Science Degree

In

Horticulture

Advisors:

Major adviser: Daniel Gebrekidan (PhD)

Co-adviser: Berhanu Abrha (PhD)

June, 2025

Mekelle, Ethiopia

Declaration

Gebregiorgis Berhe , hereby, present my MSc thesis entitled "Inter- and Intra-Row Spacing Effect on Growth, yield and economic Benefit of Garlic (Allium sativum L.) Under Furrow Irrigation in Central and North Western Zones of Tigray, Northern Ethiopia" for consideration by the Department of plant and Horticultural Sciences within the College of Dryland Agriculture and Natural Resources at Mekelle University in partial fulfillment of the requirement for the degree of Masters in **horticulture**. I sincerely declare that this thesis is the product of my own efforts.

Name of the student Gebregiorgis Berhe Signature ________ date 16/06/2025

Approval

Name of the main adviser	Signature	date
Daniel G/kidan	________	16/06/2025
Name of the co-adviser		
Berhanu Abrha	________	16/06/2025
Name of external examiner		
________	________	________
Name of internal examiner		
Alemtsehay Tsegay (PhD)	________	16/06/2025
Name of Postgraduate coordinator		
Lijalem Gebrewahid	________	16/06/2025
Name of Department head		
Wendim Ygzaw	________	16/06/2025

i

DEDICATION

This scientific paper is dedicated to my beloved mother, Beriha Gebremedhin for her strong advice and nursing me with endless love and her partnership in the success of my life.

ACKNOWLEDGEMENTS

Foremost, I would like incredibly thankful to the ultimate God for his noble and continuous support and kindness for the success of my life and my MSc thesis work.

I am sincerely gratitude to my major adviser Dr. Daniel Gebrekidan for his continuous support and essential guidance throughout the period of my study with great sociability and responsibility. I am grateful to his guidance, comments, suggestions and insightful advice and help at all stages of my research work and during the writing of my thesis. I would also like to thank my co-adviser Dr. Berhanu Abrha for his insightful comments and constructive advice in preparing the treatment arrangements and the thesis write-up. His suggestions, insightful ideas, and editorial supports were helpful for me to complete the write up of the thesis.

I would like to express my gratitude to Tigray Agricultural Research Institute which provided me with leave of absence to my MSc study and for paying my salaries regularly while I was on the study leave.

My special thanks also go to staff members of Axum Agricultural Research Center specially, Kiros Welday for his honorable and continuous support from designing the experiment up to data analysis. I would also like to thank Kidu Gebremeskel for his grateful tutorial lecture on R software and his continuous support and essential guidance to complete my study. Gebretsadikan Zebreabruk, Murute Belay, Nieayo Gidey and others who helped me during the preparation of the research site, data collection, and harvesting. I would also like to express my gratitude to drivers of the Axum Agricultural Research Center particularly for Qesis Gebregziabher Atsbeha and Abrha Hagazi for their support and facilitation of transport services starting from planting till the final harvesting. I would like to express my gratitude to Axum Agricultural Research Center which supported me with all required facilities including the permit to use the experimental filed that belong to the research center. I would also like to express my grateful to Shire Maytsebri Agricultural Research center for providing me the second experimental site Seleklekha. In this connection, I would like to thank Kiros Asgele for his help on designing the experiment.

Finally, I would like to thank my family members for their unlimited support especially my beloved mam and my brother Gebrekidan Berhe for their honorable love and helpful advice throughout my life and financial support done for my MSc thesis work.

BIOGRAPHICAL SKETCH

The author, Gebregiorgis Berhe, was born on 16 Augest 1987 at Maysiru kebele in Ahferom woreda Central Zone of Tigray from his father Berhe Yifter and his mother Beriha Gebrenedhin. He attended Elementary education (grades one to eight) at Enticho Elementary School from 1994-2001, high school education (grades nine to ten) at Enticho Secondary High School from 2002-2003, and Preparatory education from

2004-2005 at Enticho Preparatory School. After completing his elementary, secondary and preparatory education, he joined Jimma University College of Agriculture and Veterinary Medicine in 2006, and graduated with the degree of Bachelor of Science (BSc) in Horticulture in June 2008.

After graduation, he was employed in Amhara Administrative Regional state by South Gondar zone, Fogera Woreda Office of Agriculture and Rural Development as an agronomy expert in December 2009, where he worked until May 2011. In May 2011, he was employed in Tigray Administrative Regional state in Central zone, Ahferom Woreda Office of Agriculture and Rural Development as agronomy expert and worked until May 2017. He joined Tigray Agricultural Research Institute (TARI), Axum agricultural Research Center as a junior Fruit and vegetable researcher. He continued working at TARI until he joined to the post graduate program studies in Mekelle University in October, 2019 to pursue a study leading to the degree of Master of Science (MSc) in Horticulture**.**

LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
AXARC	Axum Agricultural research Center
BDW	bulb dry weight
CSA	Central Statistical Authority
DZARC	Debreziet Agricultural Research Center
EIAR	Ethiopian Institute Agricultural Research
FAO	Food and Agricultural organization
FAOSTST	Food and Agricultural organization Statistics
LSD	Least Significant Difference
MRR	Marginal Rate of Return
MARR	Minimum Acceptable Rate of Return
NMA	National Metrology Agency
RCBD	Randomized Complete Block Design
SMARC	Ssire Maytsebri Agricultural Research Center
SDW	Shoot Dry weight
TBDW	Total biomass Dry Weight

Table of Contents

List of tables

List of figures

Appendix Table

Appendix Figure

ABSTRACT

Traditionally disorganized and haphazard plant spacing is among the inappropriate agronomic practices that seriously hinder the achievement of potential garlic production in central and north eastern zones of Tigray and the region at large. Therefore, a field experiment was conducted in 2023/2024 cropping season under ridge furrow irrigation to evaluate the effect of inter- and intra-row spacing patterns on yield and yield components of garlic at Hatsebo and Selekhlekha districts in Tigray. The experimental treatments includes three inter row spacing (10, 20 and 30 cm) and three intra row spacing (5, 10 and 15 cm).The experiment was laid out in Randomized Complete Block Design (RCBD) in factorial arrangement with three replications. Results revealed that, except leaf number per plant, all yield and yield traits of garlic were significantly influenced by the interaction effect of inter and intra row spacing. In addition, the combined analysis of variance indicated that bulb diameter, clove width small, medium and large bulb size distribution, and total, marketable and unmarketable bulb yield had significantly influenced by the interaction effects of inter-row spacing × intra-row spacing × location. Longer date of maturity (145 days), higher plant height (63.5 cm), leaf length (44.05 cm, leaf width (2.31 cm), bulb diameter (5.41 cm), bulb length (4.34 cm), bulb weight (50.84g), clove weight (3.23 g), clove width (2.05 cm, shoot dry weight (4.72g) and bulb dry weight (22.51 g) were recorded from the wider inter and intra row spacing of 30 x 15 cm. However, lowest values for these parameters were recorded at the spacing 10 x 5 cm. The closest inter-row and intra-row spacing of 10 x 5 cm resulted in the highest total bulb yields of 70.05 ton/ha and 14.07 ton/ha at Hatsebo and Selekhlekha, respectively. This spacing also produced the highest unmarketable yield of 3.86 ton/ha and 4.78 ton/ha at the two locations, along with smaller bulb size distributions of 6.81 ton/ha and 6.13 ton/ha. In contrast, the wider spacing of 30 x 15 cm yielded the lowest values. The highest marketable yields of 16.31 ton/ha and 12.39 ton/ha at the Hatsebo and Selekhlekha sites respectively, along with medium bulb sizes of 9.05 ton/ha and 5.82 ton/ha, and large bulb sizes of 6.55 ton/ha and 4.67 ton/ha, were achieved through the interaction of medium inter-row and intra-row spacing of 20 x 10 cm at both locations Additionally the partial budget analysis also revealed that 20 x 10 cm inter- and intra-row spacing offered the highest MRR (1546.9%) indicating its higher profitability. Therefore, this treatment combination was suggested for use by farmers in the study areas of the Central and North Western zones and other parts of the region having similar agroecologies. However, it is essential that these findings be complemented with appropriate fertilizer recommendations on multiple locations and seasons to have a full package for garlic production under furrow irrigation.

Key words: *Garlic, inter rows pacing, intra row spacing, marketable yield, bulb size distribution.*

CHAPTER 1 INTRODUCTION

1.1. Background and justification

Garlic (Allium sativum L.) is the most important aromatic herb in the Allium family and is the second most widely cultivated crop after onions, with a high market demand worldwide (Mekonnen & Gadisa, 2021). Native to the arid and semi-arid regions of Central Asia, garlic has been domesticated since 3000 B.C. It spread to other parts of the world through trade and colonization(Uyeda *et al*., 2022).

Garlic is well-known for its pungent, edible bulbs, which are commonly used as a seasoning in many dishes. It is primarily consumed at home as a flavoring agent in various foods, including vegetable soups, meats, salads, tomato dishes, spaghetti, sausages, and pickles. Additionally, garlic is recognized as one of the most important ancient medicinal plants; it has been used to treat various ailments such as cardiovascular diseases, stomach issues, sore eyes, and earaches due to its substantial content of vitamins and minerals (KAMAU, 2019; Mengesha & Tesfaye, 2015).The world's annual garlic production was approximately 28,672,226 tons from 1,689,758 hectares of land, with an average productivity of 16.97 tons per hectare. Of this production, Europe accounts for 2.5%, America for 2.9%, Africa for 3.6%, and Asia for 91%. The leading garlic-producing countries include China, India, Bangladesh, the Republic of Korea, and Egypt, with China being the largest producer, responsible for over 73% of global production (FAOSTAT, 2023

In Ethiopia in 2001/02 cropping season, the area planted with garlic was 6,042 hectares produced 79,421 tons with an average productivity of 13.13 tons ha^{-1}. In 2020/2021, the area under garlic cultivation was increased to 14, 600 hectares with a total production rising to 113,900 tons of bulbs with 7.2 tons ha^{-1} average productivity (CACC, 2002 and (CSA 2021), which is significantly lower than the global average of 16.97 tons per hectare. This low level of production is generally attributed to inadequate agronomic practices, such as suboptimal plant population, lack of improved and adaptable varieties, low soil fertility, diseases, pests, and insufficient post-harvest technologies.

Plant population is a critical factor influencing both bulb yield and quality. An essential aspect of crop production is the development canopies that optimize light interception, photosynthesis, and the allocation of dry matter to harvestable parts. A crop canopy is typically managed by adjusting the spacing between rows and between plants within a row. Maintaining optimal plant spacing is crucial for maximizing resource utilization such as nutrients, sunlight, and soil moisture and ensuring satisfactory yield. Yield per unit area increases with plant density to a certain limit; beyond that, yield per unit area declines because competition for growth factors among adjacent plants reduces individual plant yield. Conversely, resources may be wasted with excessively wide plant spacing (Teshale & Tekeste, 2020). Implementing appropriate spacing allows farmers to maintain optimal plant density, avoiding both overcrowding and under population, which can negatively impact yield and crop quality. Several studies worldwide have shown that proper plant spacing can improve garlic production. Under normal conditions, factors such as planting date, clove size, and plant density greatly influence the growth, yield, and quality of garlic crops (Asnake et al., 2024; Teshale and Tekeste,2020).

In Ethiopia different inter and intra row spacing has been recommended by the Ethiopia Institute of Agricultural Research (EIAR) for irrigated garlic production in different years for highlands areas of the country. For instance, 40 cm x 10 cm inter and intra row spacing for single row planting (=250, 0000 plants ha-1). However, plant population and arrangement of inter- row and intra-row plant spacing vary considerably depending on agro climatic and environmental conditions, soil type, soil moisture and soil nutrient content of the Tigray and the study areas.

1.2. Statement of the problems

In Tigray in general and in central and northwestern zones of Tigray in particular, various high-value vegetable crops are intensively produced by smallholder farmers. Among these, garlic is widely produced in rainfed and irrigation for home consumption and for local markets as a source of income for many smallholder farmers. In the 2020/2021 cropping season, the total area cultivated under garlic production in Tigray in meher season was about 309.18 ha (CSA, 2021).

About 56.5 ha of land in Laelay Maychew woreda and 163 ha in Medebay Zana were covered with garlic under irrigation and produced a total of 40.2 and 1,352.9 tons with an average productivity of 7.12 and 8.3 ton ha-1, respectively (Laelay Maychew and Medeby Zana woredas office of agriculture and rural development, 2024). Its productivity is similar to the national and the regional productivity of garlic 7.2 and 6.63 ton ha-1,respectively (CSA 2021), but far below the world average productivity 16.97 t/ ha (FAOSTAT, 2023). This low productivity is attributed to many biotic and abiotic factors such as low soil fertility and inappropriate agronomic practices.

Among these, the most prevailing constraints in the Tigray region in general and in central and northwestern zones of Tigray, in particular, could be accounted to the traditional production practices employed by smallholder farmers. Farmers in the region and the study areas typically cultivate garlic using traditional practices, where cloves are simply jumbled and planted without any specified spacing between plants and rows which resulted in overpopulation and leads to intense competition for moisture, nutrients, light, and air between plants. With this in mind, the farmers also irrigate their fields with flood irrigation system, which causes water and nutrients through run-off percolation, and water logging which may generate garlic root rot and soil salinity. These activities may collectively reduce the final yield of the crop.

In Tigray, limited research has been done on garlic crops such as research on variety selection and fertilizer rates. The Axum Agricultural Research Center (AXARC) used the national recommendation of a 40 cm between row and 10 cm between plants with single-row planting pattern for garlic experimental trials under irrigation. Even though inter and intra-row plant spacing has the greatest impact on yield and yield components of the crop, there has been no clear recommendation done so far for garlic production in Tigray and in the study areas. Therefore, the present study was initiated with the following objectives:

1.3. Objectives of the study

1.3.1. Genera objective

To investigate the optimum garlic plant spacing pattern for maximum bulb yield under furrow irrigation conditions in Laelay Maychew and Medeby Zana woredas

1.3.2 Specific objectives

- To evaluate the main and interaction effect of inter-and intra -row plant spacing patterns across the testing locations for optimum bulb yield of garlic.

- To identify the most profitable inter and intra row-spacing through the cost and benefit analysis.

1.4. Research hypothesis

Different inter and intra row plant spacing patterns significantly influenced the yield and yield traits of garlic with in and across locations.

CHAPTER 2 LITERATURE REVIEW

2.1. Origin and Botanical Classification of Garlic

Garlic (Allium sativum L.) is one of the oldest and most well-known horticultural crops in history. It is believed to have originated in Central Asia, specifically in the regions of Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (Medina and García, 2007). The cultivation of garlic dates back to at least 3200 B.C. in Egypt, and from there, it spread throughout the Mediterranean, Europe, and Asia, where it became as an important part of both diet and medicine used to treat various diseases (Goldy *et al.*, 2000);(Imo & Salvation, 2019)

Botanically, garlic belongs to the Lily family and is classified under the genus Allium, which includes onions (Allium cepa), leeks (Allium ampeloprasum), shallots (Allium ascalonicum), and several other edible and ornamental species (Goldy *et al.*, 2000).

There are over 600 cultivars of cultivated garlic grown worldwide. Based on their flower stalk formation, garlic varieties are classified into two main subspecies: Allium ophioscorodon (hard-neck cultivars) and Allium sativum (soft-neck cultivars) Hard-neck garlic produces hard-stemmed flower stalks and aerial bulbils or scapes, which can be difficult to peel. These "topsetting" or "bolting" varieties thrive in cold climates. In contrast, soft-neck cultivars are more adaptable to a wider range of climatic conditions because they do not typically produce bulbils, except under environmental stress. Instead, these cultivars focus on developing larger bulbs with more cloves. Generally, soft-neck cultivars mature earlier, have white bulb colors with 10-22 cloves, are easier to peel, and possess a longer shelf-life than hard-neck cultivars (Hannan, 2001); KAMAU, 2019; Westerfield, 2021;Thompson, 2018).

Garlic varies from the onion, in which it produces a number of cloves per bulb covered with a dry and thin outer sheath but onion produced single red bulb. Cloves are made from inner thickened leaf. The crop can have an average of 6–12 flat, blade-like leaves up to 50 cm long and 60 cm in height (KAMAU, 2019)

Selecting larger cloves of the best garlic bulbs is an important factor for garlic production because larger cloves produce quality, larger size, and mature bulbs at harvest. Thus, select large cloves, smooth, fresh, and free from disease, and plant separately into the prepared hole with the pointed up side and root end down, standing erect, and cover the clove with soil which ensures a straight neck ((Mekonen and Gadisa, 2021; Westerfield, 2021).

2.2. Soil Requirements of Garlic

Garlic is shallow rooted crop with un-branched root system and has low nutrient extraction capacity. Prior to planting, soils should be well tilled and pulverized to provide a loose soil bed for bulb growth and development. Thus, it can be grown best when planted on well-drained soils with added organic matter. Sandy loam or loam soils holds the most ideal texture for growing garlic with a capable of good moisture holding capacity. The optimum soil PH required for the garlic production is ranging from 6.8 to 7.2 (Hinman, 2008). Lower soil pH inhibits plant growth, and soil pH below 5.0 can lead to plant death. Soil test should be performed before planting to determine pH and nutrient availability.(Goldy *et al*., 2000).

With the addition of organic matter, clay soils will produce garlic quite well. The soil must be kept moist as dry soil causes miss shaped bulbs. Heavy clay soils will also create misshaped bulbs and make harvesting difficult. Garlic bulbs will be small and irregular in shape if the soil is extremely dry and compacted. So, regular irrigation and adding organic matter like manure or compost to the soil is critical (Thompson, 2018; Westerfield, 2021).

Garlic is a heavy feeder, meaning it requires a significant amount of nutrients. Early in its development, garlic has high demands for nitrogen, phosphorus, and potassium. The amount of fertilizer needed depends on the soil's fertility and should be determined through soil analysis.

It is recommended to apply nitrogen (N), phosphorus (P), and potassium (K) fertilizers in a band either below the clove or within 5 cm to the side of it during planting. Additionally, nitrogen application should be completed four to six weeks before harvesting. Excessive nitrogen, especially in backyard gardens, can increase the number of plants that exhibit secondary growth(Zeleke and Derso, 2015; Westerfield, 2021).

.

2.3. Climate Requirements

Garlic is a cold weather annual crop having high nutrient and water requirement. Yield and quality of garlic varies with climate, altitude, soil and pH, soil type, cultural practices, and the variety of the crop. Therefore, the biological elasticity of garlic defines its ability to acclimate to these factors over time. Mean monthly temperature ranging from 12-24 0C, annual rainfall from 600 to 700 mm and altitude from above 2000-2800 m.a.s.l are best and ideal for garlic production (Zeleke and Derso, 2015; Westerfield, 2021).

Garlic is a cool season crop, but it prefers cool and moist period during vegetative growth and relatively dry period during maturity of bulb. To perform this process, it passes through different growth activities. Thus, cloves planted in the fall go through a dormant period and requires a period of 6–8 weeks of cool weather after planting (below 4.5^0C) for vernalization process to induce bulbing. Under adequate soil moisture and lower temperature, the cloves swell considerably forming a globular bulb with many fine roots and a pair of intertwined leaves emerged laterally from the terminal end of the bulb. Thus, the plant goes through a period of vegetative growth and Keep well watering for optimum growth (Westerfield, 2021).

Dormancy break, seedling development and leaf growth are well induced during the period of low temperatures (10-15°C) and short day time. During the growth process, when condition is changed to high temperature and long day time the vegetative growth alters to bulb formation (Attif *et al*., 2019; Westerfield, 2021).

Photoperiod and temperature play great roles in the ultimate size and formation garlic bulb. Bulb growth beginnings ensued only at a longer photoperiod and higher temperature (Atttif, *et al*,, 2019). Also the author reported that the higher bulbing rate of three cultivars occurred under the longer photoperiod of (14 h or 16 h) and higher temperatures of (25 _C or 30 _C). Long days with high temperature favor bulb initiation while short day's leads to development of secondary bulbs and hindered bulb formation.

The yield potential of garlic largely depends on the extent of vegetative growth before the onset of bulbing. When temperature increased and day length increases, bulb formation begins and development continues. Garlic should be planted in an area that receives full sun for most of the day because it requires a period of cold followed by a period of light and heat in order to develop properly. However, drought or excessively wet conditions will reduce bulb yields (Westerfield, 2021)

2.4. **Field management practice**

2.4.1. Land preparation and planting

To prepare land for planting garlic, it should be plowed to a fine tillage during dry periods, ensuring that weeds are exposed to sunlight and removed. Garlic can be planted on flat land during the rainy season or with the use of drip irrigation. Additionally, it can be planted on top of or alongside a furrow under a ridge to facilitate furrow irrigation, depending on the soil's moisture level. Cloves should be planted upright; they must not be placed on their sides or upside down. (Zeleke and Derso, 2015; Goldy et al., 2000; Westerfield, 2021).

2.4.2. Irrigation

Garlic has a shallow, root system that typically extends to about 60 cm deep, which limits its ability to extract nutrients effectively. It is sensitive to water stress throughout its growing period, especially during the bulbing phase. To ensure adequate moisture in the root zone, garlic requires a consistent supply of water. Too much water can create a "wet base," leading to bulb root rot, so it's crucial that water does not remain in the field for more than six hours in order to mitigate the risk of disease due to salinity (Westerfield, 2021).

Additionally, if the crop is growing faster than expected, it's important to compensate for any dry spells during this time (Goldy *et al.*, 2000).

To achieve maximum bulb size, the soil must be kept consistently moist throughout the production cycle. The frequency of irrigation varies based on soil type and weather conditions. Typically, garlic requires about 2.5 cm of water per week for most soil types; however, sandy soils during hot and dry conditions may necessitate up to 5 cm of water each week during the growing season (Zeleke and Derso, 2015; Goldy *et al.*, 2000). During the sprouting phase, irrigation should occur twice a week until over 80% of the planted cloves have sprouted, after which the frequency can be reduced to once a week. Fluctuations between dry and wet soil conditions can lead to irregular growth, misshapen bulbs, increased numbers of unmarketable bulbs, and reduced overall yield (Zeleke & Derso, 2015).

2.4.2. Weeding

Garlic's shallow root system and sparse canopy make it less competitive against weeds. Grass weeds are particularly difficult to manage after planting and should be harrowed before planting to expose them to sunlight during dry spells. Hand weeding is recommended to avoid uprooting or damaging young plants, and garlic should be weeded every three to four weeks depending on the severity of the weed problem (Zeleke & Derso, 2015; Thompson, 2018; KAMAU2019).

2.4.3. Harvesting

Irrigation should cease at least two weeks before the expected harvest date, which occurs at physiological maturity when the leaves turn yellow, bend down, and the necks of the bulbs become soft. This allows for the development of the bulb's papery skin. Late-season irrigation can result in rotting at the base plate, peeling and discoloration of the outer skin, and the splitting of cloves from the bulbs (Zeleke and Derso, 2015; Goldy *et al*., 2000; Hinman, 2008). Harvest the garlic when the leaves are yellowing but some green leaves remain, as more layers of dry skin on the bulbs will extend their storage life (Thompson, 2018). To confirm that the bulbs are fully mature, check a few samples for clear division into distinct cloves. Harvesting too early can lead to decay during storage, while harvesting too late can cause diseases, discoloration, and the detachment of cloves from the bulbs (Westerfield, 2021).

2.4.4. Curing

Garlic needs to be cured after harvest, which involves drying the bulbs. This process should take about two weeks and should be done in a shaded area or under diffused light to allow moisture to escape from the leaves and roots. Once curing is complete, trim the bulbs about 2.5 cm above the bulb to prevent early sprouting. Trimming too close can lead to early sprouting and shorten the storage life of the garlic (Zeleke and Derso, 2015).

2.4.5. Storage

Harvested garlic can be stored at room temperature (5°C - 25°C) for immediate consumption. However, for longer storage, it is best to keep garlic at 0°C with 60% relative humidity. Be cautious, as higher humidity levels may encourage the growth of penicillin mold and prompt root development. To preserve planting material until the next season, garlic bunches are often hung from the ceilings of houses. Under the right conditions, garlic can last for 5 to 8 months, depending on the variety. Ensuring adequate air circulation and using proper storage containers is crucial for removing heat and moisture released during storage. (Zeleke and Derso, 2015; Goldy *et al*., 2000; Thompson, 2018).

2.5. Nutritional and Medicinal Benefits of garlic

Garlic is one of the primary Allium vegetable herbs known worldwide for its production, economic value, and use as a seasoning in numerous dishes. Without the addition of garlic, many popular recipes would lose their distinctive flavor and character, which make them favorites (Mengesha & Tesfaye, 2015). Garlic serves as a vital flavoring agent in various dishes, including vegetable soups, meat, salads, tomato combinations, spaghetti, sausages, and pickles. Aside from the papery protective layers of skin and the root, the other parts of garlic have significant culinary uses. The cloves are utilized as seeds for reproduction, as well as for consumption and medicinal purposes (Zeleke and Derso, 2015).

Garlic is one of the most studied medicinal plants and has been documented in ancient Egyptian, Greek, and Roman texts for its therapeutic properties. It has been used to treat various health issues, including heart problems, headaches, insect bites, intestinal worms, and tumors (Uyeda, 2022).Garlic contains several chemical compounds, such as allicin, alliin, and ajoene. Allicin is known for its antibiotic properties and strong odor, while ajoene is responsible for garlic's anticoagulant effects. This makes garlic a remarkable herb, as it has the ability to inhibit and kill bacteria and fungi, lower blood pressure, cholesterol, and blood sugar levels, prevent blood clotting, and protect against liver damage, brain diseases, and kidney infections. Furthermore, garlic has been shown to help treat HIV infection by inhibiting cell growth and virus replication through decreased production of proteins. The sulfur compound S-allylmercaptocysteine (SAMC) in garlic hinders the growth of cancer cells in laboratory studies by binding to tubulin, a protein involved in cell reproduction. This interaction disrupts cell growth and activates proteins (JNK1 and caspase-3) that lead to tumor cell death (KAMAU, 2019)

2.6. Garlic Production in Ethiopia

Garlic is a cold weather annual crop having high nutrient and water requirement produced throughout the country mostly in the mid and highlands of Ethiopia, and has been cultivated under irrigation and rain fed conditions. In Ethiopia, garlic is produced traditionally mainly by the smallholders farmers of the country with faulty cultural practices, as a result the yields becomes low and low.

Garlic is the most important and widely used Allium species in Ethiopia next to onion. It is an important herbaceous bulb crops used as a spice or a condiment. It is mainly used for flavoring and seasoning vegetables in different dishes (Mekonnen and Gadisa 2021). It also plays a significant role in traditional medicine. Furthermore, it is a vital source of income in domestic markets and a strategic crop for poverty reduction among smallholder farmers in the country (Mekonnen and Gadisa, 2021).

In Ethiopia the number of household meher season growers practicing garlic farming is considered to be 728,806 farmers produced on 15,979.54 ha of land with the total production of 1,14,944.7 tones and average productivity of 7.2 tone/ha. In Tigray also the number of household meher season garlic growers were about 34,909 farmers with a total of 309.18 ha of land produced 20,494.76 tones bulbs with average productivity of 6.63 tone/ha. (CSA, 2021)

Ethiopia is, next to six top garlic producing countries, China, India, Bangladesh, Egypt, Spain, and South Korea (FAOSTAT, 2023). Garlic is one of the most expensive cash crops in Ethiopia for low-income smallholder producers. In 2019/20 and 2020/21, a high net return of USD 19,963.2 and USD 17,263.2 per hectare was reported, respectively (CSA, 2020/21)

2.7. Plant Population

Plant population is the arrangement of inter and intra-row spacing patterns which depend on agro-ecology, season, soil type, cropping system and crop varieties. Generally, in a fixed plot of land, as plant population increases, both spacing between rows and within rows decreased and interplant competition increased then the available resources as well reduced. On the other hand, extra wider spacing reduce inter competition while too narrow spacing increases interplant competition for resources and both miss the optimum yield of the crop (Asnake *et al*., 2024; Endalkachew *et al.*, 2024; Legese, 2023)

The growth and yield of garlic is influenced by several factors, off which plant spacing being significantly influenced the crop yield. Closer spacing can result in competition for essential resources such as soil nutrients, water, and sunlight, which can negatively affect plant growth. On the other hand, wider spacing may lead to wasted space. Therefore, it is crucial to determine the optimal inter-row and intra-row plant spacing for each crop variety under specific soil and agro-climatic conditions. The relationship between inter-row and intra-row spacing is interrelated and can significantly affect the growth, yield, and quality of garlic. Therefore, selection of the best combination of these spacings is essential for achieving higher yield and quality of garlic (Asnake *et al*., 2024; Kumar *et al*., 2018).

2.8. Effect of Inter-and Intra-Row Spacing on Growth Parameters of Garlic

Research findings indicated that the growth parameters of garlic mainly influenced by plant densities and growth factors such as nutrients, sun light and soil moisture. When the farm land has sufficient amount of growth factors, plants grown in the closest spacing compute for sun light to avoid shade effect and then become taller than plants grown in wider spacing Because plants of wider spacing has lower competition for light than narrow spaced plants.

Conversely, in conditions with limited growth factors, closely spaced plants tend to compete more for moisture and nutrients rather than sunlight, leading to shorter plants compared to those spaced further apart. Thus, wider-spaced plants exhibit enhanced growth and vigor, allowing them to accumulate more assimilates for growth and development (Asnake *et al*., 2024; Endalkachew *et al*., 2024; (Fekry, 2017; Gaikwad et al., 2018; Gebremichael *et al*., 2019; Pavithra et al., 2023).

According to Muneer *et al*.,(2017) increasing both inter-row and intra-row spacing resulted in a significant increase in plant height. The tallest and shortest plants 72.04 cm and 41.6 cm, were recorded, corresponding to inter-and intra-row spacings of 14 cm x 11 cm and 12 cm x 3 cm respectively. The highest leaf length (64.9 cm) was also observed with a spacing of 14 cm x 11 cm, while the lowest leaf length (35.5 cm) was noted at 12 cm x 3 cm.

Similarly, Raya *et al*. (2022) reported that as inter-and intra-row spacing treatment combinations decreased from 20 cm x 20 cm to 10 cm x 5 cm, plant height dropped from 70.3 cm to 39.6 cm, and leaf length decreased from 39 cm to 32.1 cm. In contrast, as intra-row spacing increased from 8 cm to 14 cm, plant height decreased from 65.77 cm to 60.89 cm, and leaf length from 49.18 cm to 46.47 cm, while leaf width increased from 1.693 cm to 2.54 cm. This suggests that plants grown in narrow intra-row spacing may compete more for sunlight instead of moisture and nutrients, while wider-spaced plants experience less competition for critical growth factors such as sunlight, moisture, and nutrients (Endalkachew *et al*., 2024).

2.9. Effect of Inter-and Intra-Row Spacing on Yield and Yield Component of Garlic

Many researchers have indicated that the yield components of bulb crops are significantly affected by plant population and planting methods. Inter-row and intra-row spacing patterns influence the weight, diameter, and length of bulbs. Higher plant populations tend to produce more small-sized bulbs than lower plant densities (Asnake *et al*., 2024; Gebremikeal *et al*., 2019; (Murmu et al., 2019;Teshale & Tekeste, 2020)

According to Ayalew (2019) fresh bulb weight and diameter of garlic were influenced by the main effects of inter-row and intra-row spacing patterns. The highest fresh bulb weight (26.93 g) and bulb diameter (4.35 cm) were obtained with the widest inter-row spacing of 30 cm. Similarly, an intra-row spacing of 15 cm resulted in a higher bulb weight of 28.76 g and a bulb diameter of 4.41 cm. Murmu *et al*. (2019) also noted that a greater bulb weight of garlic (11.60 g) and bulb diameter (3.50 cm) were achieved with the widest spacing of 12 x 10 cm planted on December 14th, while the smallest mean weight and diameter were recorded at the narrowest spacing of 4 x 10 cm.

Asnake *et al.* (2024) found that clove size and intra-row spacing influenced bulb weight, bulb diameter, and clove weight of garlic. The highest bulb weight (33.38 g), bulb diameter (4.98 cm), and clove weight (2.71 g) were recorded in response to the interaction of larger cloves planted with the widest intra-row spacing of 12.5 cm. Conversely, the lowest values of these parameters were observed with smaller cloves at closer intra-row spacing of 5 cm. (Aswani *et al*. (2022) also investigated the effects of variety and plant density on garlic bulb diameter and weight, and found that the highest mean bulb diameter (3.37 cm) and bulb weight (21.79 g) were achieved at the widest inter-row and intra-row spacing of 15 x 15 cm.

Mohamed, (2018) confirmed that plant population significantly affected bulb diameter, weight, and clove weight of garlic across two seasons. The highest average bulb diameter (5.85 cm), bulb weight (60.95 g), and clove weight (3.1 g) were obtained from a configuration of one row per 60 cm ridge width with 10 cm intra-row spacing. In contrast, the lowest bulb diameter (3.85 cm), bulb weight (33 g), and clove weight (2.1 g) were recorded from planting of three rows per 60 cm ridge width panted with 10 cm intra-row spacing.

According to Pavithra *et al*. (2023), inter-row and intra-row spacing significantly influenced onion bulb size and weight. As plant spacing patterns increased, both mean bulb weight and size also increased. The highest mean bulb weight (84.9 g) and diameter (6.8 cm) were recorded at the widest inter-row and intra-row spacing of 30 x 20 cm, while the lowest mean bulb weight (72.2 g) and diameter (5.5 cm) were noted with closer plant spacing of 15 x 10 cm. Gebremikeal *et al.* (2019) supported this finding that the highest bulb diameter (6.364 cm) and length (5.237 cm) of onion were attained at wider inter-row and intra-row spacing of 50 x 15 cm and 50 x 10 cm, respectively. Likewise, (Tegen *et al*., 2016) confirmed that the highest bulb weight (102 g) and bulb diameter (7.12 cm) were harvested from the interaction effects of inter-row and intra-row spacings of 25 cm x 10 cm and 25 cm x 8 cm, respectively.

2.10. Effect of Inter-and Intra-Row Spacing on Bulb Yield of Garlic

The higher yield and better control of over or under bulb size could be obtained if plants are grown at optimum density. Total bulb yield can be increased as population density increase but produces lower bulb quality with smaller bulb size due to higher competition for growth factors (Alemu *et al*., 2022); Gebremeskel *et al*., 2017; Fekry, 2017; Pavithra *et al*., 2023).

Plant spacing influences the growth and yield of garlic and its yield is mostly depends on the number of plants per unit area. To increase yield and to improve quality bulb grade, planting of garlic at proper spacing is considered as necessary practice. An improper and inadequate agronomic practice leads to lower productivity in garlic. Planting density has an important part in deciding the crop yield. The sowing date and planting density considered as important management practices in garlic production. (Muneer N. *et al*., 2016).

A field experiment conducted by Mengesha and Tesfaye (2015) on effect of Spacing in incidence and severity of garlic rust and bulb yield at Eastern Ethiopia indicated that a spacing of 30 x 10 cm between row and between plant were showed significant reduction and boosted higher yield under disease stressed conditions. Similarly, Kumar *et al*. (2018) compared two spacing with three nitrogen levels and reported that the interaction of 15 cm x 10 cm plant spacing applied with 150kg N ha^{-1} offered the highest total bulb yield (7.05 ton ha^{-1}).

Mohamed (2018) indicated that, appreciable bulb yield of garlic (10.02 and 8.8 t ha^{-1} was achieved when higher population density 3 rows per 60 cm ridge width planted with10 cm intra row spacing or 30 cm x 10 cm triple row planting method was used. However, lower bulb yield (7.14 and7.76 t ha^{-}) were recorded in the lower plant density 1 row per 60 cm ridge width (60 cm x 10 cm) single row planting method in two consecutive production seasons.

According to (Raya *et al*., 2022), varying plant spacing and number of cloves per hole shifted the yield response of garlic from 1.333 kg per plot planted at 10 x 15 cm with one (1) clove per hole to 5.043 kg per plot planted at 15 x 20 cm with 3 clove per hole. However, Asnake *et al*.(2024) confirmed that, different arrangement of intra row spacing and clove size affects the yield of garlic. Thus, the highest and lowest bulb yield (15.15 t ha^{-1} and 6.56 t ha^{-1}) was obtained from large sized cloves planted with 5 cm intra row spacing and small sized cloves planted with 12.5 cm respectively.

A research conducted by (Vidya, 2015) to evaluate the response of garlic to planting time and plant density (10, 15 and 20 cm inter row and 5 and 7.5 cm intra row spacing) revealed that the highest bulb yield 13.43 t ha^{-1}) was harvested from 10 x 5 cm inter and intra row spacing planted at 1^{st} November.

Aswani (2024) reported that the highest bulb yield of garlic (20.53 t ha^{-1}) was recorded from the widest inter and intra row spacing 15 cm x 15 cm compared to the closest spacing. However, (Attaya *et al*. (2024) indicated that, the highest bulb yield of onion (42.742 t ha^{-1}) was harvested at the highest population density of 20 x 10 cm inter and intra row spacing (500,000 plants ton ha^{-1}). (Atalay *et al*., 2022) also confirmed the idea in which the highest total bulb yield of onion (45.4 t ha^{-1}) was harvested from plots planted with the lowest intra row spacing 4 cm applied with 82 kg ton ha^{-1} N.

Pavithra *et al*. (2023) evaluated onion bulb yield in response to planting method and plant spacing patterns and the highest bulb yield (20.0 ton ha^{-1}) was obtained at the closer spacing of 15 x 10 cm .plant spacing configuration. In contrast to this, (Atalay *et al*., 2022) reported that the highest bulb yield of onion 31.12 ton ha^{-1} and the lowest 27.17 t ha^{-1} were obtained from the wider and shorter intra row spacing of 10 cm and 6 cm respectively.

Also an experiment conducted by (Amare *et al*. (2020) on effect of plant spacing and nitrogen and phosphorus fertilizer levels on growth, seed yield and quality of onion at Shewa Robit, Northern Ethiopia indicated that 10 x 30 cm intra and inter row spacing with single row planting followed by 20 × 30 × 50 cm between plants, row and furrow respectively planted with double row planting pattern applied with 115 P_2O_5 and 114 N kg ha^{-1} fertilizers provided higher yield and quality onion seed production.

2.11. Effect of Inter-and Intra-Row Spacing on marketable and unmarketable bulb yield

Plant population seriously affects marketable and unmarketable bulb yield. Wider spacing have lower plant population per unit area and produce quality bulbs but diminished total bulb yield. The size of the bulbs under a wider spacing did not compensate for the decrease in yield per hectare. On the other hand, in most populated plants entered to higher resource competition for survival effect, resulted lower vegetative growth habit and performs poor vegetative structures. Thus, the crop produces more small sized and defected bulbs and then produce higher unmarketable bulb yield (Alemu *et al*., 2022) Gebremeskel *et al*., 2017; Pavithra et al,, 2023).

A research conducted by Tshale and Tekeste (2020) to evaluate the response of garlic to intra-row spacing (5, 7.5, 10 and 12.5 cm) and varieties at Selekhlekha indicated that marketable bulb yield decreased with increasing trends of intra-row spacing in all tested garlic varieties. The highest marketable yield (8.05 ton ha-1) was obtained at the closest 5 cm intra-row spacing with Tsedey 92 variety but produce higher small sized marketable bulbs.

Asnake *et al*. (2024) reported that intra row spacing (5, 7.5, 10 and 12.5 cm) and clove size significantly influenced marketable and unmarketable bulb yield of garlic. The highest and the lowest marketable yield (13.44 and 4.74 t ha-1) were harvested from large sized clove planted at 7.5 cm and small sized clove planted at 12.5 cm intra row spacing respectively. However, the highest and lowest unmarketable yields (3.93 and 0.13 t ha-1) were recorded from small sized cloves planted at 5 cm and large sized cloves planted with 12.5 cm respectively. (Atalay *et al*., 2022) also evaluated yield, dry weight and quality of onion in response to nitrogen levels and inter-row spacing of (30, 24 and 20 cm) and higher marketable yield (37.93 and 37.08 t ha-1) were obtained at 24 cm and 20 cm inter row spacing respectively.

A research conducted by Gebremeskel *et al*. (2017) in Mokoni Northern Ethiopia to evaluate inter and intra row spacing in response to growth and yield and yield traits of onion with singl row (20 x 10, 40 x 10, 30 x 5, 30 x 7.5, 30 x 10 and 30 x 12.5 cm inter-and intra-row spacing respectively and double (40 and 50 cm) inter-row with the above intra-row spacings. The highest and lowest mean marketable bulb yields (25.96 and 16.1 ton ha-1) was obtained at 40 cm x 5 cm double and 30 cm x 12.5 cm single row planting pattern .However, the highest and lowest mean unmarketable yield (2.32 and 0.92 ton ha-1) was harvested at 20 x 10 cm single row and 50 x 12.5 cm double row planting method.

Fekry, (2017) evaluated three inter-row spacing (12.5, 15 and 20cm) with NPK fertilizer levels in response to growth, yield, bulb quality and storability of onion in two seasons. The highest marketable bulb yields (47.646 and 48.003 ton ha-1) were recorded from the main effects of the wider inter-row spacing of 20 cm and 125 NPK respectively. However, the highest unmarketable bulb yield (3.89 and 3.804 ton ha-1) was obtained at 12.5 cm applied with the same NPK fertilizer. In contrast to this, Gebremikeal *et al*. (2019) reported that as inter-row spacing decreased from 50cm to 20cm and intra-row spacing from 15cm to 5cm, yield was dramatically increased from 16.527 to 36.087 ton ha-1. Thus, the higher marketable bulb yield 36.087t ha-1 was attained from the narrowest inter-and intra-row spacing of 20cm x 5 cm.

2.12. Effect of Inter-and Intra-Row Spacing on Garlic marketable bulb size distribution

Plant population significantly influences the distribution of marketable bulb sizes. Widely spaced plants tend to produce high-quality, large-sized bulbs; however, this spacing often leads to a reduced total bulb yield. Conversely, densely populated plants experience greater interplant competition for resources, resulting in more small-sized bulbs, which can negatively impact the quality and price of the product. Therefore, plants at an optimum population density experience minimal interplant competition, allowing them to produce higher yields, more medium and large-sized bulbs and fewer small-sized bulbs (Tekle, 2015).

Ayalew (2009) reported that both inter-row and intra-row spacing independently and significantly affected the marketable bulb size distribution of garlic. The highest mean of small-sized bulbs (4.45 ton/ha and 6.47 ton ha^{-1}) was harvested from the narrowest inter-row and intra-row spacings of 20 cm and 5 cm, respectively. In contrast, the lowest mean of small-sized bulbs (2.16 ton ha^{-1} and 1.0 ton ha^{-1}) was obtained from the widest inter-row and intra-row spacings of 30 cm and 15 cm, respectively. Additionally, (Tegen *et al*., 2016) evaluated three inter-row spacings (15 cm, 20 cm, and 25 cm) and four intra-row spacings (4 cm, 6 cm, 8 cm, and 10 cm) in response to the yield and yield traits of onion bulbs across three locations) Woramit, Koga, and Ribb. The results revealed that bulb size distribution was significantly affected by the interaction of inter-row spacing, intra-row spacing, and location. The highest and lowest distributions of small-sized bulbs (50% and 16%) were recorded from the narrowest (15 cm x 4 cm) and the widest (25 cm x 10 cm) inter-row and intra-row spacing combinations respectively. The highest distribution of medium-sized bulbs (49%) occurred with the interaction of 15 cm inter-row and 6 cm intra-row spacing. In contrast, the highest and lowest distributions of large-sized bulbs (48% and 8%) were harvested from the widest (25 cm x 10 cm) and the narrowest (15 cm x 4 cm) inter-row and intra-row spacing patterns, respectively.

Tekle (2015) reported that, intra row spacing and nitrogen fertilizer levels significantly influenced marketable bulb size distribution of onion. As intra-row spacing increases, the distribution of small sized bulbs significantly decreased while the distribution of medium and large sized bulbs increased up to some levels of the fertilizer. When intra row spacing increased from 2.5 cm to 12.5 cm and nitrogen fertilizer from 0 kg to 123 kg N ha-1, the distribution of small sized bulb was dramatically decreased from 13.83 to 0.67 ton ha^{-1}. The highest medium and large bulb size distribution (28.27 and 8.03 ton ha^{-1}) was harvested at 5 cm and 7.5 cm intra row spacing applied with 82 kg N ha-1. However, the lowest medium and large bulb size distribution (3.86 and 0.25 ton ha^{-1}) was obtained from the narrowest intra row spacing of 2.5 cm applied with 0 kg N ha-1.

2.13. Effect of Inter-and Intra-Row Spacing on Garlic biomass Yield

Above-ground biomass refers to the total plant height, leaf length, and leaf count, all of which are influenced by plant population. Consequently, above-ground biomass is directly affected by the patterns of plant spacing. As noted by Ayalew (2009), inter-row spacing has a significant impact on the dry weight of garlic's above-ground biomass. Specifically, the highest above-ground shoot dry weight per plant (6.66 g) was recorded at a wider inter-row spacing of 30 cm compared to the narrower spacings of 20 and 25 cm. This suggests that, as inter-row spacing increases, the above-ground shoot dry weight per plant also rises. This increase may be attributed to the reduced interplant competition for growth factors in wider inter-row arrangements, allowing the plants to develop more vigorously.

In a study by Teshale and Tekeste (2020) conducted in Seleklaka, North-Western Tigray, the effects of intra-row spacing (5, 7.5, 10, and 12.5 cm) on garlic varieties were evaluated in relation to yield and yield components. The results demonstrated that the interaction between variety and intra-row spacing had a significant effect on both fresh and dry biomass yield of garlic. The highest fresh biomass, measuring 146.43 g per plant, was obtained from the Tesdey 92 variety planted with 12.5 cm intra-row spacing, while the lowest fresh biomass of 46.27 g per plant was associated with the local variety at 5 cm intra-row spacing.

Moreover, nitrogen levels and intra-row spacing were found to significantly affect the shoot dry weight of onion plants. As intra-row spacing increased, the above-ground shoot dry matter per plant also increased across the nitrogen levels tested. The highest and lowest shoot dry weights per plant recorded were 3.22 g at the widest intra-row spacing of 12.5 cm and 0.731 g at the narrowest spacing of 2.5 cm, respectively (Tekle, 2015).

CHAPTER 3 MATERIAL AND METHODS

3.1. Description of the Study Area

The experiment was conducted in 2023/2024 cropping season under ridge furrow irrigation in two locations: (i) in Hatsebo and (ii) in Selekhlekha at Axum and Shire-Maytsebri Agricultural Research Centers, respectively (Figure1). The Hatsebo and Selekhlekha sites are found in La'elay Maichew and Medebay Zana woredas, respectively which are the potential garlic growing areas located within the central and north-western Zones of Tigray regional state. These woredas are located in the semi-arid tropical belt of Ethiopia with the "Weina dega" agro-climatic zone characterized by uni-modal rainfall extends from June to September with a peak rainy month in August. These areas are categorized under mixed crop-livestock farming systems. Major crops such as Tef, Maize, Sorghum, finger millet, and chickpea are grown under a rain-fed production system, and vegetables such as Garlic Onion, Tomato, cabbage, Lettuce, and Beetroot also widely grown under irrigation

As indicated in (Table 1), the ten years average mean maximum and minimum monthly temperature indicated that, Medebay Zana woreda had somewhat higher temperature as compared to the La'elay Maichew woreda. Moreover, the soil type of the study site Selekhlekha is cambisols with 55% clay, 20% silt, 25% sand and soil textural class is clay. However, the Hatsebo experimental station soil type is a vertisols with 70% clay, 18% silt, 12% sand and soil textural class clay (Table 2).

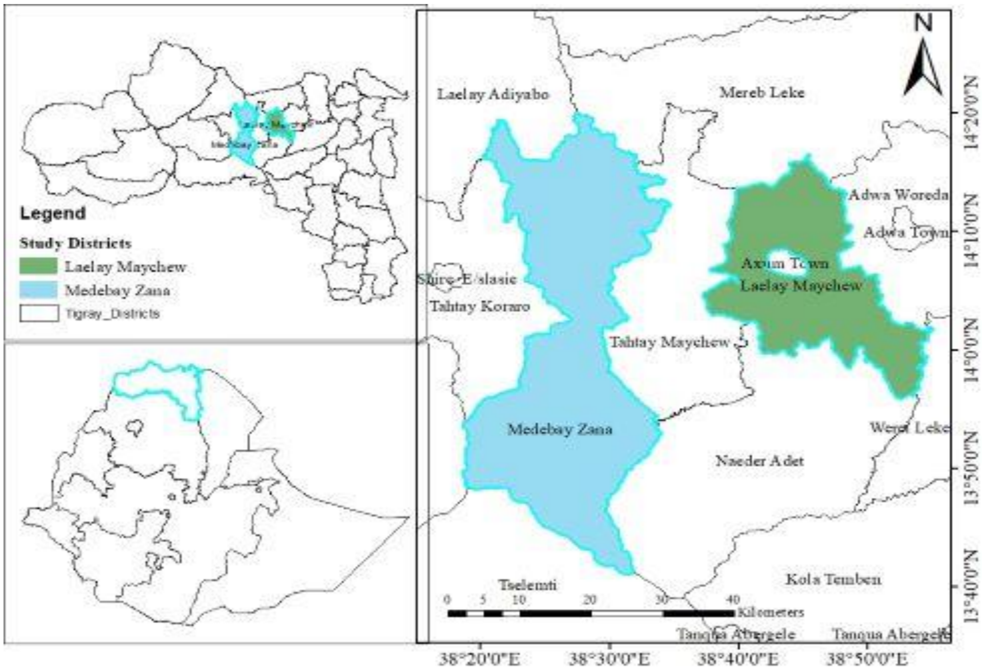


Figure 3:1 Map of the study areas.

Table 3:1 Ten years data (2010-2019) average means monthly maximum, minimum temperature and rainfall.

Months	Hatsebo			Selekhlekha		
	Temperature		rainfall (mm)	Temperature		Rainfall (mm)
	Max (⁰C)	Min (⁰C)		Max (⁰C)	Min (⁰C)	
Jan	24.01	9.4	0.00	26.09	12.88	0.00
Feb	25.02	11.1	0.00	27.43	13.77	0.00
Mar	27.137	13.0	0.90	28.87	14.48	50.00
Apr	27.14	16.1	12.60	29.10	14.56	90.60
May	28.43	15.5	114.76	29.80	15.78	10.76
Jun	25.12	14.8	208.38	28.10	12.88	0.00
Jul	23.05	13.9	490.07	24.05	13.97	198.07
Aug	22.85	13.1	510.25	24.85	13.76	470.25
Sep	23.34	12.5	190.15	25.69	14.41	190.15
Oct	21.72	11.5	15.37	25.72	11.88	30.37
Nov	22.6	10.6	30.00	26.60	11.25	40.00
Dec	21.38	9.7	0.00	26.38	11.78	0.00

Source. NMA Tigray Branch (2010-2019)

Table 3:2 Coordinate altitude and soil type, texture each study area.

	Location		Source
	Hatsebo	Selekhlekha (Adikemalic)	
Latitude	140 7 ’56.04” N	140 6 ’44.46” N	GPS
Longitude	380 46 ’4.92” E	380 27 ’49.74” E	GPS
Altitude (masl)	2095	1959	GPS
Soil texture at 30 cm depth	(70% clay, 18% silt, 12% sand)	(55% clay, 20% silt, 25% sand)	AXARC, SMARC
Soil Textural class	Textural class Clay	Textural class Clay	AXARC, SMARC
Soil type of study districts	Soil type vertisols	Soil type cambisols	AXARC, SMARC

3.2. Experimental materials

Local garlic variety was purchased from Selekhlekha model farmer and was used as planting material for both sites. Because there was no any access to get improved varieties like Tsedey 92 released by the Ethiopian Institution of Agricultural research (EIAR) duo to the genocidal war in Tigray that all these resources were completely devastated.

3.2.2. Experimental design and treatments

The treatment consisted of three inter row spacing (10 cm, 20 cm and 30 cm) and three intra rowspacing (5 cm, 10 cm, 15 cm) (Ayalew, 2009; Thompson, 2018 Zeleke and Derso, 2015; Westerfield, 2021). The experiment was laid out in Randomized Complete Block Design in factorial arrangement with three replications. The treatments were assigned to each plot within a block randomly. Plot size of 2.4m x 2.4m= 5.76 m^2 was used for each treatment. Five, four and three central harvestable double rows and two unharvestable border rows per plot were designed for the inter row spacing of 10 cm, 20 cm and 30 cm respectively. The spacing between plots and between blocks was 1m and 1.5 m respectively. Double row planting method was performed for all treatment combinations.

Table 3:3shows the treatment combination with the respective plant population per plot and per hectare.

Inter row x intra row spacing (cm)	Equivalent area (m2)	Number of plants (m2)	Number of plants per plot	Number of plants per hectare
30 x 10 x 5 cm	0.01	100	576	1,000,000
30 x 10 x 10 cm	0.02	50	288	500,000
30 x 10 x 15 cm	0.03	33	192	333,333
30 x 20 x 5 cm	0.0125	80	480	800,000
30 x 20 x 10 cm	0.025	40	240	400,000
30 x 20 x 15 cm	0.0375	26.66	160	266,666
30 x 30 x 5 cm	0.015	66.66	384	666,666
30 x 30 x 10 cm	0.03	33.33	192	333,333
30 x 30 x 15 cm	0.045	22.22	128	222,222

3.2.3. Land preparation and management practices

The land was thoroughly plowed and tilled five times at both locations to reduce soil bulk density and increase soil porosity, promoting better root development for the crop. 30 cm furrow width was maintained for each inter-row spacings following a double plant spacing pattern. For each double row planting pattern, three straight and paralleled twined line structure were designed according to the inter row spacing of 10, 20 and 30 cm width respectively with each 2.4 m length from giant cane (Arundo Donax). A total of nine twined giant canes were prepared. Each twin in both sides were marked with charcoal according the intra row spacing of 5, 10 and 15 cm, respectively to increase working efficiency and to minimize labors personal errors during planting. The time of planting was done in November 2023 under ridge furrow irrigation. Before planting, bulbs were separated into cloves and Cloves of medium sized (2 to 2.5 g) was used as planting material. Cloves were planted at the side of the marked point of the giant cane on a ridge as per the treatment combination of the design with 3 cm depth and the tip in upright position while the basal part down position and was covered with soil. A site specific NPSB blended fertilizer at a rate of 244 kg ha^{-1} and Urea at a rate of 128 kg ha^{-1} were applied which is equivalent to 92 kg P_2O_5 ha^{-1} and 105 kg N ha^{-1} (Zeleke and Derso, 2015). The entire NPSB blended fertilizer was applied during planting time and Urea fertilizer was applied in two splits, where half dose applied three weeks after planting and the rest half six weeks after planting 5 cm far to the side of the plant in band. The experiment was irrigated two times per week from planting up to more than 80% of planted cloves are sprouted in order to keep the soil moist and obtain uniform and rapid sprouting. Then after the irrigation frequency was reduced to once per week (EIAR, 2015) Cultural practices such as weeding, insect pest and disease control were applied uniformly for all treatments. Cultural practices, such as weeding and pest and disease control, were uniformly applied across all treatments. Profenofos 72 % EC (Profit) was sprayed three times at a rate of 0.5 liter per ha in 10 days interval to control onion trips (*Trips tabaci*). Propiconazole 25 % EC (Tilt) was also sprayed at 10 days interval at a rate of 1 liter ha^{-1} to control garlic rust (*Puccinia Allii* Rudolphi) Throughout the entire growth period, hoeing was performed three times, and hand weeding was performed four times to promote optimal crop growth and development

3.3. Data collection

Crop phenology, growth, yield and yield component of garlic data were collected from the central harvestable rows on the basis of sample plants and plot basis as described below.

3.3.1. Phenology and growth parameters

Days to physiological maturity: physiological maturity was recorded when 75 % of the leaves of the plants in each plot become yellow, dry and/or shown senescence.

Plant height (cm): the average height of the plant in cm was measured from the soil surface to the tip of ten randomly selected plants in each plot of the central rows at physiological maturity.

Leaf number per plant: the total number of healthy leaves was counted from the ten randomly taken plants from middle central harvestable rows at physiological maturity.

Leaf length (cm): the average length of the longest leaf, at physiological maturity was measured in cm from ten randomly taken plants in the central harvestable rows.

Leaf width (cm): the average width of leaves was recorded from ten randomly selected plants in the harvestable rows. A single leaf from each sample plants was measured at the widest part during the time of physiological maturity.

3.3.2. Yield and yield components

Bulb diameter (cm): bulb diameter was measured from ten randomly sampled plant bulbs at the widest point in the middle portion of the bulb using graduated caliper.

Bulb length (cm): was measured in length from the ten samples considered bulb diameter as indicated above. It was measured from the basal end point from the bottom scar of the bulb to the tip point of the bulb using graduated caliper.

Average bulb weight per plant (g): the average mature bulb weight per plant was recorded by weighting ten randomly sampled plant bulbs from the harvestable central rows after curing for 14 days and dividing by the number of sample plants.

Average clove weight (g): was recorded as the average weight of ten randomly taken cloves from the ten sampled plant bulbs as indicated above after curing.

Clove width (cm): the width of the cloves was recorded from ten randomly taken cloves used to measure the average clove weight. This was measured at the widest point in the middle portion of the cloves using graduated caliper.

Total bulb yield per hectare (t ha^{-1}): total bulb yield was computed from the harvested net plot of the central harvestable rows, and then converted to ton per hectare after curing for 14 days.

Marketable bulb yield per hectare (t ha^{-1}): the bulbs harvested from the net plot of the central harvestable rows which were free from defects, diseases, and damage and acceptable for the market were sorted and weighted. The weight per plot was converted in to tons per hectare as marketable yield.

Unmarketable bulb yield per hectare (t ha^{-1}): unhealthy bulbs (defected, diseased, immature, badly stained skins, and damaged, etc.) obtained from the net plot of the central harvestable rows were considered as non-marketable (not accepted by the market). The bulbs weighed per plot were converted in to tons per hectare.

Marketable bulbs size distribution (cm): marketable bulbs per net plot were graded into size categories based on their diameters as large (>5 cm), medium (4-4.9 cm) and small (<4cm) and converted in to hectare (Asrat, 2009).

Shoot dry weight (g): the total dry weight of above ground biomass of ten randomly taken plants was recorded after drying samples under sun for a week followed by universal oven drying at temperature of 70^0C for 48 hours. The average was calculated and above ground dry biological weight per plant was recorded

Bulb dry weight per plant (g): 10 sample bulbs were randomly selected from each central harvestable rows of each plot. Each sample bulb was chopped into small cubes and placed in a paper bag and then dried in a forced hot air ventilated universal oven dry at 70^0C for 48 hours and measured by electronic sensitive balance. The average values were computed by dividing the dry sampled plants to the number of plants.

Total dry biomass yield per plant (g): was recorded as the sum total of shoot dry weight and bulb dry weight per sample plant.

3.4. Statistical Analysis

The analysis of variance (ANOVA) was performed for each location using R software version 4.4.2 (2024-10-31 ucrt) to assess the effects of inter-row and intra-row spacing. The assumptions of normality and homogeneity of variance were tested using the Shapiro-Wilk test and Bartlett's test, respectively. After checking homogeneity of variance over the locations, the collected data of each location were subjected to combined analysis of variances (ANOVA) to compute significance of treatments effects on garlic yield and yield related parameters.

The combined analyses of variance for inter and intra row spacing patterns in Hatsebo and Selekhlekha location was computed to determine the effect of spacing and locations and their interaction effect for all dependent variables. Least significant difference (LSD) test was used to separate and compare treatment means at the probability alpha level of 0.05 using R software.

Correlation analysis was done by R software using metan package to generate information about the association between marketable yields and other parameters.

3.5. Partial budget analysis

The economic analysis was done for selecting profitable combinations of the inter- and intra-row spacing following the CIMMYT (1988) guidline, The cost of fertilizer and other activities were considered as a fixed cost, whereas the costs incurred for seed bulbs used for planting and labor costs engaged in planting and harvesting were considered as variable costs. The cost of seed was varied among each treatment combinations because of different plant populations that were resulted from different spacing between rows and between plants within a row. The price of garlic bulb seed during the experimental period was 230 Ethiopia Birr kg^{-1} while the cost for daily labor was 200 Birr per day. During harvesting time, the price of garlic was different according to the size of the bulbs. Thus, bulbs were categorized in to three market price levels based on their bulb diameter namely small, medium and large bulbs. Market price data were collected from four main streams of garlic market cities and towns in Tigray namely from Mekelle city, Axum, Shire and Enticho. Accordingly, the average field prices of garlic during the harvesting period were 150, 170 and 200 Ethiopian Birr kg^{-1} for small, medium and large bulb sizes, respectively.

Marketable garlic yield harvested from each treatment was reduced by 10 % in order to adjust the yield obtained from the research field (smaller field size and better crop management) to the yield that can be obtainable from the farmers' field. Under the research field relatively better crop management is performed than the farmers' field. The gross benefit was calculated by multiplying the adjusted marketable yield of each bulb size categories by their respective field price at the time of harvest. All costs and benefits were calculated on hectare basis in Ethiopian Birr (1 Ethiopian Birr = 0.0087 USD based on exchange rates on September 1, 2024). The net benefit was then calculated by subtracting the variable cost from the gross benefit. Dominance analysis was carried out by listing the treatments in an ascending order of total variable costs before calculating the marginal rate of return (MRR). According to CIMMYT, (1988),) any treatment that has a net benefit less or equal to the previous treatment was dominant and eliminated from further analysis. After dominance analysis, marginal rate of return (MRR) was calculated as a change in the net benefit divided by the change in the variable cost of the treatment.

$$MRR (\%) = 100*(\Delta NB/\Delta VC)$$

Where, the MRR is the marginal rate of return (%), NB is Net benefit which: was calculated by subtracting the total variable costs from gross benefit

CHAPTER 4 RESULTAND DISCCUSSIONS

The combined analysis of variance over location revealed that there were significant treatment effects on yield and yield-related traits. All growth metrics, yield and yield related traits were influenced by the main effects of inter-row, intra-row spacing and locations. Additionally, all these traits were also significantly influenced by the interaction of inter-and intra-row spacing. Furthermore, the combined analysis of variance indicated that bulb diameter, clove width, total, marketable and unmarketable bulb yield small, medium and large and bulb size distribution had been significantly influenced by the interaction effects of inter-row spacing × intra row spacing × location. Highly significant differences were observed among locations which impacted on the crop parameters.

4.1. Phenology and Growth Parameters

4.1.1. Days to 75% Physiological Maturity

The combined analysis of variance revealed that the main effects of inter row spacing; intra row spacing and location significantly ($P < 0.001$) influenced physiological maturity of garlic. The traits also affected ($P < 0.01$) by the interaction effects of inter row spacing with intra row spacing (Appendix Table 3).

Maturity date of garlic was delayed in response to the increment of inter and intra row spacing. Longer date of maturity (145 days after planting) was recorded from wider inter row spacing (30 and 20 cm) combined with the widest intra row spacing of 15 cm. However, the earliest date of maturity (131 days) was observed at the narrowest inter and intra row spacing 10 x 5 cm (Table 4:2). Thus, the maturity of garlic grown at wider spacing of 30 x 15, and 20 x 15 cm was delayed by 14 days as compared to garlic plants grown at the spacing of 10 x 5 cm.

The observed difference in maturity dates among the inter- and intra-row spacing attributed to increased interplant competition for growth resources in narrowly spaced plants, which promotes faster growth rate for survival than widely spaced plants (Teshale andTekeste, 2020). This result is in line with the findings of Tegen *et al*. (2016) who reported that days to maturity increased with the increasing trends of plant spacing patterns. The authors indicated that longer date of maturity (125 days) was recorded when onion was planted at the widest inter- and intra-row spacings (25 x 10 cm) whereas the shortest date of maturity (110 days after planting) was obtained from the narrowest inter and intra row spacing (15 x 4 cm). Similarly, Tegen and Jembere (2021) indicated that root carrot date of maturity was delayed with increased inter -and intra -row spacing.

4.1.2. Plant height

The combined analysis of variance demonstrated that garlic plant height was highly significantly influenced ($P < 0.001$) by the main effects of inter-row spacing, intra-row spacing, and location. Moreover, the interaction effect between inter-row spacing and intra-row spacing also had a significant impact on plant height ($P < 0.01$) (Appendix Table 3).

Garlic plants were taller with lower population densities. Specifically, as inter-row spacing increased from 10 cm to 20 cm and 30 cm, and intra-row spacing expanded from 5 cm to 10 cm and 15 cm, plant height increased from 46.75 cm to 63.5 cm.. As inter-row spacing increased from 10 cm to 20 cm and 30 cm, and intra-row spacing expanded from 5 cm to 10 cm and 15 cm, plant height increased from 46.75 cm to 63.5 cm.

In terms of the interaction between inter- and intra-row spacing, the tallest plant height (63.5 cm) was recorded at the highest spacing of 30 x 15 cm, followed by 20 x 15 cm. In contrast, the shortest plant height, measured 46.75 cm, was observed at a spacing of 10 x 5 cm and was not significantly different from the spacing patterns of 20 x 5 cm and 30 x 5 cm (Table 4:2).

This result aligns with the studies of Muneer *et al*., (2017) on garlic and Tegen *et al*. (2016) on onions, who reported that greater plant heights were associated with wider inter- and intra-row spacing, while shorter plant heights were noted at closer spacing. Furthermore, Melesse *et al*. (2024) indicated that the tallest onion plants (46.39 cm) were observed at wider inter- and intra-row spacing (40 x 25 cm), while the shortest (43.3 cm) was recorded using the broadcasting planting method. Similarly, Mohamed (2018) noted that garlic plant height increased with wider inter-row spacing.

In contrast Asnake *et al*. (2024), Endalkachew *et al*. (2024), and Gaikwad et al., (2018) observed that a decreasing trend in garlic plant height with increased intra-row spacing. This difference may be attributed to the fact that plants grown with wider spacing experience less interplant competition for growth factors such as water, soil nutrients, sunlight, and air compared to those that are planted at closer intervals (Teshale and Tekeste, 2020).

The height of plants is influenced not only by spacing patterns but also by the soil fertility of the growing area. When plants have ample resources, those grown in narrow spacing tend to compete for sunlight rather than for soil nutrients and moisture, leading to increased height compared to wider-spaced plants. However, when resources are limited, closely spaced plants focus on competing for soil nutrients and moisture rather than sunlight, resulting in reduced plant height. As a result, wider-spaced plants exhibit growth vigor as they access more assimilates for crop development (Ngullie, 2017)

4.1.3. Leaf number per plant

The combined analysis of variance revealed that garlic number of leaves per plant was highly significantly influenced by the main effect of inter-row spacing ($P < 0.01$) and location ($P < 0.001$) (Appendix Table3). The highest average leaf number count per plant (13.93) was observed at medium inter -row spacing 20 cm whereas the non -significant lowest average leaf number count per plant (12.55) compared to 10 cm was obtained at wider inter -row spacing 30 cm.

Intra -row spacing had also highly significantly ($P < 0.01$) influenced garlic number of leaves per plant. A non -significant higher number of leaves per plant (13.12) compared to 15 cm intra row spacing was recorded at 10 cm intra -row spacing while lower number of leaves per plant was obtained at the smallest intra-row spacing 5 cm (Table 4:1). Therefore, the number of leaves per plant increased as both inter -and intra -row spacing were increased.

The result is in agreement with the findings of Melese *et al*. (2024) who reported that higher number of onion leaves per plant was recorded at wider inter-and intra-row spacing 40 x 25 cm planted under ridge furrow irrigation whereas lower number of leaves per plant was obtained at the closer spacing planted using broadcasting planting method. Legese, (2023); Mebratu and Mulie, (2019) supported the idea that garlic number of leaves per plant increased subsequently as intra-row spacing increased from 6 cm to 12 cm and from 8 to 12 cm respectively. This might be due to the fact that plants at wider spacing have lower resource competition compared to closer spaced plants which produce vigorous plants with more number of leaves and enhanced quality bulbs.

Table 4:1 Main effect of inter -row and intra -row spacing on number of leafs per plant at Hatsebo and Selekhlrkha, 2024.

Inter row spacing	Treatments	Leaf number per plant
	10 cm	12.81b
	20 cm	13.33a
	30 cm	12.55b
Intra row spacing		
	5 cm	12.47b
	10 cm	13.12a
	15 cm	13.1a
SE(±)		0.158
LSD (0.05)		0.456
CV (%)		5.21

Means followed by the same letter with in a column are not significantly different at 5% probability level.

4.1.4. Leaf length

Garlic leaf length was highly significantly influenced ($P < 0.001$) by the main effects of inter-row spacing, intra-row spacing, and location. Additionally, this trait was significantly affected ($P < 0.05$) by the interaction between inter-row spacing and intra-row spacing (Appendix Table 3).

The tallest leaf length (44.05 cm) was recorded at the widest inter-row and intra-row spacing of 30 x 15 cm, while the shortest leaf length (31.75 cm) was measured at the narrowest spacing of 10 x 5 cm (Table 4:2). The observed increased in leaf length at wider inter- and intra-row spacing may be attributed to changes in vegetative growth, as these conditions provide relatively lower competition among plants for essential growth factors such as soil nutrients, moisture, light, and air. When plants have better access to these resources, they can achieve higher photosynthetic assimilation, resulting in more vigorous growth with longer plant height and leaf length. However, plants grown at closer inter- and intra-row spacing experience greater competition, which can lead to increased growth rates aimed at producing seeds for the next generation. As a consequence, vegetative growth is redirected toward bulb formation, leading to reduce plant heights and leaf lengths (Teshale and Tekeste 2020).

This finding aligns with the research conducted by Mneer *et al*. (2017) on garlic as well as Tegen *et al*. (2016) and Gebremikeal *et al*. (2019) on onions, who reported that the tallest leaf lengths for both garlic and onion were observed at wider spacings, while the shortest leaf lengths were noted at closer inter- and intra-row spacings. Similarly, Legese (2023); Asnake *et al.* (2024) reported that garlic leaf length was significantly influenced by intra-row spacing, with taller leaf lengths measured at wider spacings and shorter lengths at closer spacings due to competitive variability among plants. In addition, Afeta (2022) observed that shallot varieties were similarly affected, with higher leaf lengths measured at an intra-row spacing of 12.5 cm compared to lower lengths at closer intra-row spacing of 5 cm.

Table 4:2: Interaction effect of inter- and intra-row spacing on days to maturity, plant height, leaf length and leaf width At Hatsebo and Selekhlekha, 2024.

Inter x intra row spacing (cm)	Days to maturity	Plant height (cm)	Leaf length cm)	Leaf width (cm)
10 x 5 cm	131f	46.75d	31.750d	1.18 f
10 x 10 cm	138.0d	50.07c	35.50c	1.41 e
10 x 15 cm	142.5b	51.42c	36.20c	1.76 d
20 x 5 cm	135.5e	49.67cd	34.12c	1.38 e
20 x 10 cm	141.5c	59.23b	41.37b	1.92 c
20 x 15 cm	145.0a	61.54ab	43.43ab	2.16 b
30 x 5 cm	135.5e	49.73d	35.42c	1.39 e
30 x 10 cm	141.5c	60.58ab	42.43ab	2.09 b
30 x 15 cm	145.0a	63.50a	44.05a	2.31a
Mean	139.5	54.72	38.25	1.74
(P-value)	0.0045	0.0013	0.025	0.00005
LSD(0.05)	0.772	3.1	2.2	0.11
CV%	0.47	4.81	4.89	5.39

Means followed by the same letter with in a column are not significantly different at 5% probability level.

4.1.5. Leaf width

The combined analysis of variance indicated that the main effects of inter-row spacing, intra-row spacing, and location significantly influenced garlic leaf width ($p < 0.001$). Moreover, the interaction between inter-row spacing and intra-row spacing also had a significant effect on leaf width ($p < 0.001$) (Appendix Table 3). The highest mean leaf width of 2.31 cm was recorded at a wider spacing of 30 x 15 cm, while the narrowest leaf width of 1.18 cm was observed at a closer spacing of 10 x 5 cm (Table 4:2).

The study revealed that leaf width increased in response to increased inter-row and intra-row spacing. This finding is in consistent with Ayalew (2009), who reported that the widest inter-row spacing of 30 cm and intra-row spacing of 15 cm resulted in the highest leaf width for garlic. Similarly, Birhanu and Taye, (2017) reported that garlic plants with wider intra-row spacing produced broader leaf widths compared to those planted at closer spacing. Tekle (2015) also supported this observation in onions. Afeta (2022) further corroborated these findings, showing that shallot varieties exhibited wider leaf widths at increased intra-row spacing in comparison to closer plant arrangements.

This positive relationship may be attributed to the development of well-developed leaves at wider spacings, which reduces competition between plants and promotes vigor plant. As a result, these plants demonstrate enhanced photosynthetic efficiency.

4.2. Yield and yield Components

4.2.1. Bulb diameter

The combined analysis of variance revealed that garlic bulb diameter was significantly influenced by the main effects of inter-row spacing, intra-row spacing, and location ($P < 0.001$). The interaction effect between inter-row spacing and intra-row spacing also exerted a highly significant influence on bulb diameter ($P < 0.001$) (Appendix Table 3).

The interaction of inter-row spacing, intra-row spacing, and location had a highly significant effect ($P < 0.01$) on garlic bulb diameter. Garlic grown with a wider spacing of 30 x 15 cm exhibited a larger bulb diameter at Hatsebo (5.76 cm) compared to Selekhlekha (5.06 cm). Conversely, the closest inter-row and intra-row spacing of 10 x 5 cm resulted in smaller bulb sizes at Hatsebo (3.54 cm) and Selekhlekha (2.96 cm) (Figure4:1). Tegen an Jembere, (2021)) observed similar findings, noticing that larger carrot root diameters were attained at the Woramit experimental site compared to the Ribb growing conditions.

This difference may be attributed to variations in soil type and agro-climatic conditions. As indicated in (Table 3:1 and 3:2), the ten years average mean maximum and minimum monthly temperature was higher at Medebay Zana compared to Laelay Maychew woreda, which can impact garlic bulbing efficiency. Garlic typically suited cold conditions during vegetative growth (Atttif, J., 2019). Moreover, the cambisol at Seleklekha site as compared to the vertisol at Hatsebo which is characterized by higher water holding capacity than the Seleklekha growing conditions. Thus, garlic grown at seleklekha might influenced by lower soil moisture content as compared to that of Hatsebo site and then produced lower bulb size.

4.2.2. Bulb length

The combined analysis indicated that bulb length was significantly affected by the main effects of inter-row spacing, intra-row spacing and location, with a (p-value < 0.01).The trait also very highly significantly (P < 0.001) influenced with the interaction between inter-row spacing and intra-row spacing (Appendix Table 3).

Garlic bulb length was notably influenced by varying the inter-row and intra-row spacing patterns. The tallest bulb length (4.34 cm) was recorded at the wider spacing of 30 cm inter-row and 15 cm intra-row spacing. In contrast, the shortest bulb length of 2.41 cm was achieved at the narrowest spacing of 10 cm x 5 cm (Table 4:3).

This findings aligns with the research of Ayalew (2009) who observed that increasing both inter-row and intra-row spacing led to an increase in garlic bulb length, and vice versa. Similarly, Teshale and Tekeste (2020) noticed that the longest garlic bulb length was measured at an intra-row spacing of 12.5 cm, while the shortest was recorded at a closer spacing of 5 cm. Gebremichael *et al*.(2019) also reported that the longest onion bulb length was obtained at the widest spacing combination of 50 cm inter-row and 10 cm intra-row spacing, while the shortest bulb length was recorded at the narrowest spacing.

This trend may be attributed to the reduced competition for essential growth factors like soil nutrients, water, air, and sunlight in wider-spaced plants. Accordingly, these plants were able to accumulate more assimilates, resulting in larger and longer bulbs compared to those grown in closer spacing, which experienced under resource limitations.

4.2.3. Average Bulb Weight

The combined analysis of variance revealed that the main effects of inter-row spacing, intra-row spacing and location significantly (P < 0.001) influenced the average weight of cured garlic bulbs per plant. The trait also significantly ($P < 0.001$) influenced by the interaction of inter-row spacing and intra-row spacing, (Appendix Table 4).

Similar to the findings regarding bulb diameter and bulb length, the non-significant highest average bulb weight per plant (50.84 g) was recorded at the widest inter-row and intra-row spacing of 30 x 15 cm in comparison to 20 x 15 cm (47.38 gm). Conversely, the non-significant lowest value (15.5 g) compared to 30 x 5 cm and 20 x 5 cm was measured at the closest spacing of 10 x 5 cm (Table 4:3).

This finding is in line with the research done by Raya *et al*. (2022) which indicated that increasing inter- and intra-row spacing leads to greater bulb weight. Ayalew (2009) supported this idea that the highest garlic bulb weight was achieved at the widest spacing of 30 cm inter-row and 15 cm intra-row spacing. Similarly, Ahmed *et al*. (2017); Endalkachew *et al*. (2024); Teshale and Tekeste (2020) confirmed that larger bulb weights were observed in plants grown at wider intra-row spacing.

In summary, as inter-row and intra-row spacing increased, the bulb weight of garlic also increased, while a decrease in spacing corresponded with a reduction in bulb weight. This phenomenon may be attributed to reduced stiff interplant competition for growth factors in wider-spaced plants, thereby facilitating the translocation of assimilates and promoting the development of healthier, more vigorous plants that produce larger and heavier bulbs compared to those planted at closer spacings.

Table 4:3 Interaction effect of inter-and intra-row spacing on garlic bulb diameter, length, weiht, clove weight and clove width at Hatsebo and Selekhlrkha, 2024.

Inter x intra(cm)	Bulb length (cm)	Average Bulb weight (g plant-1)	Clove weight((g plant-1)
10 x 5 cm	2.41e	15.53f	1.19e
10 x 10 cm	2.88d	22.88e	1.69 cd
10 x 15 cm	3.23c	28.88d	1.89c
20 x 5 cm	2.76d	18.64ef	1.44de
20 x 10 cm	3.75b	41.68c	2.55b
20 x 15 cm	4.20a	47.38ab	2.78b
30 x 5 cm	2.71d	19.45ef	1.46de
30 x 10 cm	3.94b	43.18bc	2.69b
30 x 15 cm	4.34a	50.84a	3.23a
Mean	3.36	32.05	2.1
P-value	0.0003	0.00001	0.00034
LSD(0.05)	0.23	4.38	0.3
CV%	5.91	11.61	12.22

Means followed by the same letter with in a column are not significantly different at 5% probability.

4.2.4. Average clove weigh

The combined analysis of variance showed that clove weight was highly significantly influenced ($P < 0.001$) by the main effects of inter-row spacing, intra-row spacing, and location. Additionaly, the interaction between inter-row spacing and intra-row spacing also demonstrated significant effect ($P < 0.001$) on clove weight (Appendix Table 4).

The highest clove weight, 3.23 g, was achieved with the widest inter-row and intra-row spacing of 30 x 15 cm. In contrast, the narrowest spacing of 10 x 5 cm produced the smallest clove weight of 1.19 g, which was not significantly different from the weights at 20 x 5 cm (1.44 g) and 30 x 5 cm (1.46 g) (Table 4:3)

These results are consistent with the findings reported by Mohamed (2018), who indicated that the highest clove weight was observed at wider inter-row spacing. Similar conclusions were indicated by (Birhanu abd Taye, 2017). Furthermore, Asnake *et al*. (2024) also confirmed that the highest average clove weight was obtained with wider intra-row spacing, while the lowest was noted in closely spaced plants. The observed increase in average clove weight with the widening of inter-row and intra-row spacing may be attributed to the greater availability of resources for growth and development. This condition foster leads to the production of larger bulbs and cloves, as a result of less competition among widely spaced plant.

4.2.5. Clove Width

The main effects of inter-row spacing, intra-row spacing ($P < 0.001$), location ($P < 0.01$), and the interactionbetween inter-row spacing with intra-row spacing ($P < 0.001$) significantly influenced the average clove width of garlic (Appendix Table 4).

The combined analysis of variance demonstrated that clove width is significantly influenced ($P < 0.05$) by the interaction of inter-row spacing, intra-row spacing, and location. Garlic plants grown at the wider spacing of 30 x 15 cm exhibited a slightly higher clove width at Hatsebo (2.07 cm) compared to Selekhleka (2.04 cm). The lowest clove width was observed at Hatsebo (1.05 cm) and Selekhleka (0.63 cm) at the narrowest spacing of 10 x 5 cm (Figure 4:1).

The significant effect of location indicates that variations in weather conditions and soil types and texture as discussed in bulb diameter above may contribute to differences in garlic growth performance, as detailed in (Tables 3:1 and 3:2).

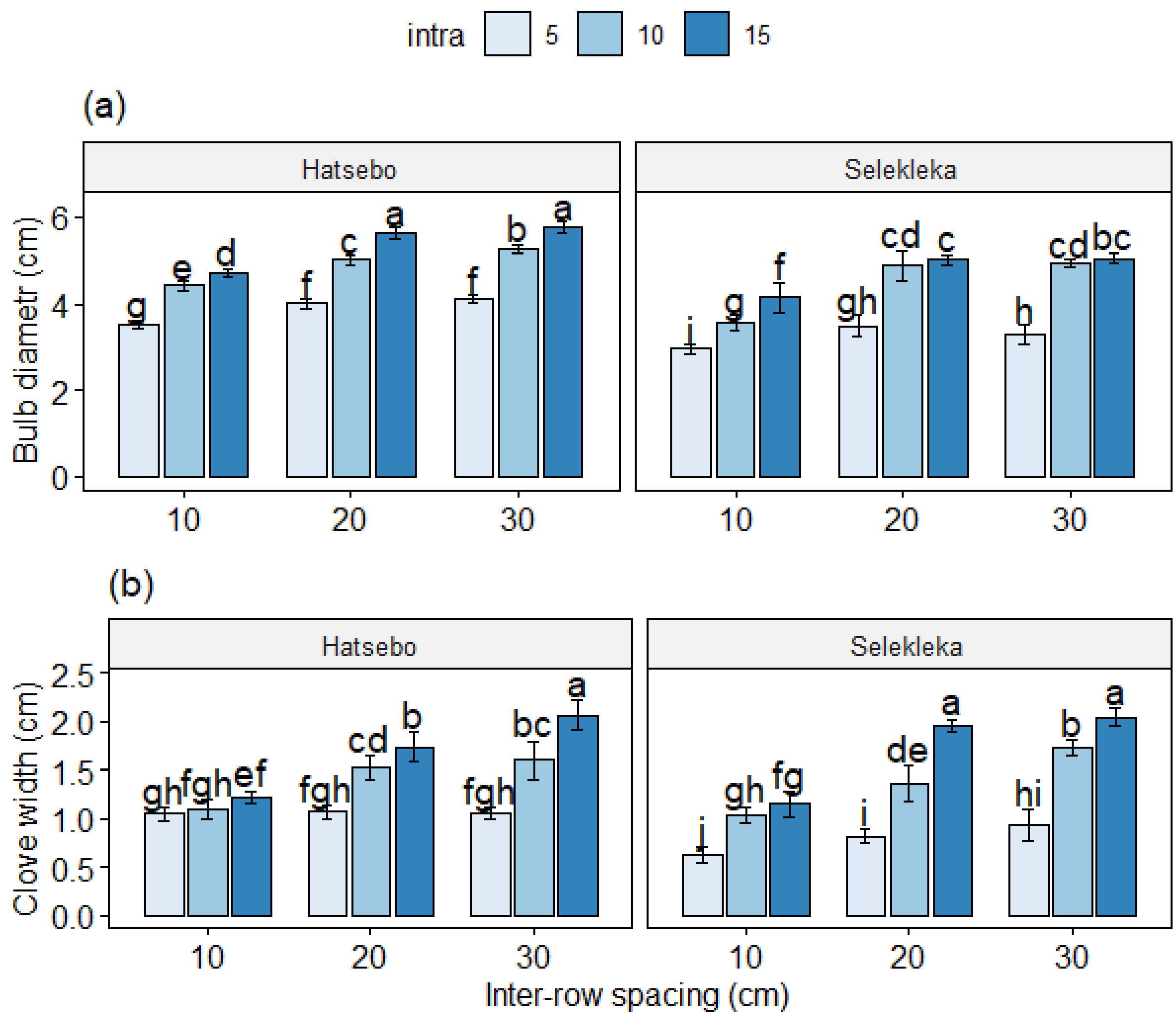


Figure 4:1 Mean bulb diameter (cm) and clove width (g) as affected by the interaction of inter row spacings, intra row spacings and location at Hatsebo and Selekhlekha, 2024.

4.2.6. Total Bulb Yield (ton $^{ha-1}$)

The combined analysis of variance revealed that the main effects of inter-row spacing, intra-row spacing, and location, as well as the interaction effects of inter-row spacing x intra-row spacing, significantly influenced the total bulb yield of garlic (P < 0.001) (Appendix Table 4).

The interaction effects of inter-row spacing x intra-row spacing x location had a very significant impact on total bulb yield (P < 0.001). The narrowest inter- and intra-row spacing of 10 x 5 cm produced a higher total bulb yield of 17.05 tons per hectare at Hatsebo, compared to 14.07 tons per hectare at Selekhlekha. In contrast, the widest spacing of 30 x 15 cm yielded the lowest values, with 8.99 tons per hectare at Hatsebo and 4.68 tons per hectare at Selekhlekha (Figure 4:2).

This significant location effect might be due to differences in weather conditions and soil types between the two sites. Variations in temperature and soil characteristics can affect the overall growth and performance of garlic. As shown in Tables 3:1 and 3:2, higher temperatures at Selekhlekha compared to Hatsebo may influence early crop growth and development. Seedling development and leaf growth are typically encouraged by low temperatures (10-15°C) and shorter day lengths (Westerfield, 2021). Furthermore, the soil type at Selekhlekha cambisol may exert lower moisture-holding capacity than the vertisol at the Hatsebo site. Consequently, garlic planted at Selekhlekha may be adversely affected by lower soil moisture content, potentially leading to lower yields compared to crops grown at Hatsebo. Reduced soil moisture significantly impacts the physiological activities of garlic (Al-Salami and Alhasnawi, 2023)

4.2.7. Unmarketable Bulb Yield (ton ha^{-1})

The analysis of variance indicated that the yield of unmarketable garlic bulbs was significantly affected ($P < 0.001$) by the main factors of inter-row spacing, intra-row spacing, and location. Additionally, the interaction between inter-row and intra-row spacing had a significant impact on unmarketable bulb yield yield (Appendix Table 4).

The combined analysis of variance across locations indicated that the interaction between inter-row spacing, intra-row spacing, and location significantly influenced unmarketable bulb yield ($P < 0.001$). In contrast to total and marketable bulb yields, the highest unmarketable bulb yield of garlic 4.78 tons per hectare was harvested under the growing conditions at Selekhlekha, compared to 3.86 tons per hectare at Hatsebo, both at the narrowest spacing of 10 x 5 cm conversely, the widest spacing of 30 x 15 cm yielded the lowest unmarketable yield with 0.08 tons per hectare at Hatsebo and 0.11 tons per hectare at Selekhlekha (Figure 4:3).

This difference may be attributed to variations in agro-ecology and soil texture, as discussed above and indicated in (Tables 3:1 and 3:2), which affect the overall growth and performance of garlic.

Higher temperature at Selekhlekha may affect the vegetative growth of the crop as it requires cold weather at early vegetative stage and higher temperature during bulb formation (McLourin et al., 2021). As a result, more unmarketable bulbs at Seleklekha could be produced compared to that of Hatsebo site. Moreover, the cambisol at the Selekhlekha site that has a lower water-holding capacity compared to the vertisols at Hatsebo, characterized by higher water retention capacity may contribute to soil moisture stress and ultimately result in the production of higher small-sized bulbs from its lower total bulb yield. Reduced soil moisture significantly impacts the physiological processes of garlic (Al-Salami & Alhasnawi, 2023)

4.2.8. Marketable Bulb Yield (ton ha^{-1})

The combined analysis of variance revealed that the marketable bulb yield of garlic was significantly influenced ($P < 0.001$) by the main effects of inter-row spacing, intra-row spacing, and location, as well as by the interaction effects of inter-row spacing and intra-row spacing ($P < 0.001$) (Appendix Table 4).

Significant interaction effects ($P < 0.001$) were also observed between inter-row spacing, intra-row spacing, and location. The highest marketable bulb yield of garlic16.31 tons per hectare was harvested at the Hatsebo experimental site, compared to 12.39 tons per hectare at Selekhlekha planted with a medium inter-row and intra-row spacing of 20 x 10 cm. However, the lowest marketable bulb yields of 8.91 tons per hectare at Hatsebo and 4.57 tons per hectare at Selekhlekh were recorded with the widest inter-row and intra-row spacing of 30 x 15 cm (Figure 4:2). Similar results were reported by (Tegen and Jembere (2021) on carrots, which indicated that higher marketable carrot root yields were obtained at Ribb compared to Woramit growing conditions.

This difference may be attributed to variations in temperature, soil type, and altitude, all of which affect garlic's growth and performance. As shown in (Tables 3:1 and 3:2), the higher temperatures at Selekhleka compared to Hatsebo may affect early crop growth and development. Seedling development and leaf growth improved in cooler temperatures (10-15°C) and shorter daylight hours ((Westerfield, 2021) Likewise, the soil type at the Selekhlekha site is characterized by lower moisture-holding capacity compared to the vertisol at Hatsebo, which retains more water. Consequently, crops at Selekhlekha may experience lower soil moisture during their growth period, leading to reduced yields compared to those grown at the Hatsebo.

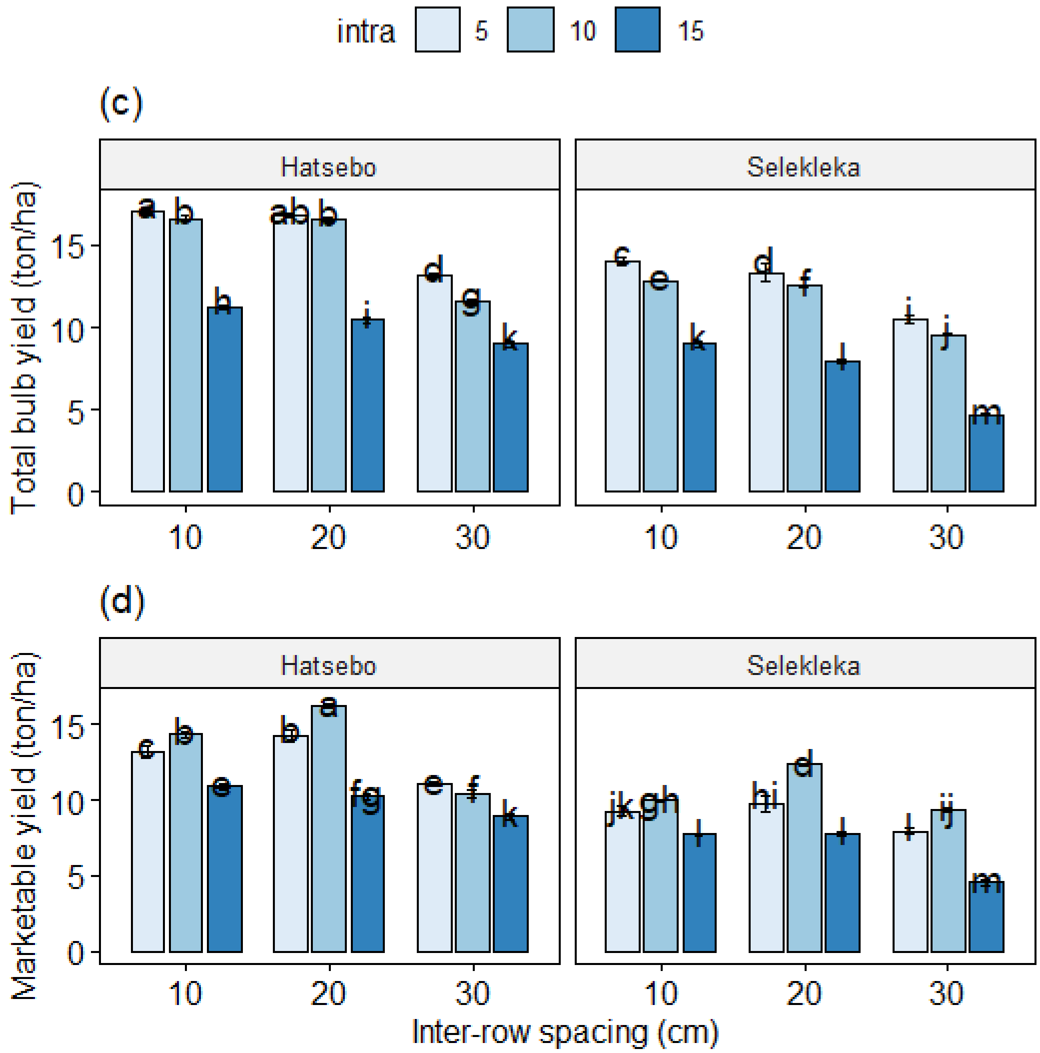


Figure 4:2 Mean total bulb yield (ton ha^{-1}) and marketable bulb yield (ton ha^{-1}) as affected by the interaction of inter-row spacing, intra-row spacing and location at Hatsebo and Selekhlekha, 2024.

Means followed by the same letter within a column are not significantly different at 5% probability level.

4.2.8.1. Marketable bulb size distribution

4.2.8.1.1. Small sized bulbs (< 4 cm)

The combined analysis of variance demonstrated that inter-row and intra-row spacing, as well as their interaction effects, significantly influenced the distribution of small-sized garlic bulbs ($P < 0.001$). Furthermore, main effect of location also had a significant effect ($P < 0.05$).

At the closest spacing of 10 x 5 cm, the highest percentage of small-sized bulbs (66.83%) was harvested. In contrast, the non-significant lowest percentage of small sized bulbs (8.16%) was observed at the widest spacing of 30 x 15 cm compared to the spacings of 20 x 10 cm and 20 x 15 cm. (Table 4:5).

Similar findings have been reported by Ayalew (2009) on garlic, Tegen *et al*. (2016) on onion and (Tegen & Jembere (2022) on head cabbage indicating that closer inter- and intra-row spacing resulted in higher yields of small-sized bulbs and cabbage heads. Likewise, Mitiku Ashenafi and Sintayehu Tenaye, (2023); Tekle (2015) noted that the highest yield of small-sized onion bulbs was occurred at the shortest intra-row spacing. This trend might be attributed to increased intense interplant competition for limited resources such as nutrients, water, and sunlight, which restricts bulb expansion and leads to a higher proportion of small-sized bulbs. Higher small-sized bulb productions at closer plant spacing negatively affect bulb quality, resulting in lower market prices.

The interaction of inter-row spacing, intra-row spacing, and location revealed that there were significant differences ($P < 0.001$) in the distribution of small sized garlic bulbs across the growing locations. Higher marketable small-sized bulbs were produced at the Hatsebo (6.81 ton per hectare) experimental site compared to the Selekhlekha growing conditions (6.13 ton per hectare) at the closer spacing of 10 x 5 cm whereas the lowest value 0.451 ton ha^{-1} at Hatsebo and 0.91 ton ha^{-1} at Seleklekha were obtained at the widest spacing of 30 x 15 cm (Figure 4:3).

More small sized bulbs observed at Hatsebo could due to the production of higher total bulb yield (17.05 ton per hectare) harvested at the narrowest spacing of 10 x 5 cm compared to that of Seleklekha experimental site with14.07 ton ha^{-1} as a result of variations in temperature and soil texture as indicated (Tables 3:1 and 3:2).

Higher temperature at Selekhlekha may affect the vegetative growth of the crop as it requires cold weather at early vegetative stage and higher temperature during bulb formation (McLourin et al., 2021). As a result, more small sized bulbs at Hatsebo could be produced from the highest total bulb yield (17.05 ton per hectare) harvested at the narrowest spacing 10 x 5 cm compared to that of Seleklekha site with 14.07 ton ha^{-1}. Moreover, the cambisol at the Selekhlekha site has a lower water-holding capacity compared to the vertisols at Hatsebo, characterized by higher water retention capacity may contribute to soil moisture stress and ultimately result in the production of lower small-sized bulbs from its lower total bulb yield. Reduced soil moisture significantly impacts the physiological processes of garlic (Al-Salami & Alhasnawi, 2023)

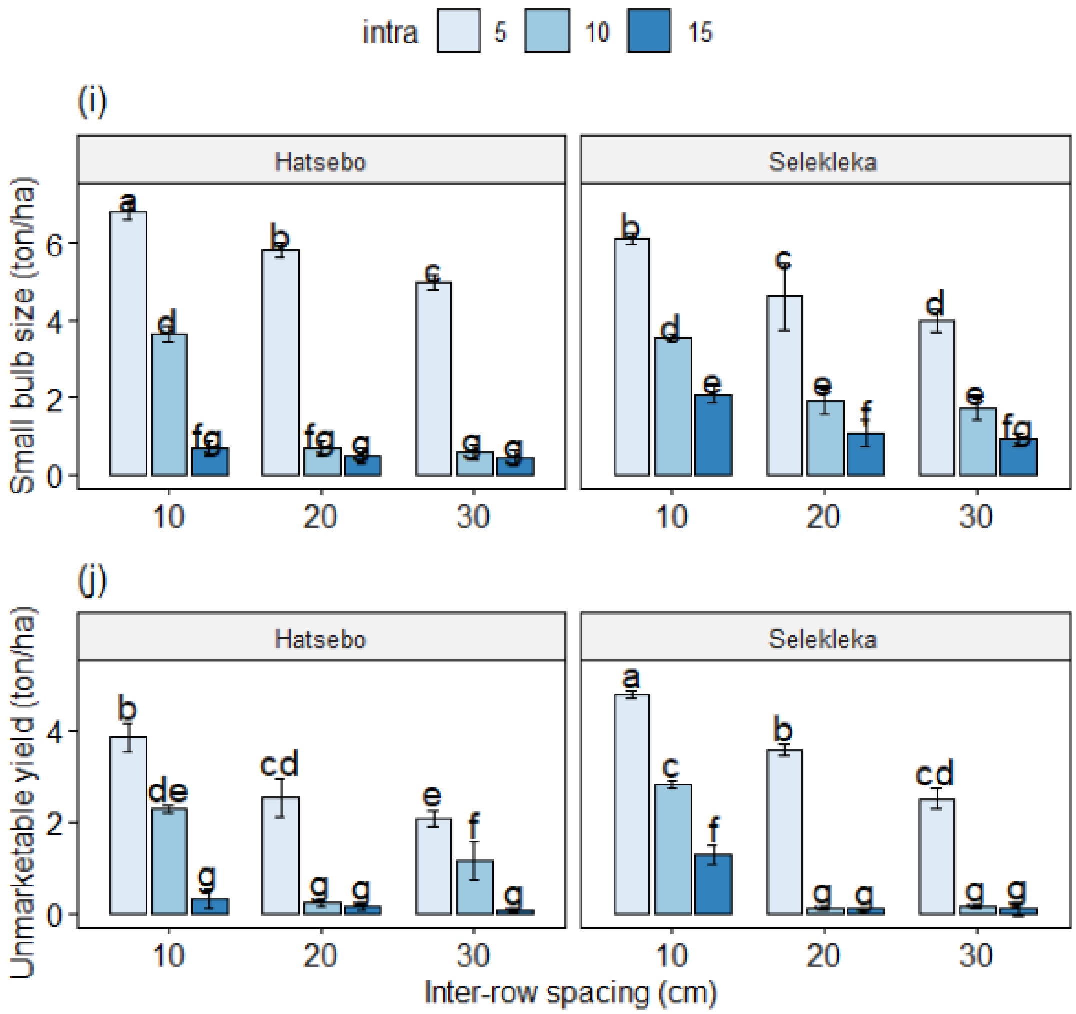


Figure 4:3 Mean unmarketable bulb and small size bulb distribution (ton ha^{-1}) as affected by the interaction of inter-row spacing, intra-row spacing and location at Hatsebo and Selekhlekha, 2024.

4.2.8.1.2. Medium sized bulbs (4-4.99 cm)

The combined analysis of variance revealed that the main effects of inter-row spacing, intra-row spacing, and location, as well as the interaction effect of inter-row and intra-row spacing ($P < 0.001$), significantly influenced the distribution of garlic medium bulb sizes (Appendix Table 5).

The non-significantly higher medium bulb size (54.29%) compared to 10 x 15 cm, 10 x 10 cm, 20 x 10 cm, and 30 x 10 cm was observed at the spacing of 20 x 15 cm. However, the lowest bulb size (29.49%) was recorded at the narrowest inter-row and intra-row spacing of 10 x 5 cm. (Table 4:5).

This finding aligns with the result of Tekle (2015) who noted that the weight of medium onion bulb size distribution increased with medium intra-row spacing. Similarly, Tegen *et al*. (2016) observed that the highest medium onion bulb size was achieved with the interaction of medium inter-row and intra-row spacing. Mitiku Ashenafi and Sintayehu Tenaye, (2023) also confirmed that the highest medium bulb size of onion (15.15 tons per hectare) was attained at an intra-row spacing of 10.5 cm, while the lowest (6.16 tons ha^{-1}) was at 2.5 cm.

The results suggest that the maximum distribution of medium bulb sizes at appropriate inter-row and intra-row spacing is likely due to reduced interplant competition and effective land usage, leading to increased individual bulb weight and improved overall quality.

The combined analysis of variance across the locations similarly indicated that the distribution of medium bulb sizes was significantly affected by the interaction of inter-row spacing, intra-row spacing, and location ($P < 0.05$). In contrast to small-sized bulb distribution, the highest medium bulb size (9.05 tons ha^{-1}) was recorded at Hatseb, compared to Selekhlekha, which yielded 5.82 tons ha^{-1}, from plants grown at the medium inter-row and intra-row spacing of 20 x 10 cm (Figure 4:4). The significant location variability in medium and large bulb size distribution might be might be due to differences in Temperature and soil type as indicated in (Table 3:1 and 3:2) and discussed in (Figure 4:3).

4.2.8.1.3. Large bulb size distribution (> 5 cm)

The main effects of inter-row spacing, intra-row spacing, and location and the interaction effect of inter-row spacing and intra-row spacing, significantly influenced the distribution of garlic large bulb sizes ($P < 0.001$) (Appendix Table 5). The quantity of large-sized bulb distribution was increased at wider plant spacing. Highest percentage of large bulb size (48.29%) was achieved from the interaction of the wider inter -and intra -row spacing of 30 x 15 cm while the lowest bulb size (5.94%) was recorded at the closest inter -and intra -row spacing of 10 x 5 cm (Table 4:4).

This result is in agreement with the findings Tegen *et al*. (2016) on onions and Tegen and Jembere (2022) on head cabbage, who indicated that larger bulb sizes increased with wider inter-row and intra-row spacing, recorded at 25 x 10 cm for onions and 65 x 50 cm for head cabbage respectively. Likewise, Ayalew (2009) on garlic and Tekle (2015) on onions reported that higher yields of large bulbs were achieved with medium inter-row and intra-row spacing. Moreover, Mitiku Ashenafi and Sintayahu Taye (2023) confirmed that the higher yield of large-sized bulbs (10.8 tons per hectare) was harvested at an intra-row spacing of 10.5 cm, while the lowest yield at 2.5 cm.

The significant increase in large bulb size distribution with medium inter-row and intra-row spacing, and a decrease in small-sized bulbs, might be attributed to reduced competition among adjacent plants for resources. This allows for better translocation of assimilates to maximize bulb expansion.

Large bulb size distribution was also significantly influenced by the interaction of inter-row spacing, intra-row spacing, and location ($P < 0.001$). Similar to medium-sized bulbs, garlic grown under the medium inter-row and intra-row spacing of 20 x 10 cm yielded the highest large bulb size (6.55 tons ha^{-1}) at Hatsebo compared to Selekhlekha (4.67 tons ha^{-1}). Conversely, the lowest value of large bulb size 0.074 tons ha^{-1}at the Hatsebo and 0.54 tons ha^{-1} at the Seleklekha were harvested from the closest spacing of 10 x 5 cm (figure 4:4).

This difference may be attributed to variations in agroclimatic conditions and soil types, which influence the growth and development of garlic (Tables 3:1 and 3:2). The Hatsebo site, situated at a higher elevation with moderate temperatures and light vertisols, produced larger bulbs compared to Selekhlekha, which has a higher temperature and the cambisol soil with lower water retention capacity. The cambisol at Selekhlekha, combined with higher temperatures, may lead to lower soil moisture content, and adversely affecting the physiological activities of garlic. This could result in reduced leaf growth and plant height, ultimately producing smaller bulbs and fewer large-sized bulbs (Al-Salami & Alhasnawi, 2023).

The results indicate that the highest distributions of medium and large bulb sizes were observed with medium inter-row and intra-row spacing of 20 x 10 cm. This combination likely approaches the optimal plant population density, leading to lower resource competition and minimizing unproductive land, which in turn increases individual bulb weight and enhances the quality of medium and large bulbs.

Table 4:4 Interaction effect of inter-and intra-row spacing patterns on small, medium and large bulb size distribution of garlic at Htsebo and Seleklekha, 2024.

Inter x intra(cm)	Smalls bulb size distributions %	Mediums bulb size distributions %	Larges bulb size distributions %
10 x 5 cm	66.83a	29.49d	5.94f
10 x 10 cm	31.23d	48.57abc	23.65d
10 x 15 cm	16.51d	51.43ab	29.63c
20 x 5 cm	47.15b	45.41bc	9.66ef
20 x 10 cm	9.71fe	51.31ab	39.98b
20 x 15 cm	8.56fe	54.29a	41.45b
30 x 5 cm	43.42b	46.73bc	12.86e
30 x 10 cm	12.23de	49.16abc	40.34b
30 x 15 cm	8.16fe	43.23c	48.29a
Mean	27.09	46.62	27.98
P-value	0.0027	0.00016	0.0024
LSD(0.05)	5.79	6.39	4.91

Means followed by the same letter within a column are not significantly different at 5% probability level.

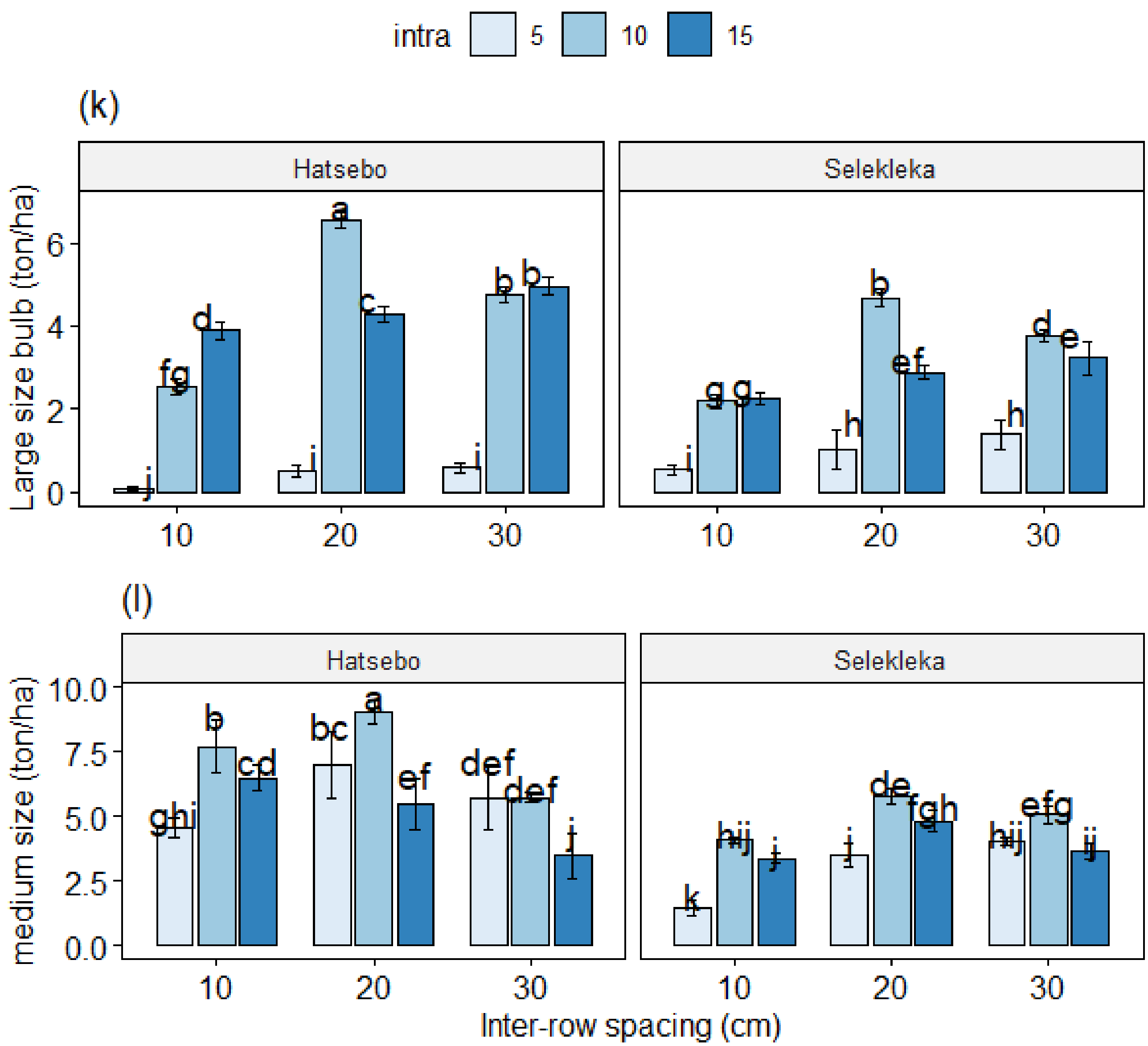


Figure4:4 Mean medium and large size bulb distribution (ton ha^{-1}) as affected by the interaction of inter-row spacing, intra-row spacing and location at Hatsebo and Selekhlekha, 2024.

4.2.9. Above ground shoot dry weight

The dry weight of above-ground shoots varied significantly (P < 0.001) as influenced by the main effects of inter-row spacing, intra-row spacing, and location. As well, the interaction of inter-row spacing and intra-row spacing significantly affected this trait (P < 0.05) Appendix Table 5).

As plant spacing increased, the dry weight of individual garlic shoots also increased. The highest shoot dry weight (4.72 g) was recorded from plants harvested at the wider spacing of 30 x 15 cm, while the lowest value of 2 g was observed at the closest spacing of 10 x 5 cm (Table 4:5).

This finding is in agreement with the studies of Ayalew (2009); Mohamed (2018) on garlic and Attaya *et al*. (2024) on onions, who indicated that the shoot dry weights of garlic and onions increased with wider row spacing. Similarly, Moges and Masrie, (2019) noted that a higher shoot dry weight of shallots (4.99 g) was recorded at the widest intra-row spacing of 20 cm, compared to the lower weight of 2.45 g at the closest spacing 5 cm.

Growing garlic at lower plant populations tends to yield higher shoot dry weights due to an increased availability of resources. With fewer plants competing for resources, each plant receives more assimilates, which promotes the growth and development of robust foliage, ultimately resulting in a greater accumulation of dry matter. More assimilates lead to higher shoot dry weight.

4.2.10. Bulb dry weight

The combined analysis of variance indicated that the main effects of inter-row spacing, intra-row spacing, and location, as well as the interaction of inter-row and intra-row spacing ($P < 0.001$), significantly influenced garlic bulb dry weight (Appendix Table 5). Bulb dry weight significantly increased with wider inter-row and intra-row spacing. The widest spacing of 30 x 15 cm resulted in the highest bulb dry weight of 22.51 g, while the narrowest spacing of 10 x 5 cm recorded the lowest weight 5.86 g per bulb (Table 4:5).

The result is in line with the findings of Ayalew(2009) who reported that higher garlic bulb dry weight per plant was achieved with wider inter-row and intra-row spacing of 30 cm and 15 cm, respectively. Similarly, Muneer *et al*. (2017) found that higher bulb dry weight obtained at 16 x 5 cm, while the smallest weight was noted at 12 x 3 cm. Mohamed (2018) also indicated that a higher bulb dry weight was obtained from planting one row per ridge compared to two or three rows. This is likely due to lower plant density, which allows higher assimilation and results in larger bulbs, thus contributing to higher bulb dry weight.

4.2.11. Total biomass dry weight

The combined analysis of variance demonstrated that main effects of inter -row spacing, intra -row spacing and location significantly (P < 0.001) influenced total biomass dry weight of garlic. As well the trait also significantly (P < 0.001) affected by the interaction effects of inter -row spacing and intra row spacing (Appendix Table5). Total biomass dry weight increased as inter - and intra -row spacing increased. Highest total biomasses dry weight (27.22 g) was recorded from plots planted using 30 x 15 cm. In contrast to this, the least value (7.86 g) was obtained from plots of 10 x 5 cm (Table 4:5).

The result is in agreement with the findings of Ayalew (2009) who noticed that as the spacing between and with plants increases, the total biomass dry weight also increases.. Similar observations were also indicated by Legese (2023); Teshale and Tekeste (2020) confirmed that higher total biomass dry weight of garlic was obtained at wider intra-row spacing, while the lowest values were recorded at the narrowest spacing. This phenomenon might be associated to reduced competition for resources between plants, and allowing for more vigorous plant growth and larger bulb development than higher plant densities.

Table 4:5: Interaction effect of inter-and intra-row spacing on above ground shoo, bulb dry weight and total biomass dry weight at Hatsebo and Selekhlekha, 2024.

Inter x intra spacing(cm)	Shoot dry weight (g)	Bulb dry weight (g)	Total biomass dry weigh (g)
10 x 5 cm	2.00g	5.86h	7.86i
10 x 10 cm	3.14e	11.35f	14.49f
10 x 15 cm	3.484d	14.51e	17.99e
20 x 5 cm	2.39f	6.58h	8.97h
20 x 10 cm	3.89c	16.19d	20.08d
20 x 15 cm	4.43b	20.57b	25.01b
30 x 5 cm	2.57f	8.57g	11.14g
30 x 10 cm	4.14dc	18.18c	22.3c
30 x 15 cm	4.72a	22.51a	27.22a
Mean	3.42	13.81	17.23
P-value	0.0194	<0.001	< 0.001
LSD(0.05)	0.282	1.094	1.08
CV%	7.005	6.73	5.32

Means followed by the same letter with in a column are not significantly different at 5% probability level.

4.3. Partial budget Analysis

Marketable garlic bulb yield obtained from Hatsebo and Selekleks sites were combined and used for the economic analysis. Table 5:1 shows the garlic seed cost, labor cost, total variable cost, gross and net benefit earned from the different treatment combinations of inter- and intra-row spacing. Among the 9 treatment combinations tested, 5 treatments were dominated and excluded from the marginal analysis (Table 5:2). In comparison with the inter- and intra-row spacing of 30*15 cm, a spacing of 20 cm inter-row and 15 cm intra-row spacing offered a MRR of 614.5%. The only difference in these spacing patterns was only in the inter-row spacing. The analysis indicates that reducing the inter-row from 30 to 20 cm offered more return because of more garlic yield that was harvested from relatively denser plant population. When compared with 20*15 cm of inter- and intra-row spacing, the spacing of 30*10 cm gave a MRR of 489.1%. Even though these treatments have difference in both the inter- and inter-row spacing, the latter treatment had more population density because of the narrower spacing between plants within a row which consequently resulted in relatively more yield in the latter treatment than the former ones. In comparison with 30*10 cm of inter- and intra-row spacing, the spacing of 20*10 cm further gave a MRR of 1546.9% (Table 5:3). The spacing between plants within a row was the same (10 cm) in these treatments. The only difference was the inter-row spacing where the latter treatment had a narrower spacing between the rows which consequently resulted in more population density and garlic yield in the latter treatment.

On the basis of the ranking of the residual analysis, 20*10 cm was the most profitable treatment to the farmers who grow garlic in the study area. This treatment is then followed by 30*10 cm, and 20*15 cm inter-and intra-row spacing in profitability.

Table 4:6 Seed, labor and total variable cost, gross benefit and net benefit obtained from different inter- and intra-row spacing. (Combined data from Hatsebo and Selekleka was used for the economic analysis).

Inter *intra row spacing (cm)	Seed cost (Birr)	labor cost (Birr)	Total variable Cost (Birr)	Gross benefit (Birr)	Net benefit (Birr)
10 * 5	479159	43400	522559	1391721	869162
10 * 10	239584	21700	261284	1812686	1551402
10 * 15	159712	14460	174172	1494198	1320026
20 * 5	383334	34720	418054	1649407	1231353
20 * 10	191659	17360	209019	2320636	2111617
20 * 15	127777	11774	139551	1542766	1403216
30 * 5	319442	28934	348376	1527732	1179356
30 * 10	159712	14460	174172	1746733	1572561
30 * 15	106481	9640	116121	1375371	1259250

Gross benefit was calculated based on garlic bulbs which were sorted into large, medium and small size categories (Appendix Table 6).

Table 4:7: Dominance analysis for the different inter- and intra-row spacing evaluated in Hatsebo and Selekleka sites, 2024. (Combined data was used for the economic analysis)

Inter *intra row spacing (cm)	Seed cost (Birr)	labor cost (Birr)	Total variable Cost (Birr)	Gross benefit (Birr)	Net benefit (Birr)	Dominance Analysis
30 * 15	106481	9640	116121	1375371	1259250	
20 * 15	127777	11774	139551	1542766	1403216	
10 * 15	159712	14460	174172	1494198	1320026	D
30 * 10	159712	14460	174172	1746733	1572561	
20 * 10	191659	17360	209019	2320636	2111617	
10 * 10	239584	21700	261284	1812686	1551402	D
30 * 5	319442	28934	348376	1527732	1179356	D
20 * 5	383334	34720	418054	1649407	1231353	D
10 * 5	479159	43400	522559	1391721	869162	D

Table 4:8 Marginal rate of return (MRR, %), and residual analysis for the non-dominated inter- and intra-row spacing evaluated in Hatsebo and Selekleka sites, 2024.

Inter * intra row (cm)	Seed cost (Birr)	labor cost (Birr)	Total variable Cost (Birr)	Gross benefit (Birr)	Net benefit (Birr)	MRR (%)	Minimum rate of return (100%* TCV)	Residua (Birr)	Rank in residual
30 * 15	106480	9640	116120	1375371	1259250		116120	1143129	
20 * 15	127776	11774	139550	1542766	1403216	614.5	139550	1263665	3
30 * 10	159712	14460	174172	1746733	1572561	489.1	174172	1398389	2
20 * 10	191659	17360	209019	2320636	2111617	1546.9	209019	1902598	1

Net benefit (NB) was calculated by subtracting total variable costs from the gross benefits obtained from the adjusted marketable bulbs, which were graded and multiplied by their respective price levels. The highest net benefit, to 2,111,617 Eth-Birr per hectare, was achieved from the medium inter- and intra-row spacing treatment of 20 x 10 cm with a double-row planting pattern.

Marginal rate of return was analyzed to compare the cost and net benefit of the treatments using the procedure described by CIMMYT (1988). All treatment combinations were arranged in an ascending order of their total variable costs (TVC). Any treatment combinations that have a net benefit equal to or less the than previously arranged treatment were dominated and eliminated from further analysis and the non-dominated are selected.

Marginal rate of return (MRR) was calculated as a change in the net benefit divided by change in total variable costs of the treatment combinations and expressed in percentage. The marginal rate of return (MRR) was calculated by taking the change in net benefit divided by the change in total variable costs for the treatment combinations, and this was expressed as a percentage. The highest MRR recorded was 1546.9%, which was associated with the medium inter- and intra-row spacing treatment combination of 20 x 10 cm.

According to CIMMYT (1988), the minimum acceptable marginal rate of return for farmers falls within the range of 50% to 100%. The study revealed that the MRR for all selected treatments exceeded 100% (see table), indicating that these treatment combinations are economically viable. Therefore, the inter- and intra-row spacing treatment combination of 20 x 10 cm is the most economically important treatment recommended for garlic-growing farmers, as it offers a moderate cost of production and significantly higher net benefits of 2,111,617 Eth-Birr per hectare.

4.4. Correlation Analysis

The purpose correlation analysis between different response variables was used to determine how the yield components and growth characters affecting the marketable bulb yield of garlic. Accordingly, the correlation analysis indicated that marketable bulb yield was very highly significantly and positively correlated with total bulb yield (r=0.9***), medium bulb size distribution (r=0.72***), number of leaves per plant (r=0.48***). It also significantly and negatively(r=-0.30**) correlated with clove width. However, marketable bulb yields none significantly correlated with the rest response variables because, the highest marketable bulb yield of garlic was obtained from the medium inter and intra row spacing with medium value of these response variables. Teshale and Tekeste (2020) indicated that marketable bulb yield of garlic was very highly significantly and positively correlated with total bulb yield (r=0.9***) and harvest index (r=0.62***). The authors also indicated that marketable bulb yield was none significantly and negatively correlated with days to maturity, plant height and leaf length.

Total bulb yield was very highly significantly and positively correlated with medium bulb size distribution (r=0.44***), small size bulb distribution(r=0.61***), unmarketable bulb size distribution (r=0.57***), total biomass dry weight (r=0.52***) and highly significantly and positively (r=0.42**) correlated with number of leaves per plant, and leaf width (r=0.1**). The trait also significantly and negatively correlated with bulb dry weight (r=-0.52***), clove width (r=-0.52***), plant height (r=-0.46***), clove weight (r=-0.53***), bulb length (r=-0.55***), bulb dry weight (r=0.-52***) soot dry weight (r=-0.51***), average bulb weight (r=-0.39**), maturity (r=-0.31*) and leaf length (r=-0.28*). Teshale and Tekeste (2020) showed that garlic bulb yield was negatively correlated with plant height, leaf length and leaf width bulb diameter and average bulb weight.

Small size bulb distribution is very highly significantly and positively (r=-0.90***) only with unmarketable bulb yield. However it is very highly significantly and negatively correlated with bulb diameter(r=-0.86***), leaf width (r=-0.82***), total biomass dry weight (r=-0.87***), average bulb weight (r=-0.82***), days to maturity (r=-0.82***), leaf length(r=-0.72***), plant height (r=-0.76***), clove weight (r=-0.84***) and bulb length (r=-0.86***). Similarly unmarketable bulb yield so do the as small size bulb distributions that it is significantly and negatively correlated with all response variables except with small size bulb distributions correlated positively. This implies that as small sized bulb distribution increases, consequently unmarketable bulb yield increased.

Unlike small size bulb distribution medium size bulb distribution significantly and positively correlated with bulb diameter (r=0.36**), leaf width (r=0.35*), total biomass dry weight (r=0.28*), average bulb weight (r=0.29*), days to maturity (r=0.48***), leaf length (r=0.37*), plant height (r=0.27*) and large bulb distribution (r=0.41**). However the trait is significantly and negatively correlated with unmarketable bulb yield (r=-0.35**). Similar to medium size bulb distribution, large bulb size distribution also significantly and positively correlated with bulb diameter (r=0.82***), leaf width (r=0.78***), bulb dry weight (r=0.81***) and number of leaves per plant (r=0.42**). Also this trait is very highly significantly and negatively correlated with small bulb size distribution (r=-0.89***) and unmarketable bulb yield of garlic (r=-0.81***), The positive correlation of medium and large bulb size distribution with the growth and yield response variables indicated that as inter and intra row spacing increases, interplant competition decreased as a result the value of the growth and yield parameters increased and thereby the value of medium and large bulb size distribution increased. Guesh (2015) reported that is small size bulb distribution only significantly and positively correlated with unmarketable bulb yield but significantly and negatively correlated with the other response variables. On the contrary way, medium and large bulb size distributions were significantly and negatively correlated with unmarketable bulb yield and small bulb size distributions and positively correlated with the other response variables.

Bulb diameter was very highly significantly and positively correlated with leaf width (r=0.95***), avegage bulb weight (r=0.90***), days to maturity (r=0.90***), leaf length (r=0.87***), clove width (r=0.85***), plant height (r=0.84***), clove weight (r=0.85***) and bulb length (r=0.96***). Similarly, Average bulb weight significantly and positively correlated with maturity period (r=0.87***), leaf length(r=0.85***) clove width (r=0.82***), plant height (r=0.84***), clove weight (r=0.87***) and bulb length (r=0.89***). This significant positive correlation indicated that, bulb diameter and average bulb weight increased in response to the increasing patterns of inter and intra row spacing which lowers interplant competition and increased the growth and yield components of garlic. Fakhar, et al. (2019) supported this result

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The findings of this research indicated that the performance of garlic regarding all growth yield and yield traits except the total grand mean of unmarketable and small sized bulb distributions of garlic was better at the Hatsebo location as compared to Selekhlekha growth conditions. Even though there was an interaction effect between spacing and location, the overall trend of the spacing remained relatively consistent across locations. Consequently, it is unnecessary to provide location-specific recommendations for each site. The research findings clearly noticed that yield per hectare was significantly influenced by the varying levels of inter-row and intra-row spacing patterns. Total bulb yield, unmarketable yield and the distribution of small sized bulb distributions increased in response to the decreasing trends of inter and intra row spacing. The narrowest spacing of 10 cm × 5 cm which accommodates 1,000,000 plants ha^{-1} produced significantly highest total bulb yields of 70.05 ton/ha and 14.07 ton/ha at Hatsebo and Selekhlekha, respectively. This spacing also produced the highest amount of unmarketable yield of 3.86 ton/ha and 4.78 ton/ha at the two locations, along with smaller bulb size distributions of 6.81 ton/ha and 6.13 ton/ha. In contrast, the lowest values for these parameters were observed at the wider treatment combination of 30 x 15 cm, which supported with the with lowest plant population 222,222 plants ha^{-1}. Notably, the medium inter-row and intra-row spacing of 20 x 10 cm which accommodates 400,000 plants ha^{-1} produced significantly the highest marketable yields, recorded as 16.31 ton/ha and 12.39 ton/ha at the Hatsebo and Selekhlekha sites respectively, along with medium bulb sizes of 9.05 ton/ha and 5.82 ton/ha, and large bulb sizes of 6.55 ton/ha and 4.67 ton/ha, This spacing pattern optimize plant population, reduce interplant competition, and minimize missed gaps in planting, leading to the production of more medium and large, quality bulbs with fewer defects compared to closer planting arrangements.

Conversely, while lower plant densities with wider inter- and intra-row spacing yielded larger and higher-quality bulbs, they negatively impacted the marketable bulb yield of garlic due to a diminished yield per unit area. Even though higher bulb yield were obtained at the narrowly spaced inter and intra row spacing of 10 x 5 cm in both locations, most proportion of the harvested bulbs are of smaller bulb size and unmarketable bulbs because of stiff interplant competition between adjacent plants between rows and within rows of plants.

Based on the findings, it can be concluded that 20 x 10 cm with double row planting pattern is the best inter-row and intra-row spacing treatment combination. The economic analysis result also revealed that 20 x 10 cm inter-and intra-row spacing recorded the highest net benefit (2,111,617 Eth-Birr ha^{-1}) with an acceptable marginal rate of return (1546.9%). Consequently, this treatment combination is deemed optimal for garlic production in the Central and North Western zones, as well as in other regions with comparable agro-ecological conditions, due to the consistent trends observed across various locations.

5.2. Recommendation

It is recommended to use a spacing of 20 cm between rows and 10 cm between plants in a row adjusted with 30 cm furrow width (30 cm x 20 cm x 10 cm) with double row planting pattern under ridge furrow irrigation because of its effect on offering higher marketable with quality garlic bulbs and its profitability. However, it is essential that these findings be complemented with appropriate fertilizer recommendations on multiple locations and seasons to have a full package for garlic production under furrow irrigation conditions.

6. REFERENCES

AFETA, B. M. (2022). Effect of Intwa-Row Spacing and Rates of NPS Fertilization on Bulb Yield and Related Traits of Shallot (*Allium cepa* L.var.ascalonicum) in Chiro District West Hareghe. M.Sc. Thesis Presented to the School of Plant Sciences. Pp.55

Ahmed, I., Khan, M. A., Khan, N., Ahmed, N., Waheed, A., Yazdan, F., Khan, S., and Aslam, S. (2017). Impact of Plant Spacing on Garlic Rust (*Puccinia allii*), Bulb Yield and Yield Component of Garlic (*Allium sativum* L.). *Pakistan Journal of Agricultural Research*, 30(4), 380–385.

Al-Salami, M. O. G., and Alhasnawi, N. J. R. (2023). Effect of Water Stress and Selenium Spraying on Vegetative and Yield Indicators of Garlic (*Allium sativum* L.) *IOP Conference Series: Earth and Environmental Science*, 1262(5), 1-7.

Alemu, D., Kitila, C., Garedew, W., Jule, L., Badassa, B., Nagaprasad, N., Seenivasan, V., Saka, A., and Ramaswamy, K. (2022). Growth , yield , and yield variables of onion (*Allium Cepa* L .) varieties as influenced by plantspacing at DambiDollo , Western Ethiopia. *Scientific Reports*, 12(25063), 1–9. https://doi.org/10.1038/s41598-022-24993-x

Amare, G., Mohammed, W., and Tana, T. (2020). Effect of Plant Spacing and Np Fertilizer Levels on Growth , Seed Yield and Quality of Onion (*Allium cepa* L .) at Shewa Robit , Northern Ethiopia: *The Open Biotechnology Journal*, 14(13), 12–22.

Asfaw Zeleke and Eshetu Derso (2015). Production management of major vegetable crops in Ethiopia, December 2015, Addis Ababa, Ethiopia. Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; KOPIA Ethiopia Centre, Addis Ababa, Ethiopia. Printed at Eth-Cana Printing Press, Addis Ababa, Ethiopia. 149 pages

Asnake, D., Alemayehu, M., and Misganaw, M. (2024). Optimum intra-row spacing and clove size for the economical production of garlic (*Allium sativum* L.) in Northwestern Highlands of Ethiopia. *Open Agriculture*, 9: 20220226, 1–10.

Aswani, N., K Karjadi, A. and EfendiN, M. A. (2022). Combination of genotype , plant spacing , and plant density for improving growth and yield of garlic national varieties Combination of genotype , plant spacing , and plant density for improving growth and yield of garlic national varieties. *IOP Conf. Series: Earth and Environmental Science*, 1018 (2022) 012005, 1–11.

Atalay, D., Alemayehu, M., and Ayana, D. (2022). Effects of Intra-row Spacing and Nitrogen Fertilizer Rates on Growth , and Yield of Onion (*Allium cepa* L .) Under Irrigation in Mecha District of Amhara , Ethiopia. *International Journal of Bioorganic Chemistry*, 7(1), 17–22.

Attaya, E., Bardisi, A., Osman, A., Ismail, H., Alwutayd, K. M., Al-shammari, W. B., Nadi, A., Al-qahtani, S. M., Ibrahem, S., and Abdelaal, K. (2024). Effect of nitrogen fertilization levels and plant density on dry weight , yield components and bulb quality of onion plant. *Notulea Botanicea Horti Agrobotanici*, 52(1), 1–15.

Atttif, J., Chani, I., Amin, B., and Hayat, S. (2019). Influence of Different Photoperiod and Temperature Regimes on Growth and Bulb Quality of Garlic (*Allium sativum* L.) Cultivars. *Agronomy*, 9 (879), 1–21.

Ayalew, A. 2009. Effect of Inter and Intra Row Spacings on Yield and Growth of Garlic (Allium sativum L.) Varieties ta Dabat, Northern Ethiopia. M.Sc. Thesis Presented to the Department of Plant Science, Hawssa Uuniversity, Pp .106

Bachman, J. and Hinman, T. 2008. Garlic organic production. National Sustainable Agriculture Information Service: ATTRA 1-800-346-9140 www.attra.ncat.org , Pp. 1-6.

Birhanu Lencha Taye Buke. (2017). Effects of Clove Size and Plant Density on the Bulb Yield and Yield Components of Garlic (*Allium sativum* L .) in Sodo Zuria. *Journal of Natural Sciences Research*, 7: 8–16

Central Agricultural Census Commission (CACC). 2002. Report on the preliminary result of area, production and yield of temporary crops (Meher season private peasant holdings). Part II. Ethiopian Agricultural sample Enumeration, (2001/2002). Federal Democratic Republic of Ethiopia, Central Statistical Authority, Volume 1, Addis Ababa,Pp.1-115.

Central Statistical Agency (CSA). 2021. The preliminary results of area, production and yield of temporary crops. Statistical Bulletin, Volume 1, Addis Ababa, Ethiopia. CSA (Central Statistical Agency). Agricultural sample survey, report on area and production of major crops (Meher season private peasant holdings) 2020/2021. Federal Democratic Republic of Ethiopia, Central Statistical Agency, Addis Ababa, Ethiopia, Statistical Bulletin 590; 2021.https://www.statsethiopia.gov.et/wpcontent/uploads/2021/05/2013-Meher-Report. Final pdf, Pp.1-139.

CIMMYT (International maize and wheat improvement center). 1988. From Agronomic Data to Farmer Recommendations: An Economics Workbook. DF, Mexico,Pp.1-59.

Endalkachew, B., Zerihun , T. and Demelash, G. (2024). Effect of Intra Row Spacing on Growth, Yield Components and Yield of Garlic (*Allium sativum* L .) at Fitch, North Showa Zone of Oromia, Ethiopia. *Annals of Experimental and Molecular Biology*, 6(1), 1–6.

Esuyawukal-Moges1+, K., Esuyawukal-Moges1+, K., and Biruk-Masrie2, Z. (2019. Growth and yield Response of Shallot (*Allium cepa var . aggregatum*) Varieties to Intra-Row in Eastern Amhara, Ethiopia. *Current Research in Agricultural Sciences*, 6(2), 157–168.

Fakhar, F., Biabani, A., Zarei, M., and Moghadam, A. N. (2019). Effects of cultivar and planting spacing on yield and yield components of garlic (*Allium sativum* L .). *Italian Journal of Agronomy*, 14(303), 108–113.

FAOSTAT Food and Agriculture Organization of the United Nations Statistics) 2023 https://www.fao.org/faostat/en/#data/QCL *accessed; 8/1*/2025.

Fekry, W. A. (2017). Fekry, W. A. (2017). Impact of plant density and NPK fertilizers rates on onion (*Allium cepa* L .) growth , yield , bulb quality and storability. *Middle East Journal of Applied Sciences*, 07(04), 766–777.

Gaikwad, D. G., Shinde, S. J., Panchal, K. N., and Moklikar, M. S. (2018). Studies on Influence Response of Plant Density on Growth and Yield of Garlic (*Allium sativum* L .). *International Journal of Current Microbiology and Applied Sciences*, *6*, 2891–2897.

Gebrekorkos, G., Berhe, H., and Abera, K. (2017). Effect of inter and intra row spacing on the yield and yield components of Onion (*Allium cepa* L at Mehoni. *African Journal of Plant Science*, 11, 86–91.

Gebremichael, Y., Asgele, K., Gebretsadik, G., and Abebe, E. (2019). Effects of inter and intra-row spacing on yield and yield attributes of onion (*Allium cepa* L.) under North Western zones of Tigray. *International Journal of Life Science*, 7:2320-7817 (p) 518–524.

Goldy, R., District, S., & Agent, V. (2000). Producing Garlic in Michigan. Southwest Michigan Research & Extension Center: Michigan University Extension, PP. 1–12.

Hannan, R. M. (2001). Crop Profile for Garlic in Washington Crop Profile for Garlic in Washington. USDA/Western Regional Plant Introduction Station: Washington State University, PP. 1-6.

Imo, C., and Salvation, J. (2019). Medicinal Properties of Ginger and Garlic. *A Review*. *Current Trends Biomedical Eng and Biosci*. 2019; 18(2):0048 555985. DOI: 10.19080/CTBEB.2019.18.55598518(2). Pp.1-52.

Kamau, J. M. (2019). Garlic, Turmeric and Ginger Farmers Guide. Agri Busines and Moder Farming:Pascal Logistic International, Pp.1-50.

Kumar, P., Kumar, S., and Aulakh, S. S. (2018). Effect of spacing and nitrogenous fertilizer on growth and yield parameters of garlic (*Allium sativum* L .). *International Journal of Chemical Studies*, 6(4), 356–359.

Legese, D. G. (2023). Intra Row Spacing Effect on Growth and Yield Performance of Garlic((*Allium sativum* L .) at Wolkite University , Gurage Zone , Central Ethiopia. *Journal of Plant Sciences*, 11(5), 160–163.

McLourin, J., Westerfield, R., Adams, D. and Eaker, D. 2023. Garlic Production for the Gardener. Cooperative Extension Service: University of Georgia College of Agriculture and Environmental Science, PP. 1-8.

Mebratu, M., & Mulie, M. (2019). Intra Row Spacing Effect on Growth Performance of Garlic (*Allium Sativum* (L .)) at Wolaita Sodo Southern Ethiopia. *Journal of Natural Sciences Research*, 9(19), 47–53.

Medina, J. D. and García, H.S. 2007. Garlic Post-harvest Operations. Food and Agricultural Organizations of United Nations, 1(3): 1-14.

Mekonnen, A., and Gadisa, N. (2021). Agronomic Practices for Improving Garlic (*Allium sativum* L.) Production and Productivity in Ethiopia Review. *World Journal of Agricultural Sciences*, 17(6), 469–477.

Melesse, M. G., Zeleke, A. A., & Zegeye, B. H. (2024). The effect of bed types and inter-rows spacing on yield and quality of onion in Fogera District of South Gondar Zone , Northwestern Ethiopia. *Advancement in Science and Technology Research*, 6(2437–1319), 1–7.

Mengesha, W., and Tesfaye, A. (2015). Effect of Spacing in Incidence and Severity of Garlic Rust (*Puccinia Allii (Rudolphi*.) and Bulb Yield and Related Traits of Garlic at Eastern Ethiopia. *Journal of Plant Pathology & Microbiology*, 6(10),1–4.

Mitiku Ashenafi and Sintayehu Tenaye. (2023). Yield and Yield Components of Onion as Influenced by Intra-Row Spacing and Nitrogen Fertilizer Levels. *Asian Journal of Research in Crop Science*, 8(4), 109–124.

Mohamed, A. S. B. and H. E. (2018 Effect of Plant Density on Growth and Yield of Two Garlic Cultivars Under Sohag Climatic Conditions. *Journal of Productivity and Development* 23 (3), Pp. 679-690.

Muneer, N., Hussain, M., Ahmad, M. J., Khan, N., Hussain, N., and Hussain, B. (2017). Effect of planting density on growth, yield and quality of Garlic(*Allium sativum* L.) at Rawalakot, Azad Kashmir. *International Journal of Agronomy and Agricultural Research*, 10(1), 42–51.

DK Murmu, TK Hembram, A. D. and B. Das. (2019). Influence of planting time and spacing for growth and yield of garlic (*Allium sativum* L.). *Journal of Pharmacognosy and Phytochemistry*, 8(1), 1054–1056.

Ngullie, R. (2017). Effect of plant and row spacing on growth and yield of onion under Mokokchung district of Nagaland. *International Journal of Plant Sciences,* Pp. 28–35.

Pavithra, A., Suchitra, V., Nirosha, K., Goud, R. P., and Saravanan, L. (2023). Study on Efficacy of Planting Methods and Spacing on Growth and Yield Attributes of Onion Produced through Bulb Sets. *Biological Forum – An International Journal*, 15(10), 33–38.

Raya, J., Perahu, T., Java, W., Padjadjaran, U., and Java, W. (2022). Effects of Plant Spacing and The Number of Loves per Planting Hole on Purple Bloch Disease,Growth and Yield of Garlic. *Applied Ecology and Environmental Research,* 20(6):5197-5207.

S.H. Abou Khadrah, and W. K. L. A. (2017). Yield and Quality Response of Onion (*Allium cepa var . cepa*) To Different Planting Date, Methods and Density. *Egypt.J.Agron.*, 39(2), 203–219.

Tegbew, W., Nigussie, D., and Kebede, W. (2018). Yield and Yield Components of Onion (*Allium cepa var . cepa*) Cultivars as Influenced by Population Density at Bir Sheleko, North-Western Ethiopia. *Academic Research Journal of Agricultural Science and Research,* 6(3), 72-192.

Tegen, H., & Jembere, M. (2021). In fl uences of spacing on yield and root size of carrot (*Daucus carota* L .) under ridge - furrow production. *Open Agriculture*, 6: 826–835.

Tegen, H., and Jembere, M. (2022). Influences of inter - and intra - row spacing on the growth and head yield of cabbage (Brassica oleracea var . capitata) in western Amhara. *Open Agriculture*, 7: 392–400

Tegen, H., Jembere, M., Mihiretu, E., and Enyew, A. (2016). Influences of inter and intra row spacing on yield , yield component and morphological characteristics of onion (*Allium cepa* L .) at Western Amhara region. *African Journal of Agricultural Research*, 11(20), 1797–1804.

Tekle, G. (2015). Growth, Yield and Quality of Onion (Allium cepa L.) as Influenced by Intra-raw Spacing and Nitrogen Fertilizer Levels in Central Zone of Tigray, Northern Ethiopia. M.Sc. Thesis Presented to the College of Agriculture and Environmental Sciences, Haramaya University. Pp.75

Teshale, M., and Tekeste, N. (2020). Growth and Yield Response of (*Allium sativum* L.) to Intra-row Spacing and Variety at Selekeleka , Northern Ethiopia: *The Open Biotechnology Journal*, 15: 1–11.

Thompson, C. (2018). Organic Garlic Production. Michigan State University Extension. Pp.1-8.

Uyeda, J., Tavares, K., Paull, R. E., Wages, S., and Baligad, L. (2022). Garlic Production Guidelines for Hawai‘i.University of Hawai‘i at Mānoa: College of Tropical Agriculture and Human Resources. 808: 1-7.

Vidya, G. (2015). Effect of Planting and Plant Densities on Yield and yield contribbuting Characters in Garlic *(Allium sativium L.) Plant Archives*. 15 (2), 2015 pp. 947-952

Appendix Table

Appendix table 8:1: Treatments mean comparison for the interaction effects of inter-and intra-row spacing on plant height (PH), leaf length (LL), leaf width (LW) at Hatsebo and Selekhlekha, 2024.

. Inter x intra(cm)	Plant height		Leaf length		Leaf width	
double row planting	Hatsebo	Selekhlekha	Hatsebo	Selekhlekha	Hatsebo	Selekhlekha
30 x 10 x 5 cm	48.9e	44.6c	34.33f	29.17d	1.37h	0.99f
30 x 10 x 10 cm	51.23de	48.9c	36.73ef	34.27c	1.62g	1.21e
30 x 10 x 15 cm	53.43d	49.4c	38.67e	33.73c	1.94f	1.57d
30 x 20 x 5 cm	52de	47.33c	36.97ef	31.27cd	1.57g	1.196e
30 x 20 x 10 cm	60.16c	58.3b	43.8d	38.93b	2.113e	1.72d
30 x 20 x 15 cm	61.93bc	61.14ab	45.86bcd	41ab	2.35cd	1.97bc
30 x 30 x 5 cm	51.63de	47.83c	37.67e	33.17c	1.58g	1.21e
30 x 30 x 10 cm	63.43bc	59.73ab	44.9cd	39.97b	2.29d	1.91c
30 x 30 x 15 cm	64.06ab	62.63ab	47.87ab	40.23b	2.53ab	2.09ab
Significance level	**	*	*	**	**	***
Grand mean	57.11	54.43	41.81	36.62	2.01	1.62
LSD(0.05)	3.55	5.085	2.84	3.43	0.13	
CV%	3.67	5.51	4.006	6.11	4.25	3.76

ns=non-significant, *, ** and *** indicates significant difference at probability alpha levels of 0.05 and 0.01and 0.001 respectively

Appendix table 8:2: Treatments mean comparison for the interaction effects of inter-and intra-row spacing on clove weight (CWT), clove width (CWDTH), shoot dry weight (SDW) and bulb dry weight (BDW) at Hatsebo and Selekhlekha, 2024.

. Inter x intra(cm)	CWT (gm)		CWDTH (cm)		SDW(gm)		BDW(gm)	
double row planting	Hatsebo	Selekhlekha	Hatsebo	Selekhlekha	Hatsebo	Selekhlekha	Hatsebo	Selekhlekha
10 x 5 cm	1.21f	1.17e	1.05d	0.63h	2.15	1.85	7.613i	4.1h
10 x 10 cm	1.733de	1.65d	1.103d	1.04ef	3.35	2.93	13.17g	9.535f
10 x 15 cm	2.09d	1.7d	1.23d	1.15e	3.74	3.23	16.373f	12.639e
20 x 5 cm	1.45ef	1.44de	1.07d	0.82gh	2.55	2.22	8.353i	4.813h
20 x 10 cm	2.81c	2.293c	1.52c	1.36d	4.29	3.49	18.193e	18.629c
20 x 15 cm	2.76c	2.80ab	1.73b	1.96b	4.68	4.18	22.513c	14.186e
30 x 5 cm	1.39ef	1.54de	1.06d	0.93fg	2.72	2.43	10.323h	6.82g
30 x 10 cm	2.95bc	2.43bc	1.6bc	1.73c	4.48	3.81	20.106d	16.25d
30 x 15 cm	3.48a	2.97a	2.07a	2.04ab	5.01	4.43	24.406b	20.602b
Significance level	**	***	***	**	ns	ns	***	***
Grand mean	2.36	2.08	1.46	1.39	3.8	3.33	16.64	12.61
LSD(0.05)	0.498	0.38	0.21	0.11	0.39	0.44	1.520	1.623
CV%	12.45	8.07	8.63	8.07	5.99	7.85	5.38	7.42

ns=non-significant, *, ** and *** indicates significant difference at probability alpha levels of 0.05, 0.01 and 0.001 respectively.

Combined Analysis

Appendix table 8:3: Combined mean squares for maturity date plant, height (PH), (leaf number per plant (LN),leaf length (LL), leaf width (LW), Bulb dinmeter (BD), Bulb length (BL) and average bulb weight (AVBW).

Source of variation	DF	Maturity	PH	LN	LL	LW	BD	BL
Rep	2	1.06	14.97	2.02	33.56	0.044	0.15	0.018.
Inter	2	73.5***	386.26***	2.83**	196.17***	1.16***	3.99***	3.66***
Intra	2	474.5***	508.39***	2.47**	281.86***	2.65***	10.83***	7.98***
Location	1	504.17***	101.11***	19.80***	338.50***	2.05***	4.39***	0.36**
Inter : intra	4	2**	39.93**	0.62 ns	11.26*	0.09***	0.19***	0.33***
Inter : location	2	0.17ns	2.32 ns	0.14 ns	2.59 ns	0.00 ns	0.073*	0.013 ns
Intra : location	2	2.17*	7.81 ns	0.045 ns	3.38 ns	0.00 ns	0.06 ns	0.000 ns
Rep : location	2	0.06 ns	51.68**	1.72 ns	12.92*	0.002 ns	0.072*	00.089
Inter :intra : location	4	0.67 ns	1.44 ns	0.57 ns	2.32 ns	0.001 ns	0.09**	0.045
Residuals	32	0.43	6.93	0.45	3.5	0.01	0.02	0.04

ns = non significance *, ** and *** indicates significant difference at probability alpha levels of 0.05, 0.01 and 0.001 respectively.

Appendix table 8:4 Combined mean squares for clove weight average bulb weight(AVBW) (CWT), clove width (CWID),total bulb yield(TBY) marketable bulb Yield (MBY) and unmarketable bulb yield (UNMBY).

Source of variation	DF	AVBW	CWT	CWID	TBY	MBY	UMBY
Rep	2	60.10	0.09	0.048	0.09	0.085	0.000
Inter	2	1266.17***	3.71***	1.37***	72.81***	44.797***	13.35***
Intra	2	2901.38***	7.85***	2.69***	153.49***	67.18***	39.88***
Location	1	1650.26***	0.59**	0.1**	132.15***	159.073***	1.25***
Inter : intra	4	181.71***	0.47***	0.21***	0.98***	3.12***	1.68***
Inter : location	2	80.73**	0.03 ns	0.04*	0.16**	1.19***	1.11***
Intra : location	2	93.96**	0.21 ns	0.12***	0.10*	0.65***	1.11***
Rep : location	2	65.96*	0..39**	0.02 ns	0.074 ns	0.044 ns	0.005 ns
Inter : Intra : location	4	18.3 ns	0.11 ns	0.03*	1.83***	2.82***	0.22**
Residuals	32	13.85	0.07	0.01	0.03	0.059	0.042

ns = non significance *, ** and *** indicates significant difference at probability alpha levels of 0.05, 0.01 and 0.001 respectively.

Appendix table 8:5 Combined mean squares for small, medium, large bulb sise distribution, shoot dry weight (SDW), bulb dry weight (BDW) and total biomass dry weight (TBDW) as affected by inter -row, intra -row spacings and location at Hatsebo and Selekhlekha, 2024**.**

			Meansquare				
Source of variation	Df	Small	Medium ton	Larges	SDW	BDW	TBDW
Rep	2	0.087	0.875	0.054	4.25	159.31	215.42
Inter	2	14.99***	10.696***	10.47***	17.39***	696.25***	933.18***
Intra	2	97.55***	18.996***	60.38***	3.23***	186.7***	239.06***
Location	1	0.63*	62.977***	6.44***	0.20*	15.52***	19.13***
Inter : intra	4	1.72***	4.54***	3.97***	0.021 ns	0.04 ns	0.11 ns
Inter : location	2	0.000 ns	7.661***	0.2*	0.13 ns	0.14 ns	0.52 ns
Intra : location	2	4.65***	3.21***	5.83***	0.10 ns	9.38***	11.3***
Rep : location	2	0.04 ns	1.635**	0.1.3 ns	0.019 ns	0.01 ns	0.06 ns
Inter :intra : location	4	0.64***	0.98*	0.392***	0.057 ns	0.86 ns	0.48 ns
Residuals	32	0.092	0.31	0.050	0.057	0.86	0.48

ns = non significance *, ** and *** indicates significant difference at probability alpha levels of 0.05, 0.01 and 0.001 respectively.

Appendix table 8:6 seed kg/ha, Seed cost, total seed cost, labor/ha, labor cost, total labor cost and total variable cost, for different inter- and intra-row spacing. (Combined data from Hatsebo and Selekleka was used for the economic analysis).

Inter*intra row spacing (cm)	Seed kg/ha	seed cost/kg (Birr)	Total seed cost/ha (birr)	Labor/ha	Wedge/day (Birr)	Total labor cost (Birr)	Total variable cost(birr)
10 * 5	2083.3	230	479159	217	200	43400	522559
10 * 10	1041.67	230	239584	108.5	200	21700	261284
10 * 15	694.4	230	159712	72.3	200	14460	174172
20 * 5	1666.67	230	383334	173.6	200	34720	418054
20 * 10	833.3	230	191659	86.8	200	17360	209019
20 * 15	555.55	230	127776	58.87	200	11774	139551
30 * 5	1388.88	230	319442	144.67	200	28934	348376
30 * 10	694.4	230	159712	72.3	200	14460	174172
30 * 15	462.96	230	106480	48.2	200	9640	116121

Appendix table 8:7: Combined unadjusted and adjusted marketable yield and total gross benefit obtained from the different combination of inter- and intra-row spacing based on marketable bulb size categories and their price value harvested from Hatsebo and Selekhlekha location, 2024.

Inter*intra spacing	Small bulb size distributions				Medium bulb size distributions				Large bulb size distributions				Total gross benefit (Birr ha^{-1})
	yield (kg ha^{-1})	Adjusted yield (kg ha-1)	Harvest price (Birr kg^{-1})	Gross benefit (Birr ha^{-1})	yield (kg ha^{-1})	Adjusted yield (kg ha-1)	Harvest price (Birr kg^{-1})	Gross benefit (Birr ha^{-1})	yield (kg ha^{-1})	Adjusted yield (kg ha-1)	Harvest price (Birr kg^{-1})	Gross benefit (Birr ha^{-1})	
10 * 5	6471.8	5824.62	150	873693	3021.1	2718.99	170	462228.3	310	279	200	55800	1391721.3
10 * 10	3603	3242.7	150	486405	5903.8	5313.42	170	903281.4	2350	2115	200	423000	1812686.4
10 * 15	1376.3	1238.67	150	185800.5	4952.8	4457.52	170	757778.4	3059	2753.1	200	550620	1494198.9
20 * 5	5237.5	4713.75	150	707062.5	5265	4738.5	170	805545	760	684	200	136800	1649407.5
20 * 10	1283	1154.7	150	173205	7435.5	6691.95	170	1137631.5	5610	5049	200	1009800	2320636.5
20 * 15	788.66	709.794	150	106469.1	5175.8	4658.22	170	791897.4	3580	3222	200	644400	1542766.5
30 * 5	4488.5	4039.65	150	605947.5	4871.8	4384.62	170	745385.4	980	882	200	176400	1527732.9
30 * 10	1126.3	1013.67	150	152050.5	5411	4869.9	170	827883	4260	3834	200	766800	1746733.5
30 * 15	662.8	596.52	150	89478	3581	3222.9	170	547893	4100	3690	200	738000	1375371

Appendix table 8:8 correlation analysis between marketable bulb yield and growth and yield traits of garlic at Hatsebo and Selekhlekha, 2024.

Variables	NL	MBD	MBY	TBY	SBD	UMY	BD	LW	TBDW	BDW
NL	1.00									
MBD	0.51***	1.00								
MBY	0.48***	0.72***	1.00							
TBY	0.42**	0.44***	0.90***	1.00						
SBD	−0.29*	−0.23ns	0.24ns	0.61***	1.00					
UMY	−0.31*	−0.35**	0.14ns	0.57***	0.90***	1.00				
BD	0.42**	0.36**	0.03ns	-0.43**	-0.86***	-0.88***	1.00			
LW	0.43**	0.35*	−0.04ns	0.1**	−0.82***	−0.83***	0.95***	1.00		
TDW	0.41**	0.28*	-0.16ns	0.52***	−0.89***	-0.87***	0.95***	0.94	1.00	
BDW	0.41**	0.28*	-0.16ns	-0.52***	-0.88***	-0.87***	0.95***	0.94***	1.0***	1.00
SDW	0.41**	0.28*	-0.15ns	-0.51***	-0.91***	-0.87***	0.94***	0.92***	0.97***	0.96***
ABW	0.43**	0.29*	-0.04ns	-0.39**	-0.82***	-0.78***	0.9***	0.92***	0.92***	0.92***
MRTY	0.56***	0.48***	0.07ns	-0.31*	-0.82***	-0.81***	0.9***	0.93***	0.91***	0.91***
LL	0.53***	0.37*	0.7ns	-0.28*	-0.72***	-0.75***	0.87***	0.89***	0.87***	0.86***
CWD	0.23ns	0.12ns	-0.30*	-0.62***	-0.77***	-0.83***	0.85***	0.86***	0.89***	0.89***
PH	0.29*	0.27*	-0.12ns	-0.46***	-0.76***	-0.80***	0.84***	0.87***	0.85***	0.84***
CWT	0.34*	0.14ns	-0.21ns	-0.53***	-0.84***	-0.79***	0.85***	0.87***	0.88***	0.88***
BL	0.33*	0.19ns	-0.24ns	-0.59***	-0.86***	-0.86***	0.90***	0.88***	0.93***	0.92***
LBD	042**	0.41**	0.11ns	-0.28*	-0.89***	-0.81***	0.82***	0.78***	0.82***	0.81***

Variables	SDW	ABW	MRTY	LL	CWD	PH	CWT	BL	LBD
SDW	1.00								
ABW	0.91***	1.00							
MRTY	0.90***	0.87***	1.00						
LL	0.87***	0.85***	0.86***	1.00					
CWD	0.86***	0.82***	0.74***	0.80***	1.00				
PH	0.83***	0.84***	0.76***	0.82***	0.90***	1.00			
CWT	0.89***	0.87***	0.77***	0.81***	0.88***	0.87***	1.00		
BL	0.92***	0.89***	0.81***	0.84***	0.91***	0.88***	0.92***	1.00	
LBD	0.84***	0.84***	0.76***	0.73***	0.67***	0.73***	0.80***	0.79***	1.00

ns=non-significant, *, ** and *** indicates significant difference at probability alpha levels of 0.5, 0.01 and 0.001 respectively and the – sign= negatively correlated.

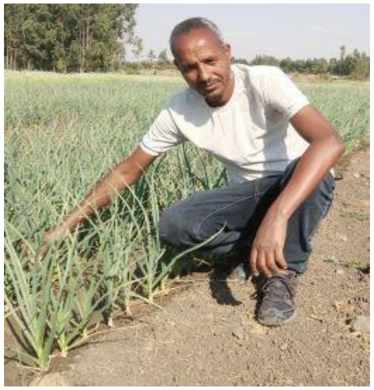
NL=number of leaves per plant, MBD=medium bulb size distribution MBY= marketable bulb yield ,TBY= total bulb yield, SBD= small bulb size distribution, UMY unmarketable yield, DB bulb diameter, LW= leaf width, TBDW=total biomass dry weight, BDW=bulb dry weight, SDW=soot dry weight, ABW =average bulb weight, MRTY = maturity, LL =leaf length, CWD = clove width, PH= plant height, CWT =clove weight, BL =bulb length and LBD =large bulb size distribution.

Appendix Figures

Hatseo (A) Selekleka (B) Selekleka (B) Double lines (C

D Furrow design with 30 cm width E= 10 cm inter row spacing F= 20 cm inter row spacing G=30 cm inter row spacing

Appendix Figure 9:1 Land preparation and experimental design at Hatsebo location(A), Selekleka (B) and double lined twin giant cane designed according to each inter row spacing and marked with a charcoal corresponding to each intra row spacing for double row planting pattern (C) as presented 10 cm inter row spacing (E), 20 cm (F) and 30 cm (G).



Hatsebo =30 cm* 10 cm Seleklwka =10 cm* 5 cm Selekleka=10* 15 cm inter and intra row spacing

Selekleka =20*10 cm Hatsebo =20 * 10 cm Hatsebo=30 *10 cm (inter-and intra-row spacing respectively)

Appendix Figure 9:2 Vegetative growth and performance of garlic as influenced by spacing patterns at Hatsebo and selekhlekha, 2024.

Research practice(A) Slekleka (s) Hatsebo (H) Hatsebo (H) Farmers practiece Hatsebo (B)

Hatsedo (H) Hatsebo (H) Selekleka (S) Hatsebo (H) Selekleka (S)

Harvesting (C)

Appendix Figure 9:3 Research and farmers practice (A and B) and harvesting trends across the tested locations (C), 2024.

Appendix Figure 9:4 Data recording on bulb size catagories, fresh weight of chopped cloves and oven drying prossece. .

Appendix Figure 9:5 Data collection on marketable price of garlic according to size categories from four marketing center in Tigray.

Appendix Figure 9:6 Quality bulbs from the border rows of the experiment harvested at Hatsebo, 2024.

Appendix Figure 9:7 Vegetative performance of garlic during the the4th month planted with 30 cm * 15 cm inters-and intra-row spacing at Hatsebo site, 2024.