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Garlic (*Allium Sativum L.*) response to Nitrogen fertilizer rate and Intra-row spacing in Enderta Woreda, South Eastern Tigray, Northern Ethiopia

By:

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A Thesis

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In

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DECLARATION

I, Teklu Hishe Gebrekidan , hereby present my thesis entitled "Garlic (*Allium Sativum* L.) response to N rate and Intra-row spacing in Enderta, Tigray, Ethiopia" for consideration by the Department of Dryland crops And Horticultural Sciences within the College of Dryland Agriculture and Natural Resource, at Mekelle University , in partial fulfillment of the requirement for the degree of Master in Horticulture. I, the undersigned, declare that this thesis is my original work and has not been presented for any other award, and that all sources of materials used in this thesis are duly acknowledged. No other person has published a similar study, which I might have copied, and at no stage will this be published without my consent and that of the Dry land Crop and Horticultural Science Department.

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DEDICATION

This thesis manuscript is dedicated to my dearest mother, Kiros Amberay; my sister, Tirhas Hishe and my father, Hishe Gebrekidan .Their unwavering support, patience, and encouragement have been vital throughout my life, guiding me from childhood to the present. During difficult times, their confidence in me and constant prayers provided me the strength I needed to overcome challenges. I am profoundly grateful for their love and active involvement in my journey, which has been essential to my success and personal growth.

BIOGRAPHICAL SKETCH

The author, Teklu Hishe Gebrekidan, was born in Quiha town, in the South-eastern zone of Tigray, Northern Ethiopia, on 28, March 1988 from his father Ato Hishe Gebrekidan and His mother Weyzero Kiros Amberay. He attended his elementary school at Embamamo Elementary School. After he completed his elementary education, he attended his high school and preparatory at Weldu Niguse preparatory school. After completing his high school and preparatory school education in 2005, he joined Jimma University, College of Agriculture and Veterinary Medicine, and graduated with BSc Degree in horticulture in June 8, 2008.

Soon after graduation, he was employed in Maichew Agricultural, Poly Technique College as a Graduate Assistant and Lecturer. In October 2014, he was employed by the Mekelle University as Assistance Researcher. He joined Mekelle University in October 2020 to pursue his post graduate studies leading to Master of Science Degree in horticulture.

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ABBREVETIONS AND ACRONYMS

ANOVA	Analysis of variance
MRR	Marginal rate of return
HI	Harvest index
Kg	Kilogram
Ha	Hectare
Cm	Centimeter
N	Nitrogen
ESS	Ethiopian Statistics Service
DzARC	Debrezeit Agricultural Research Center
FAO	Food and Agriculture Organization
CSA	Central Statistical Agency
RCBD	Randomized complete block design
P	Phosphorous:
K	Potassium:
EC	Electron conductivity:
CEC	Cation exchange capacity

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ABSTRACT

Garlic (Allium Sativum L.*) is one of the most ancient widely cultivated vegetable crop, and propagated by cloves and used for food medicinal purposes. However, its productivity is far below the demands. This is due low soil fertility; inappropriate planting density, and major diseases. A field experiment was conducted at Mekelle University Endayesus compus to study the effect of different nitrogen levels and intra- row spacing on yield and yield component of garlic during 2024 irrigation season using a local variety of garlic. The treatments consisted of four levels of nitrogen fertilizer (0,46,69 and 92 kg N ha $^{-1}$), and three levels of intra- row spacing (5, 10 and 15 cm) arranged in randomized completely block design replicated three times each. Data were collected on plant growth, bulb yield and yield components and garlic rust diseases infestation level. The result showed that the different nitrogen rates significantly ($P<0.01$) affected garlic plant height, leaf length, leaf dry weight and marketable yield. Besides, intra row spacing significantly ($P<0.05$) influenced all garlic parameters except leaf number, clove number, and harvest index. Similarly, their interaction had significant effect on marketable yield and total bulb yield. The least and highest diseases severity and incidence percentages (4.1 &19.4) and (20 & 55%) was recorded from plots spaced at 5 & 15cm respectively. The highest 9 t ha^{-1} total bulb yield was recorded at 5 cm intra -row spacing and 69 kg of nitrogen fertilizer. The highest marketable yield of 8.1 t ha^{-1} was recorded from application of 46kg N spaced at 5 cm of intra-row spacing. Cost benefit analysis indicated that the highest (2,134,200) and lowest (1,162,533.34***)*** ETB ha^{-1} net return was earned from 46 and 69 N ha^{-1} spaced at 5 and 15 cm intra row spacing respectively. The maximum marginal rate of return (8690%) was obtained from plots treated with 46 kg N and 10 cm intra row spacing. In garlic production, the application of nitrogen fertilizer at rates exceeding 92 kg ha^{-1}, combined with an intra-row spacing of 15 cm, has been found to be uneconomical. Such practices not only result in excessive costs but also lead to diminishing returns in terms of yield. Based on these findings, it is recommended that farmers should reduce nitrogen fertilizer application to 46 kg N ha^{-1} and adjust the intra-row spacing to 10 cm. This rate of nitrogen and intra row spacing is expected to optimize fertilizer use efficiency, reduce unnecessary input costs, and enhance the overall profitability of garlic production.*

Key words: *bulb yield, cost benefit, garlic, intra row spacing, and nitrogen fertilizer*

1. INTRODUCTION

1.1. Background

Garlic (*Allium Sativum* L.) is one of the most ancient widely cultivated spice crop, used for food and medicinal purposes (Diriba et al., 2013). It has pungency characteristic and propagated by cloves. It adds to the taste of foods and enhances its digestibility (Ashenafi and Tenaye, 2023). Garlic contains different essential minerals, vitamins and many other substances beneficial for human health (Bongiorno et al., 2008). Garlic is rich in essential nutrients such as sugar, protein, fat, calcium, potassium, phosphorus, sulfur, iodine, fiber, and silicon, along with various vitamins). It has numerous medicinal properties, including lowering cholesterol and blood pressure, strengthening the liver, and acting as an antifungal, anti-inflammatory, and antioxidant. (Okoro et al., 2023) Besides, it is used to treat a wide range of conditions, including skin diseases, cancer, asthma, arthritis, infections, digestive problems, kidney stones, diabetes, anemia, jaundice, and eye disorders like cataracts and night blindness (Tesfaye and Mengesha, 2015).

Garlic is being produced by several world countries including China, India, Bangladesh, the Republic of Korea and Egypt. Of these, China accounting more than 75% of global production (Galgaye, 2022). Global bulb crop productions are about 10 million tons per annum, which represents only 10% of the global bulb production with opportunities to be boosted up by 19 % as the crop is being demanded both locally and internationally (Etana, 2018).

In Ethiopia, garlic is an important bulb crop produced for home consumption as a spice, medicinal plant and as a source of income for farmers (Mulatu et al., 2014). As a cash crop, it is a source of foreign currency earnings with exports reaching Europe, the Middle East, Africa and USA (Alamarie et al., 2014; Berhanu and Berhanu, 2014; Kilgori et al., 2007). The annual average area covered by garlic is about (16411.19 ha) with total production (159,093.58 tons). Its consumption per capita per annum was about 1.74 and 5.9 kg in rural and urban areas respectively (Yeshiwas et al., 2018). As a result, it ranked as the fourth most cultivated vegetable crop, following cabbage, peppers and potatoes which are produced by 2.23, 1.3 and 1.15 million households respectively (Alamarie et al., 2014; Kumar et al., 2021).

Garlic grows in a wide range of climatic and soil conditions, mainly in the mid-altitudes and highlands of the country mainly produced by smallholder farmers in Tigray both under irrigation and rain-fed conditions (Asnake et al., 2024). Several studies have reported that garlic is highly sensitive to fertilizer application rates, row spacing and plant density (Ashenafi and Tenaye, 2023) which play a significant role in improving garlic yield and its susceptibility to common diseases. Spacing between rows of plants affects garlic growth, yield and its bulb marketability (Asnake et al., 2024). This depends on soil fertility status, climatic factors and crop variety (Kilgori et al., 2007). So, this has to be determined to boost up its productivity (Naruka and Dhaka, 2001). Thus, optimizing fertilizer application and row spacing at the micro farm level is crucial for improving productivity across diverse agro-ecologies.

Garlic is popular vegetable crop in Tigray with area coverage of (540.97 ha) and inadequate productivity due to its high domestic and export demands (CSA, 2018; Garmame, 2022). Despite its low productivity, garlic continues to be a market-oriented high-value vegetable crop which is being produced in rotation with other vegetables (Gebremedhin et al., 2010). Therefore, addressing these issues through improved agricultural practices like N fertilizer and row space optimization could enhance garlic yields, supporting its continued role as an important market-oriented crop in the region.

1.2. Statement of the problem and justification

Garlic production in Tigray remains far below the demands. Its average productivity (5.31 t ha^{-1}) in Tigray became insubstantial compared to the national (10 t ha-1) and world average yields (19.32 t ha^{-1}) (CSA, 2018; Gebretsadik 2016). This significant yield reduction is believed to be due to lack of optimum population density, severe disease infestations, and depletion of soil nitrogen availability (Ashenafi and Tenaye, 2023; Asnake et al., 2024; Garmame, 2022; Singh et al., 2010). Declining in garlic yield led to produce scarcity and garlic prices inflation (Hamma et al., 2013). This is highly linked with high cost of fertilizer which became unaffordable to most smallholder farmers that indirectly increase garlic market price exponentially (Mebratu. & Mulie, 2019).

Garlic is a high-value crop that is intensively cultivated in irrigated sites of Enderta wereda, known for its favorable growing conditions (Teshale and Tekeste, 2021). The application of fertilizers and proper spacing is essential for maximizing garlic yield and ensuring economic profitability, yet the practices in the region often follow national blanket recommendations that might not be optimized for local conditions. Farmers commonly apply nitrogen fertilizers at rates of 100 kg N ha^{-1}, and they use a row spacing of 10 cm, which are based on generalized guidelines (Assefa et al., 2015;

Mebratu and Mulie, 2019). However, these national recommendations do not always align with the specific needs of garlic in different agro-ecological zones. The variability in fertilizer application rates by farmers, based on personal preferences or accessibility, further complicates this issue (Garmame, 2022). This often leads to inefficiencies where fertilizer application rates are not adjusted for the specific conditions of the farm, resulting in both fertilizer deficits and excesses, which can negatively affect garlic growth and yield (Teshale and Tekeste, 2021).

Despite the importance of proper nitrogen fertilization, there is limited understanding regarding the precise relationship between fertilizer application rates, intra-row spacing, and garlic yield, as well as the economic profitability of these practices. Several studies have indicated that excessive or insufficient nitrogen application can impact garlic growth, yield, and quality (Asnake et al., 2024; Garmame, 2022). Fertilizer application not only influences the vegetative growth of the plant but also affects garlic's resistance to diseases and its ability to thrive in dense planting conditions (Singh et al., 2010). Therefore, little research has been conducted on how nitrogen fertilizer rates and plant population densities interact to influence garlic's resistance to major diseases, which are prevalent in the region (Garmame, 2022).

One of the primary objectives of nitrogen fertilizer management in garlic cultivation is to ensure that the right amount of nutrients is supplied, taking into account the plant population density per unit area. This is because nitrogen is a critical nutrient for garlic, but its impact on yield and disease management can vary depending on spacing, density, and other environmental factors (Asnake et al., 2024). For instance, adjusting intra-row spacing could help optimize plant growth by reducing competition for nutrients and light, which is especially important when fertilizer application is optimized to match plant density (Teshale and Tekeste, 2021). Studies have shown that excessive plant density can lead to overcrowding, which increases the risk of diseases and limits the effective use of fertilizer (Singh et al., 2010). On the other hand, low plant density might result in underutilization of space and poor yield.

Furthermore, optimizing intra-row spacing alongside the correct nitrogen application rate is essential for achieving a sustainable and profitable garlic production system. It allows for better space utilization, optimized fertilizer usage, and improved crop health, all of which contribute to higher economic returns (Asnake et al., 2024; Garmame, 2022). Therefore, research on the appropriate nitrogen fertilizer rate and intra-row spacing, tailored to specific agro-ecological conditions, is crucial for enhancing garlic production in Enderta wereda. Such studies could not only boost yield but also help farmers manage their resources more effectively, improving both economic returns and environmental sustainability.

Therefore, it is imperative to conduct further research to determine the optimal nitrogen fertilizer rates and intra-row spacing for garlic cultivation, especially in regions like Enderta wereda. The findings from such research could help to bridge the gap in knowledge regarding the relationship between fertilizer application, plant density, and garlic yield. By understanding and implementing more region-specific recommendations, farmers could achieve better garlic yields, enhanced disease management, and improved profitability (Teshale and Tekeste, 2021; Asnake et al., 2024).

1.3.Objective

1.3.1. General Objective:

- The general objective of this study was to investigate the impact of intra row spacing and nitrogen fertilizer rates on garlic productivity and its economic feasibility.

1.3.2. Specific Objectives:

- To evaluate the response of garlic to different N rates and intra-row spacing,

- To determine the best N fertilizer rate and intra row spacing for optimum garlic yield,
- To assess the economic feasibility of different rates of nitrogen fertilizer and intra row spacing on garlic marketable bulb yield.

2. LITERATURE REVIEW

2.1.Importance and Distribution of Garlic in Ethiopia

In Ethiopia, garlic is one of the important bulb crops grown and used as a spice or a condiment throughout the country. It is mainly used for flavoring and seasoning vegetables in different dishes. Garlic's primary economic value, both for consumption and propagation, comes from its numerous cloves. It is used as ingredient of local stew ‘wot’ and has also a tremendous use in the formulation of local medicines (Mulatu et al., 2014). It is the second most widely cultivated Allium species in Ethiopia next to onion (Yayeh, 2017). From among the vegetable crops cultivated in the country, it ranks second in the number of vegetable grower landholders cultivating garlic, next to Ethiopian cabbage. In Ethiopia the Alliums group (onion, garlic, and shallot) are important bulb crops produced by small and commercial growers for both local use, home consumption and export (Fekadu & Dandena, 2006). These crops serve as a source of income to many peasant farmers in many parts of the country (Tabor & Zeleke, 2000). Garlic contributes to the national economy as an export commodity (Fekadu & Dandena, 2006). Garlic is exported to Europe, Middle East and North America (DzARC, 2006). Garlic is a fundamental flavor enhancer in various dishes, including vegetable crops, meats, salads, spaghetti, sausages, and pickles (Brewster, 1994).

2.2. Garlic production and productivity in Ethiopia

Garlic, an ancient vegetable propagated vegetative through cloves, ensures uniform crop production with consistent quality traits such as flavor and nutritional properties (Salomon, 2002). The garlic bulb consists of numerous cloves, which are swollen bladeless storage leaves and the primary economic organ. While bolting may occasionally occur, seed formation is rare (Brewster, 1994).

In 2022, garlic was cultivated globally on 1,662,384 hectares, with a total production of 29,149,437.7 tons (FAOSTAT, 2024). The leading producers of garlic include China, India, and the Republic of Korea (FAO, 2024). In Ethiopia, garlic, along with other alliums like onions and shallots, is a vital bulb crop cultivated by both smallholder and commercial farmers for local consumption and export. The average yield of garlic in Ethiopia was 9.34 tons per hectare (CS2018).

In 2018, Ethiopia's garlic production was estimated at 178,221.9 tons from an area of 19,412.49 hectares, with a productivity rate of 9.18 tons per hectare (CSA, 2018). According to CSA (2021), in the 2020/2021 cropping year, garlic was grown on approximately 15,979.54 hectares in the Tigray region, yielding 7.19 tons per hectare. During the 2020/2021 Meher season, garlic was cultivated on 30,946.22 hectares by 1,996,018 landholders, producing 1,938,797.93 quintals of bulbs (ESS, 2022). Garlic cultivation is widespread across Ethiopia, both in irrigated and rain-fed conditions, and across various agro-climatic zones (ESS, 2024).

However, the productivity of garlic in Ethiopia remains low due to several factors, including the lack of improved and high-yielding varieties, the unavailability of quality seeds, low soil fertility, inappropriate agronomic practices, inadequate pest and disease management, and insufficient marketing and post-harvest technologies (Getachew and Asfaw, 2010). Agronomic practices, such as plant population density, are highly dependent on the environment, crop purpose, and variety (Getaneh, 2022).

Despite its importance as cash crop globally and a major horticultural crop in Ethiopia, garlic’s productivity continues to be hindered by improper production technologies, such as plant density, fertilization practices, and pest and disease control. This research aims to address these challenges and enhance garlic productivity by implementing appropriate plant density measures (Yeshiwas et al., 2018).

In Ethiopia, vegetable production is primarily carried out by smallholder farmers, especially those residing near major towns. These farmers grow vegetables, including garlic, on small plots of land. Garlic is an essential cash crop that helps subsistence farmers, particularly in the mid- and lowlands, improve their livelihoods (FAO, 2006). After onions, garlic is the most commonly cultivated Allium species in the country.

Garlic thrives at elevations ranging from 700 to 1800 meters above sea level (Mulatu et al., 2014). However, due to the prevalence of diseases during the main cropping season, it is recommended to grow garlic in tropical regions using irrigation rather than relying on rainfall (EIAR, 2007). This helps mitigate the risk of disease infections that can significantly reduce yields.

Garlic is not only important for local consumption but also plays a vital role in Ethiopia's export market, contributing to foreign exchange earnings (EIAR, 2007). Despite its significance, garlic productivity remains low. Several factors contribute to this issue, including the use of poor-quality planting materials, imbalanced fertilization (especially nitrogen), suboptimal irrigation practices, limited access to improved varieties, and inadequate pest and disease management techniques. Additionally, the lack of proper agronomic practices further hampers its productivity (EIAR, 2007).

In summary, while garlic is an important crop for both domestic use and export, its productivity in Ethiopia is constrained by various challenges. Addressing issues like low-quality planting materials, improper irrigation, and pest management practices is crucial for improving garlic yields and strengthening its role in the Ethiopian economy.

2.3. Planting and preparing planting materials

The best planting materials are healthy, medium-to-large cloves that are fully developed and free from diseases, insect pests, and physical damage (Parreño et al., 2023). The quality of the cloves directly affects the growth and yield of the garlic crop.

For a hectare of land, the required quantity of planting materials ranges between 800 and 1200 kg, depending on the bulb size and planting distance (EIAR, 2007). In Ethiopia, the recommended planting spacing for improved garlic varieties is 10x15x30 cm. This involves placing plants 10 cm apart within the row, 15 cm between rows, and 30 cm between double rows (EIAR, 2007). The cloves are typically planted at a depth of 3 to 5 centimetres, which is measured from the top of the clove to the soil surface. In lighter or organic soils, a shallower planting depth of around 5 cm is acceptable.

However, it is essential to avoid overcrowding when planting garlic, as too-dense planting can lead to intense competition for nutrients, water, and light, potentially stunting plant growth and reducing overall yield. Careful attention to spacing is critical to ensuring optimal growth and maximizing the productivity of the garlic crop.

2.4. Effect of Intra Row Spacing on Growth of the Garlic Plant

Intra-row spacing has a significant effect on plant height, with a decrease in plant height observed as the spacing between plants increases. The tallest plants are typically found at the narrowest intra-row spacing, as noted by Teshale and Tekeste (2021). This could be due to increased competition for light at higher plant densities, where plants tend to grow taller in search of more sunlight. On the other hand, at wider spacings, there has less competition for light and other resources, which minimizes the impact of plant density on plant height (Endalkachew et al., 2024).

Intra-row spacing also influences other plant characteristics, such as leaf width, leaf length, and the number of leaves per plant, all of which show significant variation with changes in spacing (Martha, 2019). The largest bulb length has been recorded at the widest intra-row spacing, while the smallest bulb length occurs at narrower spacings (Teshale & Tekeste, 2021). This is supported by previous studies, including Tewachew (2016), which also showed that garlic bulb length is greater at wider intra-row spacings compared to narrower ones. The increase in bulb length with wider spacing is likely due to improved access to nutrients, space, and moisture, which reduces competition for these vital growth resources. In conclusion, intra-row spacing affects not only plant height but also bulb yield. A decrease in spacing results in an increase in plant height, but a reduction in spacing can lead to higher bulb yield, which is linked to better light interception by the crop's leaf canopy (Brewster, 1994).

2.5. **Nutrient requirement of the garlic crop**

Garlic serves as source of several nutrients for human. The volatile oil in garlic contains various sulfur compounds, which contribute to its strong aroma, unique taste, and pungency, as well as its health benefits (Salomon, 2002). Additionally, garlic is rich in calcium, phosphorus, and potassium, while its leaves provide protein, and vitamins A and C (Mahmood, 2000). Compared to other bulb crops, garlic offers greater nutritional value.

Despite its significance and rising production levels, garlic productivity remains low in many regions worldwide due to genetic and environmental factors impacting its yield and yield-related characteristics (Nonnecke, 1989). In numerous garlic-growing areas, a lack of available nutrients often serves as a limiting factor, second only to soil moisture, as it affects the uptake and release of nitrogen (N), phosphorus (P), and potassium (K).

The availability of water is crucial for soil organic matter (FAO, 2003). To enhance garlic production, it is essential to consider the application of various fertilizers in terms of type, timing, and rate, as these are limiting factors (Brewster and Butler, 1989). Additionally, producing robust sprouts is vital for successful garlic cultivation, which can be achieved through balanced nutrient applications (Potgieter, 2006). The application of balanced fertilizers is fundamental for maximizing crop yields from currently cultivated land, with the nutrient requirements of crops aligning with their physiological needs and anticipated yields (Ryan, 2008).

Garlic; possess shallow, unbranched root systems, which limit their ability to efficiently absorb nutrients from the soil. This characteristic makes garlic particularly reliant on supplemental fertilization for optimal growth and yield. The most effective method of fertilizer application for garlic is through banding, a technique that involves placing fertilizers in concentrated bands near the plant roots. This allows for more efficient nutrient uptake, ensuring that fertilizers are applied directly to the areas where the roots are most active (Jones et al., 2004). Banding minimizes nutrient loss and maximizes absorption, addressing the limitations of garlic’s root system (Li et al., 2022) Moreover, this method reduces the risk of nutrient leaching and promotes healthier growth, leading to improved bulb size and yield (Lee et al., 2025). Consequently, fertilizer banding is a crucial practice for achieving the best results in garlic cultivation.

2.5. 1. Effect of nitrogen fertilizer rate on garlic production

Garlic is an essential vegetable crop widely cultivated in Ethiopia, both under rain-fed and irrigated conditions. However, the productivity of garlic at both the national and regional levels remains suboptimal due to inadequate agronomic practices, particularly poor fertilization strategies concerning both the type and application rate. Nitrogen, a vital macronutrient, plays a significant role in enhancing garlic yield and quality. It promotes the growth of the plant by increasing the number of leaves, leaf length, and overall plant size, which is crucial for maximizing photosynthesis and, consequently, bulb development (Kumar et al., 2022).

Garlic, in particular, requires a substantial amount of nitrogen during its early growth stages to ensure vigorous vegetative growth and optimal bulb formation (Singh et al., 2020). Nitrogen deficiency can limit the plant's ability to develop adequately, leading to stunted growth and reduced yield. However, excessive nitrogen can lead to excessive vegetative growth at the expense of bulb formation, affecting the overall productivity (Ali et al., 2020).

In Ethiopia, garlic is particularly susceptible to nutrient deficiencies, especially immobile nutrients, due to its shallow and unbranched root system, which limits its ability to access nutrients deep in the soil (Gurung et al., 2022). As a result, garlic responds positively to fertilization, with nitrogen application being one of the most effective ways to improve its productivity. Nitrogen is often deficient in soils, and garlic absorbs it in larger quantities compared to other nutrients, highlighting the need for efficient nitrogen management in garlic farming systems (Abdelkader, 2019). Thus, optimizing nitrogen fertilizer rates is critical for achieving higher garlic yields and improving farm productivity in Ethiopia.

Under varying nitrogen (N) conditions, the plant lengths of different varieties showed significant differences, which can be attributed to the distinct genetic responses of each variety to the availability, uptake, and utilization of nitrogen (Hossein et al., 2014). Similar findings were reported by Zaki et al. (2014) and Zaman et al. (2011), who observed improved performance of garlic under optimal nitrogen conditions. Specifically, they noted that the height of garlic plants increased from 42.4 cm to 64.7 cm as nitrogen levels rose from 0 to 200 kg N ha-1. In the present study, the purple top variety performed better than the local white variety, a result that aligns with Abraham et al. (2015), who also reported varied responses of garlic varieties to different nitrogen conditions.

It has been highlighted that a significant differences in the number of leaves per plant among different rates of nitrogen (N) on leaf development (Kevlani et al., 2023). Nitrogen plays a crucial role in leaf growth, chlorophyll formation, and overall plant development. Similarly, previous study by Abadi Assemaw (2015) has emphasized the importance of nitrogen for photosynthesis and cell division. On the other hand, insufficient nitrogen leads to chlorophyll deficiency, resulting in smaller leaves and potential necrosis (Tibebu, 2020).

Similarly, higher nitrogen rates (150 kg ha^{-1}) improved garlic growth and yield, while reduced nitrogen rates (100, 50, and 0 kg ha^{-1}) resulted in lower growth, bulb development, and yield characteristics (Kevlani et al., 2023). The increased nitrogen application positively affected garlic performance, suggesting the experimental soil was severely nitrogen-deficient. This deficiency, exacerbated by continuous cropping, has led to a decline in crop yields (Abbas et al., 2019). The findings indicate that optimal nitrogen supplementation is necessary for achieving acceptable garlic yields.

Similar positive effects of nitrogen on bulbous crops like onion have been observed in other studies (Galgaye, 2023; Kevlani et al., 2023), with researchers like Merga et al (2019) and Teshale and Tekeste, (2021) noting significant improvements in bulb size with optimal nitrogen supply to onion crops. These findings underscore the essential role of nitrogen in enhancing crop growth and yield.

It has been noted that total productivity increased with nitrogen doses up to 64 kg/ha. Conversely, Backes et al. (2008) conducted research that indicated maximum bulb production was achieved with a nitrogen dose of 268 kg/ha, yielding 14,250 kg/ha. However, these findings differ from those of Lima et al. (2020), whose studies revealed that applying nitrogen doses as high as 360 kg/ha did not result in increased bulb productivity for the *Roxo Pérola de Caçador* cultivar.

Proper nitrogen application enhances plant growth, leaf development, and bulb formation, but both deficiency and excess can reduce productivity, and higher nitrogen doses improve growth and yield, but excessive nitrogen may not always result in increased productivity.

3. MATERIALS AND METHODS

3.1. Description of the Study Area

The experiment was conducted at Mekelle University’s Endayesus campus (Agronomy research site), situated at $13^0 28'45.2''$ N, $39^0 29'24.3''$ E, at an altitude of 2225 m above sea level. Characterized by lower mean annual precipitation (p) and higher potential evapotranspiration (PET), and semi-arid climate with an aridity index ranging from 0.2 to 0.5 (Haftom et al., 2019). The annual rainfall ranges between 450 and 550 mm (Gebremichael, 2023) and average annual temperature is 18^0C (Beyene, 2015). The soil type is dominantly silt loam based on surface soil (0–30 cm) analyses (Habtegebriel and Boydom, 2016).

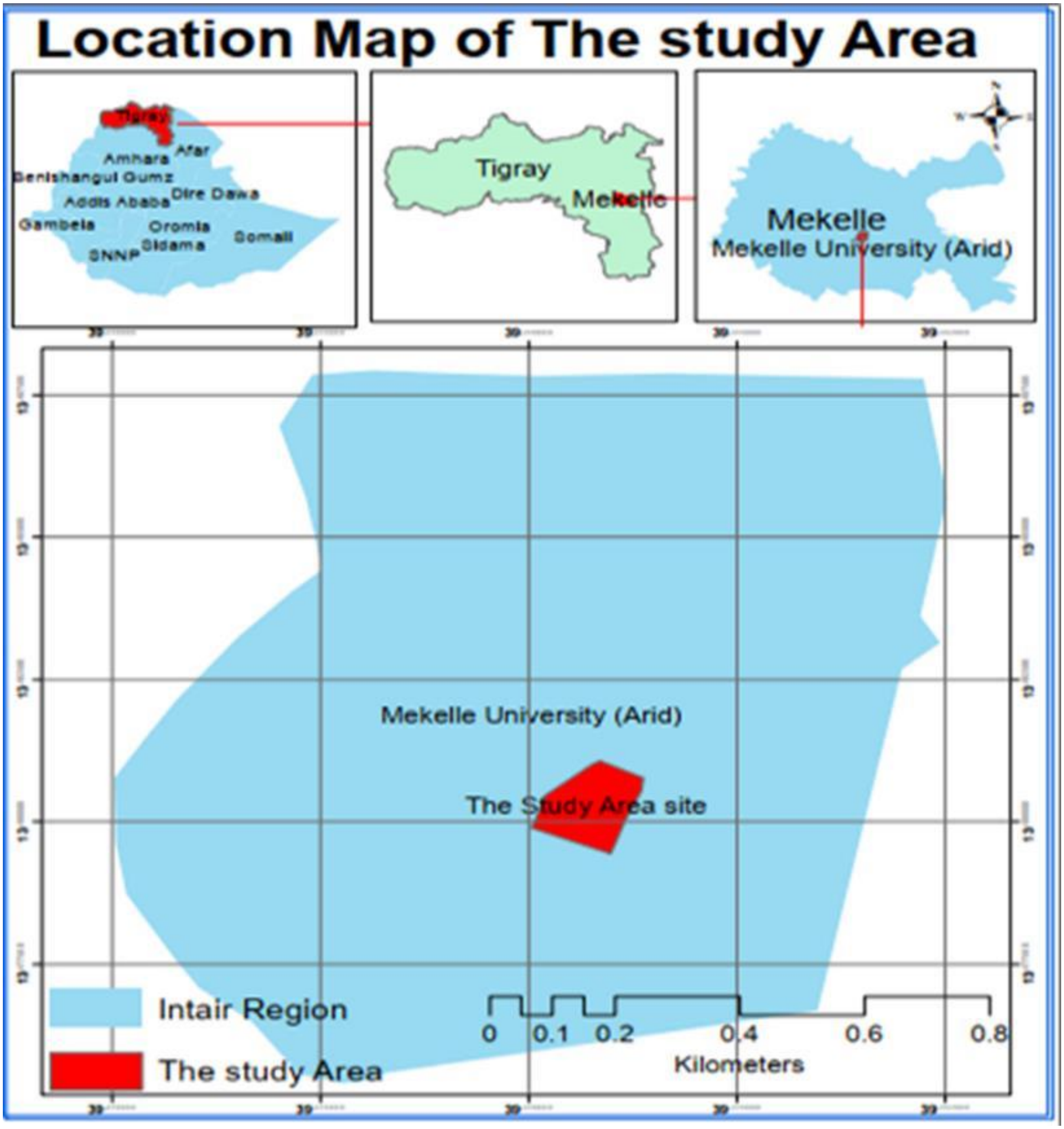

Figure 1.Map of study area

3.2.Characteristics of Experimental Materials

Local garlic cultivar obtained from the local market was used for the study. The cultivar’s cloves were uniform in size which had attractive white colored good pungency, good marketability and is well preferred by farmers and consumers. These selection characteristics were evaluated through visual inspection, as well as consultations with experienced peasant farmers who had many years of experience in growing garlic.

3.3.Treatments and Experimental Design

The field experiment was conducted using 3x4 factorial experiments in randomized complete block design (RCBD) with three replications. The experimental factors were nitrogen fertilizer rates (0, 46, 69 & 92 kg/ha) and three levels of intra row spacing (5, 10 and 15cm). The levels of each factor were combined and there were a total of 12 treatments. The plot size was 2 m x 1.5 m, and each plot had six rows. The space between rows and blocks was 30 cm and 1m respectively. The cloves were planted at a depth of 4 cm.

3.4.Experimental Procedures

Prior to planting of garlic cloves, the field was ploughed and harrowed with oxen. Following the breakdown of large clods into a fine tilth, 36 plots measuring 2 m x 1.5 m were designed, with 12 plots in each replication. Then, the local variety of garlic plant which was free of disease, damage, a clove that was not lost its moisture and did not show any change in color due to some infections or molding, aging and / or rotting, were planted on well prepared raised ridges at a depth of 4 cm. During planting, Triple Super Phosphate (TSP) (60 kg ha^{-1}) was applied uniformly to all experimental plots to enhance garlic nutrients uptake and water efficiently, especially in its early growth stages. Nitrogen fertilizer for respective plots was side dressed in a split in two applications; with half dose applied two weeks after emergence and the remaining half dose five weeks after emergence (Mahmood, 2000). Irrigation was supplied through furrow irrigation method at four days interval for the 1st month and then extended to seven days interval and stopped two weeks before harvesting.

3.5. Soil sample and analysis

Soil samples were collected both before planting and after harvest. Using an auger, samples were randomly taken across the experimental field in a zigzag pattern. Prior to planting, three samples were collected from the topsoil layer at a depth of 30 cm because garlic has a shallow root system, and most of its active root growth occurs within the topsoil layer, especially in the first 30 cm, and combined in a bucket to represent the entire site. Additionally, a composite soil samples from each plot were collected at a random. The soil was broken into small crumbs and thoroughly mixed to determine how the soil has changed during the growing season and what residual effects remain that could affect future crops. From this, a 1 kg composite soil sample was placed into a plastic bag, with replication prepared to analyze the soil's physicochemical properties.

The soil was air-dried and sieved using a 2 mm mesh. Soil pH was measured from a suspension with a 1:2.5 soil-to-water ratio, using a glass electrode connected to a digital pH meter. Soil texture was assessed by the sedimentation method (Hazelton and Murphy, 2016).

The soil samples were also tested for total nitrogen, available phosphorus, exchangeable potassium, organic matter, Total nitrogen content was analyzed via the Kjeldahl method (Jackson, 1958). Available phosphorus was extracted using 0.5 M $NaHCO_3$, following the method outlined by Olsen et al. (1954). Extractable potassium was measured with a flame photometer after extraction with 0.5 M ammonium acetate, as per Hesse (1971).

3.6.Data Collection

Eight randomly chosen plants from the middle four rows in each plot were used to collect data on growth, yield, and yield related parameters including overall bulb yield, marketable and unmarketable bulbs. At maturity, leaf length and plant height was measured with a ruler. Clove number per bulb was manually counted while bulb length and bulb diameter (at its widest point), of eight randomly selected bulbs was measured using digital caliper at the time of harvesting. Mean bulb weight was measured shortly after the bulbs were cured using a digital balance. At the time of harvesting, fresh and dry bio mass were calculated using a digital balance.

Dry biomass weight was determined after the biomass oven dried at 70^{o}c for 72 hours (Guesh et al., 2025; Lemma et al., 2003). Bulbs weighing 20-160 g were classified as marketable, while those weighing less than 20 g or showing signs of disease, decay, or physiological disorders were considered unmarketable (Lemma & Shimelis, 2003). After curing, the total bulb yield was recorded by summing both marketable and unmarketable bulbs, and expressed in kilograms per hectare.

To assess rust disease incidence on a weekly basis, 10 plants were randomly selected from the plot as soon as the first symptoms of rust appeared. Disease incidence (% DI) was calculated as

$$\text{Disease Incidence}(\%DI) = \left(\frac{\text{Number of infected plants}}{\text{Total number of selected plants}}\right) \times 100$$

Disease severity was measured by estimating the percentage of leaf area covered by rust lesions on each of the 10 selected plants. This was done by visually assessing the extent of infection on the leaves and calculating the proportion of leaf surface affected by rust (scoring out of 5). Using the approach 0-5 scale, where 0 represents no symptoms and 5 indicates more than 75% of the leaf area affected. The average disease severity across all 10 plants in each plot was then used for statistical analysis to evaluate the overall impact of rust on the crop. Disease assessments were performed weekly to track the progression of infection and to capture temporal changes in disease dynamics. This approach provided a comprehensive measure of both the spread and intensity of garlic rust over the growing season.

The correlation coefficient between garlic phenology, growth and yield components was analyzed using standard statistical methods. The correlation (r) values were categorized as follows: 0.00–0.10 (negligible), 0.10–0.39 (weak), 0.40–0.69 (moderate), 0.70–0.89 (strong), and 0.90–1.00 (very strong) to assess the strength of relationships between variables (Schober et al., 2018).

3.7.Partial budget analysis

Treatment-related costs and benefits were evaluated in the partial budget based on garlic marketable bulb yields during the 2024 off season. For the economic analysis, inputs at planting and garlic bulb yield at harvesting were valued at market prices. All costs and benefits were measured in Ethiopian birr. Cost of nitrogen fertilizer, purchased cloves for planting, and labor cost for planting plots of cloves at different intra spacing were considered as variable costs, and the partial budget analysis assumed only variable costs. The marketable bulb yield was adjusted downward by 10% in order to minimize the effects of experimental plots that were small in size compared to farmer fields (Gebreegziher et al., 2023). Then, the total revenue was calculated by multiplying the adjusted yield with the average selling price of marketable bulb yield. The net benefit was also calculated by subtracting the total variable cost from gross benefit, and benefit cost ratio was estimated by dividing net benefits to total variable costs in each respective plots.

NB= GB-TVC……………………………………………………..eq [1]

Where NB= the net benefit arise from all alternative treatments

GB= Gross benefit earned from all alternative treatments

TVC= Total cost incurred from all alternative treatments. In order to properly screen among alternative technologies it is necessary to evaluate the increase change in net income (ΔNB) as the difference between changes in total revenue (ΔTVC);

$\Delta NB = \Delta GB - \Delta TVC$ in this case it is also necessary to compare the extra benefit (marginal benefit) with extra cost (marginal cost) which Marginal rate of return (MRR) and is calculated as

$$\mathbf{MRR\ \% = \frac{\Delta NB}{\Delta TVC} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq\ [2]}$$

Where MRR is the Rate of return and is used to assess relative profitability among alternative treatments. It measures the percentage increase in net income in relation to each additional input of expenditure (ΔTVC).

The dominance analysis procedure was used to choose profitable treatments from the fertilizer range tested. Marginal rate of return (MRR) per unit of investment in change of field management practices, which was calculated considering a pair of non-dominated treatments itemized in the order of increasing total variable cost. Minimum acceptable rate of return 50-100% is usually adequate for farmers. Farmers should be willing to change from one treatment to another if the marginal rate of return of that change is greater than the minimum acceptable rate of return (CIMMYT, 1988).

3.8.Data Analysis

The data collected on garlic growth, yield, and yield components were analysed using GenStat statistical software (version 18). To ensure the validity of the results, the assumptions of normality and homogeneity of variances were first checked. This step was crucial to confirm that the data met the necessary requirements for accurate statistical analysis.

Once the assumptions were verified, an analysis of variance (ANOVA) was conducted to determine whether statistically significant differences existed among the treatment levels, which were based on intra-row spacing and nitrogen fertilizer rates. ANOVA was used to assess if the variations in garlic yield and its components were influenced by these treatments.

To identify specific differences among treatment means, the Least Significant Difference (LSD) test was employed at a 5% probability level. The methodology for this test followed the procedures outlined by Gomez and Gomez (1984), allowing for effective comparison and interpretation of the treatment effects.

4. RESULT AND DISCUSSION

4.1. Result on Selected Soil Physico-chemical Properties Prior to Planting

The results of the soil analysis from Table 4.1 indicate several important characteristics of the soil at the experimental site in Mekelle University Endayesus campus experimental plot.

Total Nitrogen Content: The total nitrogen content was measured at 0.10%, which falls into the low category according to the classification by Ötvös et al. (2021). For reference, nitrogen levels between 0.15% and 0.25% are considered medium, while levels exceeding 0.25% are classified as high. This low nitrogen content suggests that the soil may not provide sufficient nutrients for optimal plant growth.

Available Phosphorus: The available phosphorus content was recorded at 5.5mg/kg, categorizing it as medium based on the criteria established by Olsen et al. (1954). This level of phosphorus is generally adequate for supporting plant development.

Cation Exchange Capacity (CEC): The cation exchange capacity of the soil was found to be 35.73 meq/100 g, which is classified as high according to Egel et al. (2014). CEC is an important measure that reflects the soil's ability to retain and exchange essential cations, including hydrogen (H), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe), and aluminum (Al). A higher CEC indicates a better capacity to hold nutrients, which is favorable for plant growth.

Electrical Conductivity and pH: The soil exhibited an electrical conductivity of 0.41 dS/m and a pH level of 7.7, which is close to alkaline. Based on EthioSIS (2014), soil pH is classified into five categories: strongly acidic (< 5.5), moderately acidic (5.6 - 6.5), and neutral (6.6 - 7.3), moderately alkaline (7.3 - 8.4), and strongly alkaline (> 8.4).

Organic Carbon Content: The organic carbon content of the soil was measured at 2.55%, which is categorized as low. According to Tekalign (1991), soils with organic carbon levels exceeding 3% typically do not require additional nitrogen fertilizer. The low organic carbon level indicates that the soil may not have sufficient organic matter to support healthy plant growth Ontl T. A., & Schulte, L. A. (2012).

In summary, the soil analysis revealed deficiencies in both total nitrogen and organic carbon, suggesting that the application of nitrogen fertilizer is necessary to enhance garlic production at the experimental site. The nutrient profile indicates that while the soil has adequate phosphorus and a high cation exchange capacity, the low nitrogen and organic carbon levels could hinder optimal crop yields.

Table 4.1: Physico chemical Properties of the experimental soil

Soil properties	Values	Soil Status

Soil chemical property		
PH(1:2.5H_2O)	7.7	Alkaline
Organic Carbon (%)	2.55	Low
Total Nitrogen (%)	0.10	Low
Available Phosphorous(mg/kg)	5.55	Medium
CEC(cmol (+)kg	35.73	High
Electrical Conductivity(ds/m)	0.41	Non –Saline
Soil physical property		
Sand (%)	18.000	
Silt (%)	58.000	
Clay (%)	24.000	
Textural Class	Silt Loam	

4.2. Effect of intra row spacing and nitrogen fertilizer rates on garlic growth, yield and diseases infestation levels

The analysis of variance (ANOVA) shown that the application of different nitrogen rates under different intra -row spacing significantly affected garlic productivity. The main effect of nitrogen rates significantly ($P<0.01$) affected garlic plant height, leaf length, leaf dry weight and marketable yield. Besides, the main effect of intra row spacing significantly ($P<0.05$) influenced all the studied garlic parameters except leaf number, clove number and harvest index. Similarly, their interaction effect had a non-significant impact on most studied parameters except marketable yield and total bulb yield (appendix 4.1).

4.3. Effect of nitrogen fertilizer rates and intra-row spacing on garlic growth and biomass materials

4.3.1. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Plant height

The effect of both nitrogen rates and intra row spacing significantly influenced garlic plant height (Table 4.5). Nitrogen fertilizer had a strong and clear positive impact on plant height, with significant differences across all levels of application. Plant height was significantly increased with the increasing nitrogen rates where the tallest (50.64 cm) and shortest (32.69 cm) heights were measured from 92 kg N. ha^{-1}, and 0 kg N.ha^{-1}, respectively (Table 4.5).

The increase in plant height with increased rates of nitrogen application could be attributed to nitrogen's role in promoting vegetative growth. Similar results have been observed in other Allium crops where nitrogen application increased plant height, contributing to better light capture and nutrient utilization (Naruka and Dhaka, 2001). A higher nitrogen fertilizer level may have caused the plants to grow taller because the nutrient is more readily available, which promotes protein synthesis and increases the accumulation of carbohydrates (Kenea and Gedamu, 2020). This may have led to an increase in the number and length of leaves on the plant. Furthermore, according to Hordofa et al. (2020), the increase in plant height at medium intra-row spacing could be due to there is less competition between plants for growth factors like light, water, and nutrients which could improve growth and noticeably taller plants.

Intra-row spacing had significantly affected garlic plant height. The tallest garlic plant height (44.5 cm) was measured from 10-cm spacing while 42.49 cm from 15 cm spacing. Garlic plants under 5 cm spacing were the shortest at an average of 40.7 cm (Table 4.5).This trend indicates that a wider spacing favors better conditions for the growth of garlic plants to attain higher height. This is may be due to lower inter-plant competition regarding resources such as light, water, and nutrients favoring better growth and development under normal conditions of plants (Nawaz et al., 2020).

The higher the intra-row spacing, the less the competition, and, therefore, better plant height, as the plants can access more nutrients. Similarly, several researches have shown that lower intra-row plant competition with wider spacing promotes favorable root growth and efficient nutrient uptake that may have a direct effect on aboveground growth parameters (Teshale and Tekeste, 2021). Improved light penetration and plant spacing at wider spacing can favor improved photosynthetic efficiency, hence increased growth and height of plants. Increased height in garlic plants at 10 cm and 15 cm spacing agreed with similar trends observed in allium crops, where the optimal vegetative growth and maximum plant height are supported within a moderate spacing regime (Legese, 2023).

Moreover, narrower spacing 5 cm could further bring down the maximum growth due to root expansion and lower nutrient availability per plant. Input resources sharing in higher plant densities can also result in stunted growth (Asnake et al., 2024). The reduced height at narrow spacing would support findings that plant height is inversely proportional to density in other alliums, such as onions and shallots, in which optimum plant height was normally realized with moderate to wider spacing (Teshale and Tekeste, 2021).

Over all, optimal nitrogen and spacing may be vital agronomic practices to achieve the ideal plant architecture that would in turn affect bulb size and yield quality.

4.3.2. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Garlic Leaf Length

The main effects of nitrogen fertilizer rates and intra-row spacing had significantly influenced garlic leaf length. Nitrogen application at the rate of 92 kg /ha resulted in the longest (44.25 cm) leave length, and the shortest leaf length (31.8 cm) was recorded from the control (0 kg/ha) treatments (Table 4.5). This trend indicates that with more available nitrogen, the leaves were longer. Increasing nitrogen fertilizer, from 0 kg ha^{-1} to 92 kg ha^{-1} N fertilizer, enhanced garlic leaf length by about 39%, which means that the response was quite strong to nitrogen fertilization. In line with this result, Teshome et al. (2015) reported that vegetables' leaf height enhanced with increased rates of nitrogen fertilizer. This is due to the characteristics of nitrogen that favored vegetative growth of plants.

Regarding the intra-row spacing effect, garlic plants that had a spacing of 10 cm had the longest leaf length (40.3 cm), while the shortest (37 cm) leaves were from plants which grew under 5 cm spacing (Table 4.5). This could be attributed to reduced competition for light and nutrients, hence giving each plant an opportunity to allocate more resources for the growth of leaves. In parallel, it has been reported that in garlic and other alliums spacing results in optimum access of light and proper resource allocation, hence increased leaf growth (Wassie et al., 2022). The large increase in leaf length can be explained by the fact that nitrogen allows for an increase in vegetative growth because of its promoting effects on the production of chlorophyll and photosynthesis efficiency (Ashenafi and Tenaye, 2023; Omari et al., 2023). Therefore, improved nitrogen levels responsible for better leaf elongation and structure, highly important for higher light interception and finally better photosynthesis.

4.3.3. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Garlic Leaf Number (LN)

The quantity of leaves per plant exhibited none statistical variation across different nitrogen rates and intra row spacing treatments (Table 4.5). However, plants that received 0 kg ha^{-1} of nitrogen yielded slightly more leaves (11.4 leaves) per plant. This consistent leaf count across varying nitrogen levels implies that nitrogen no predominantly affects the development of new leaves in garlic (Kumar et al., 2018). Although it is likely that other factors such as response the studied variety and environmental conditions play a more substantial role in determining the leaf number in garlic.

In examining intra-row spacing, the number of leaves exhibited a relatively same trend, showing no significant variances across different spacing treatments. These findings imply that, although spacing does influence the size and length of individual leaves primarily due to decreased competition; it does not markedly affect the total leaf count per garlic plant. Several studies have reported similar results, demonstrating that intra-row spacing predominantly influences plant size and biomass distribution rather than the leaf count per plant (Magray et al., 2021; Mebratu and Mulie, 2019; Nawaz et al., 2020).

This suggested that an optimized nitrogen application and intra-row spacing may enhance the vegetative growth of garlic rather than emerging additional leaf, which is crucial for improving overall crop yield. However, it is important to consider the interplay of various factors in agricultural practices as well.

4.3.4. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Disease Severity (DS) and Disease Incidence

The results showed that nitrogen rates had no statistically significant effect on either disease severity or incidence (table 4.3). Regarding the intra-row spacing effect on disease severity, high level of disease severity (19.4%) was measured at the narrow spacing (5 cm) between plants while low disease severity (4.1%) was measured at 15 cm spacing between plants. Indicating that garlic diseases susceptibility level are highly sensitive to rate of nitrogen fertilizer application and the available spaces between plants or plant density (Sharma, 2020).

In contradiction, earlier works have indicated that increased levels of nitrogen enhance plant susceptibility to disease which might create favorable conditions for pathogen infections, particularly rust diseases (Ahmed et al., 2017, Darabi and Dehghani, 2004). Nitrogen's role in disease susceptibility can be complex, as it may depend on factors such as the form and timing of fertilizer application, as well as environmental conditions such as temperature and humidity.

While intra-row spacing significantly affected disease severity and disease incidence ($p < 0.001$). The highest disease severity (19.4%) was recorded in plants that had the narrowest spacing, 5 cm, while the widest spacing, 15 cm, had the lowest disease severity of 4.1%. Similarly, significant differences in the incidences of the disease between different intra-row spacing was observed, where disease incidence was highest in plots with 5-cm spacing at 55.8%, followed by that in 10-

cm-spaced plots. The lowest disease incidence was 21% observed in 15 cm spacing between plants (Table 4.3).

In line with current investigation, it has reported, that narrower intra-row spacing creates crowding among the plants, thereby possibly facilitating the development of conditions highly favorable to the spread and establishment of the pathogens, particularly rust diseases. This is supported by the work of Tadesse and Dejene, (2018) who noted a high disease severity in the densely spaced plants, due to reduced airflow and increased humidity, both favoring pathogen proliferation. Wider row spacing on the other hand permits good aeration and better light penetration into the crop canopy, hence reducing favorable conditions for disease development (Imtiaz Ahmed et al., 2017). In this study, wider spacing (15 cm) not only reduced the severity of disease but also lowered disease incidence, likely due to the reduced plant-to-plant contact and the improved microclimate around the plants.

In line with the finding study conducted in Pakistan showed that the maximum level of disease severity (55.66%) and incident (79%) were observed in plots planted with 10 cm spacing while the lowest level of disease severity (45.33%) and disease incidence (67%) were noted in plots planted with 20 cm spacing (Ahmed et al., 2017).

Overall, it could be stated that, intra-row spacing plays a more crucial role than nitrogen fertilization in reducing garlic disease incidence and severity, particularly for rust diseases.

4.3.5. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on total biomass (TB)

The main effect of nitrogen fertilizer and its interaction with intra-row spacing had no significant influence on total biomass (appendix1),whereas the main effect of intra row spacing highly significantly affect garlic total biomass (Table 4.6).

Maximum total biomass (12.3t/ha) was recorded with the intra row spacing of 5 cm, while minimum total biomass (6.6 t/ha) was found with 15 cm intra row spacing (Table 4.6). The highest total biomass (12.3 t ha^{-1}) recorded from plots treated with 5 cm intra row spacing had an increment of 46% from the least recorded total biomass of 6.6 t ha^{-1} at 15 cm intra row spacing.

The total biomass of garlic tends to be higher at narrower intra-row spacing because this planting density may optimized the use of available resources such as light, water, and nutrients in the growing environment. In narrow spacing more plants experience reduced competition with weeds, leading to better overall resource efficiency. Additionally, higher plant populations per unit area contribute to increased biomass despite potential reductions in individual plant size (Legese, 2023).

The interaction effect of nitrogen fertilizer rate and intra-row spacing on garlic bulb biomass was found to be non-significant in this study. This result is consistent with findings by Hamma et al. (2013) who reported a no significant interaction between fertilizer application and row spacing on bulb biomass. This suggests that, in certain conditions, the main effect of nitrogen rate and intra row spacing may not interact in a way that significantly affects bulb development. Therefore, it is important to consider that other environmental factors (such as soil type, irrigation and climate) could also influence the interaction between nitrogen application and spacing, potentially leading to varying results across different studies.

Furthermore, Kumar et al. (2018) noted that, although spacing and nitrogen fertilization exerted independent positive effects on garlic growth, their combined influence did not consistently yield a significant increase in biomass (particularly under suboptimal soil conditions). Similarly, Mebratu and Mulie (2019) emphasized that the effect of row spacing and nitrogen rates on garlic yield and biomass was more heavily influenced by environmental factors, such as soil fertility and irrigation practices. This suggests that the interaction effect may not always be apparent in every context.

4.3.6. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on total bulb yield (TBY)

Total bulb yield was not influenced by the main effect of different level of nitrogen fertilizer, while the main effect of intra-row spacing and its interaction effect with nitrogen significantly ($p<0.005$) affected garlic total bulb yield (appendix 1) .Addition of more nitrogen rates did not increase garlic yield. Similarly, it has been suggested that an increase in N fertilizer dose did not significantly increase garlic yield (Aliyu et al., 2007). This finding was also in agreement with a Habtamu *et al.* (2016) who concluded that yield increases significantly as population density increases.

Increasing the intra row spacing from 5 to 15 cm significantly decreased the total bulb yield by 43% (Table 4.7). However, increasing the intra row spacing from 10 to 15 did not change total bulb yield. This result shows that plants grown at intra row spacing of 5 cm produced the higher mean total bulb yields. In consistent to the present finding Jamil Mohammad, and Zuraiqi (2002). Reported that, closer intra row spacing of 5 cm increased bulb yield by 7.6% over 10 cm.

Table 4.2: Interaction effect of nitrogen fertilizer and intra row spacing on total bulb yield (TBY)

Treatments				
N fertilizer Kg/ha	Intra row spacing(cm)			Mean
	5	10	15	
0	7.227^{cd}	6.707^{bc}	4.541^{b}	6.17
46	9.057^{e}	7.679^{cd}	4.617^{b}	7.1
69	8.578^{de}	5.77^{ab}	4.534^{b}	6.2
92	7.088^{bc}	7.34^{cd}	7.34^{a}	7.25
Mean	7.98	6.874	5.25	
SE(±)	0.4			
LSD	1.3			
CV	11.9			
P –value	0.03			

N= nitrogen rate ,LSD(5%)= Least significant difference (5%), CV(%) = coefficient variation in percent, means with the same letter(s) or without letters are not significantly different at 5% level of significance, SE= standard error of means

The highest total bulb yield (9.057 t/ha) was observed at a nitrogen application rate of 46 kg/ha with 5 cm intra-row spacing. Whereas the lowest yield (4.534 t/ha) was recorded at a nitrogen application rate of 69 kg/ha with 15 cm intra-row spacing (Table 4.2).

The highest mean total bulb yield (7.98t/ha) was recorded at 5 cm intra row spacing. Whereas the lowest mean total bulb yield (5.25t/ha) was observed at 15 cm intra row spacing.

At null nitrogen fertilizer rate the lowest mean total bulb yield (6.17t/h) was recorded which indicating that nitrogen fertilizer positively impacts garlic yield. The highest mean bulb yield 7.25 t/ha) was also observed at 92 kg/ha nitrogen fertilizer rate (Table 4.2)

Recent studies have consistently highlighted the essential role of nitrogen rate and intra row spacing on influencing garlic yield (Teshale and Tekeste, 2021). At wider spacings, excessive nitrogen resulted in decreased yield because of nitrogen leaching and inadequate uptake. Similarly, Bililign, (2022) found that garlic plants cultivated at narrower spacing (5-7 cm) derived greater benefits from moderate nitrogen applications (30–45 kg/ha); but, those grown at wider spacing required increased nitrogen inputs to attain comparable yields. It can be conclude that wider spacing improved the plant's capacity to absorb nutrients across a broader area.

At wider spacings, garlic plants faced less competition for nutrients and were less responsive to nitrogen, resulting in lower yields despite higher fertilizer application. This highlights the importance of optimizing both spacing and nitrogen levels for maximum yield.

4.3.7. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Harvest Index

The results revealed that neither nitrogen fertilizer rates nor the spacing between plants did not reslt in a significant effect on the harvest index. These results tend to indicate that, within the conditions of this experiment, variations in nitrogen fertilization and intra-row spacing probably do not strongly affected the allocation of biomass to the harvestable portion of garlic plants.

However, the opposite result was reported by Teshale and Negasi (2021) where the intra-row spacing at 5 cm yielded the highest harvest index of 50.41%, whereas at the wider intra-row spacing of 12.5 cm, it had the lowest harvest index of 35.69%. The contradiction with current result might be variation in the testing locations in garlic biomass partitioning efficiency.

This is consistent with the findings of Khan et al. (2002), who noted that more narrow spacing in garlic is quite often associated with a higher harvest index, even though the total yield may not be at the maximum. In contrast, wider spacings generally are less competitive between plants for space, allowing the individual plants to develop their vegetation more, but this at times leads to a lower biomass translocation to the bulb and thus lowers the harvest index.

The non-significant effect of nitrogen on the harvest index could be attributed to the specific growing conditions, such as soil fertility, moisture availability, and environmental factors, which may have limited the potential influence of nitrogen (Tekle, 2015).

Table 4.3: Main effect different rate of nitrogen fertilizer and intra- row spacing on disease severity, disease incidence level and harvest index**.**

Factor	Treatment	DS (%)	DI (%)	Harvest index
N fertilizer(kg/ha)	0	6.87	38.1	0.65
	46	10.5	48.33	0.65
	69	14.	29.7	0.68
	92	8.16	41.78	0.68
SE(±)		2.5	8.8	0.01
$LSD_{0.05}$		NS	NS	NS
CV		17	1.9	6.8
p- value		0.21	0.5	0.28
S (cm)	5	19.4^{a}	55.83^{a}	0.6
	10	6.2^{b}	41.9^{ab}	0.66
	15	4.1^{b}	20.75^{b}	0.69
SE(±)		2.1	7.6	0.01
$LSD_{0.05}$		6.38	22	NS
CV		17	66.9	6.8
P –value		<.001	0.013	0.12

s=intra row spacing, N = Nitrogen, DS=disease severity, DI=disease incidence, LSD (5%) = Least significant difference (5%), CV (%) = coefficient variation in percent, means with the same letter(s) or without letters are not significantly different at 5% level of significance.

4.3.8. Effect of effect of Nitrogen fertilizer rate and Intra row spacing on Marketable Yield

There were statistically significant differences among nitrogen fertilizer rates and intra row spacing. Moreover, the interaction effects of nitrogen rates and intra row spacing was also significant (appendix 1).

The highest marketable bulb yield (8.1 kg) was obtained from plots treated with 46 kg N/ha spaced at 5 cm which was followed by yields at 10 cm (7.4 kg) and the lowest marketable yield (4.3 kg) was harvested from plots treated with 69 kg N ha^{-1} and 15 cm spacing (Table 4.4).

At the closest spacing of 5 cm, the highest mean marketable yield (6.9t/ha) was observed with 46 kg/ha of nitrogen fertilizer with mean marketable yield of (6.6 t/ha) (table 4.4).

Table 4.4: Interaction effect of nitrogen fertilizer rates and intra-row spacing on marketable yield

Treatment	MY			Mean
N fertilizer (kg/ha)	S (cm)			
	5	10	15	
0	6^{bc}	6.2^{bcd}	4.3	5.5
46	8.1^{e}	7.4^{cde}	4.3	6.6
69	7.6^{de}	5.4^{ab}	4.1	5.7
92	6.2^{bcd}	7^{cde}	4.3	5.8
Mean	6.97	6.5	4.25	
SE(±)	0.46			
LSD.05	1.3			
CV (%)	13.3			
p- value	0.042			

MY= marketable yield, N= nitrogen fertilizer rate, S= intra row spacing LSD (5%) = Least significant difference (5%), CV (%) = coefficient variation in percent, means with the same letter(s) or without letters are not significantly different at 5% level of significance.

Yield tends to decline as the spacing widens from 5 cm to 15 cm spacing at the same nitrogen rate except at 92 kg N rates where yield was fluctuated (Table 4.4). Similarly, Tena et al (2024) reported that the highest garlic yield was achieved at 48 kg/ha N when compared to 0 kg/ha and 72kg/ha N application. In regard to the main effect of spacing, maximum yield (6.5 t/ha) was found in 10 cm intra row spacing while low yield (4.3 t/ha) was recorded in 15 cm spacing. In line with the current study, Murmu et al (2019) reported that the narrow plant spacing gave high yield whereas wider plant spacing reduces marketable yield of garlic. A study conducted in the Tigray region showed that planting garlic with 5 cm intra-row spacing gave the highest marketable bulb yield of 8.05 t ha^{-1} while the lowest marketable bulb yield of 4.944 t ha^{-1} was obtained from 12.5 cm intra-row spacing (Teshale and Negasi, 2021). The highest total bulb yield recorded from large-sized cloves planted at narrow intra-row spacing might be due to an increased plant population per unit area of land that in turn leads to the production of more bulbs (Asnake et al., 2024).

In general, optimal rate nitrogen application and narrower intra-row spacing significantly enhances garlic yield, primarily by improving plant population density and resource allocation.

4.3.9. Effect of Nitrogen fertilizer rate and Intra row spacing on Unmarketable Yield

Result showed that there was no statistically significant difference between the effect of nitrogen fertilizer rates and its interaction effect on unmarketable yield. However, intra row spacing treatments had statistically significant effect on unmarketable yield (Table 4. 6).

The lowest unmarketable yield was recorded at 15 cm spacing whereas the highest was at 5 cm spacing (Table 4.6).

This finding is consistent with Gebretsadik and Dechassa (2016), who reported that wider intra-row spacing reduced the production of unmarketable garlic bulbs. The reduction in unmarketable yield at wider spacing may be due to decreased competition for nutrients, light, and space, allowing garlic plants to grow more uniformly and produce higher-quality bulbs. In contrast, narrow spacing increases competition, leading to smaller, malformed, or damaged bulbs that are classified as unmarketable. Kumar et al. (2018) found that closer plant spacing increased the 00incidence of poorly formed bulbs, especially under suboptimal nutrient conditions. Similarly, Mebratu and Mulie (2019) observed that narrow intra-row spacing caused increased competition for resources, resulting in more unmarketable bulbs due to stunted growth and irregular bulb development.

Asnake et al. (2024) emphasized that optimal row spacing is critical for reducing unmarketable bulb production by promoting better bulb development and overall plant health

4.3.10. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Leaf Fresh Weight (LFW)

The application of different nitrogen fertilizer rates had no significant effect on the leaf fresh weight of garlic (Table 4.5). Similarly, it has reported that, nitrogen does not affect biomass weight, rather it is a crucial component in many enzymes and proteins that are necessary for plant growth (Abera and Adinew, 2023). Several studies by Shumbulo et al. (2024); Getachew & Asefa, (2021) show contrasting effects of nitrogen fertilizer rates on garlic boosted garlic leaf fresh weight, likely due to enhanced chlorophyll content and improved nutrient uptake. However, Abdissa et al.2011) observed that excessive nitrogen led to excessive vegetative growth, reduced bulb formation and overall productivity, including leaf fresh weight. This suggests that nitrogen's effect on growth parameters, such as leaf weight, varies based on factors like plant variety, environmental conditions, and nutrient balance, making the relationship complex and context-dependent.

Leaf fresh weight was significantly influenced by intra-row spacing (table 4.5). The highest leaf fresh weight of 9.05 gram was recorded at 15 cm spacing, followed by 10cm (8.9g), whereas the least leaf fresh weight was produced at 5cm spacing (6.9g). Indicating, about 31% increase in leaf fresh weight from 5cm spacing to 15cm spacing, which implies that lesser competition for resources such as light and soil nutrients improves biomass as in this case. This is consistent with the results of Mebratu and Mulie (2019) have stated that wider spacing allows each plant to have larger leave sizes because of less competition. In nutshell, nitrogen’s effect on garlic leaf fresh weight varies, while wider spacing (15 cm) improves growth by reducing competition. Optimizing both nitrogen application and spacing is essential for better garlic yield.

4.3.11. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Garlic Leaf Dry Weight (LDW)

Application of different nitrogen fertilizer rates had significantly affected garlic leaf dry weight (Table 4.6). The lowest leaf dry weight (2.17 g) was recorded from 69 kg N ha^{-1}; while the highest leaf dry weight (2.8 g) was realized at 92 kg N ha^{-1} which was higher by 16.67% over the rest nitrogen rates (Table 4.6). This suggested that a moderate increment in nitrogen application can enhance dry matter accumulation within the leaves probably due to enhanced photosynthetic activity and increased nutrient availability for optimal plant growth.

Recent studies align with these findings, demonstrating the crucial role of nitrogen in promoting dry matter accumulation in plants. This is agreed with research works reported by Getachew & Asefa, (2021) that nitrogen fertilization significantly increased the dry weight of garlic leaves, with the optimal nitrogen rate varying depending on environmental conditions and soil characteristics. Similarly, Kumar et al. (2018) noticed a positive relationship between nitrogen rates and leaf dry weight in garlic, suggesting that higher nitrogen levels enhance the plant's ability to accumulate organic matter, possibly by stimulating chlorophyll production and improving nitrogen assimilation.

The intra row spacing also has a significant effect on leaf dry weight. The highest leaf dry weight of 2.8 g was recorded at the 10 cm spacing while the least 2.1 g at 5 cm spacing which is a difference of around 25 % (Table 4.6). This suggest that better growth of leaves is achieved when the spacing is wider most probably because the competition for resources is less intense.

The interaction of nitrogen rates and intra- row spacing was not significant on leaf dry weight although increased rate of nitrogen slightly increased leaf dry weight in general. This result contradicted the reports of Gessessew et al. (2015). The discrepancy may be attributed to differences in experimental conditions such as soil type, variety climate, or nitrogen sources.

4.3.12. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Bulb Fresh Weight (BFW)

The application of varying rates of nitrogen fertilizer and its interaction with intra-row spacing demonstrated no significant impact on garlic bulb fresh weight. This indicates that nitrogen fertilization may not serve a significant role in promoting the growth of garlic bulbs, which function as the primary storage organs of the plant. Although nitrogen is crucial for overall plant health and leaf development, its effect on bulb development seems to be less pronounced. This finding is consistent with the research conducted by Abera and Adinew (2023), who suggested that factors beyond nitrogen (like soil type, plant variety and environmental conditions) could be more influential in determining bulb weight.

The spacing between garlic plants in a row significantly impacted the fresh weight of the bulbs. Plants spaced at 15 cm produced the heaviest bulb weight (33.6 g), followed by those at 10 cm spacing (32.6 g) but the bulbs at a spacing of 5 cm exhibited the lowest fresh weight (24.3 g). Similarly, the largest bulb diameter (39.7 mm) was recorded at both 15 cm and 10 cm spacing, whereas the smallest bulb diameter (36.5 mm) was observed at the closest spacing of 5 cm (Table 4.5). This variation in bulb weight which represents about 34.2% increase when comparing the closest spacing of 5 cm to the widest spacing of 15 cm. This underscores the critical role of diminished underground inter-plant competition in optimizing bulb size and weight. In parallel to the present finding, it has been noticed that wider intra row spacing not only facilitates ample room for garlic root expansion and nutrient absorption, but it also promotes improved bulb development (Hordofa et al., 2020; Nawaz et al., 2020; Mebratu and Mulie, 2019). Wider intra-row spacing significantly enhances garlic bulb weight and diameter by reducing competition.

Table 4.5: Main effect different rate of nitrogen fertilizer and intra- row spacing on plant height, leaf length, leaf number, leaf fresh weight and bulb fresh weight

Factor	Treatment	plant height (cm)	leaf length (cm)	leaf number	leaf fresh weight (g)	Bulb fresh weight (g)
Nitrogen fertilizer kg/ha	0	32.69^{a}	31.8^{d}	11.4	8.4	28.3
	46	40.88^{b}	37.6^{c}	11.19	8.5	31.3
	69	45.68^{c}	40.6b	11.06	7.2	29.8
	92	50.64^{d}	42.5^{a}	11.24	8.6	31.3
SE(±)		0.9	0.8	0.2	0.7	1.7
LSD$_{0.05}$		2.6	2.3	NS	NS	NS
CV (%)		6.4	6.3	5.8	27	17
p-value		<.01	<.001	0.73	0.52	0.59
intra -row spacing (cm)	5	40.7^{b}	37^{b}	11.38	6.9^{b}	24.3^{b}
	10	44.5^{ab}	40.3 ^{a}	11.26	8.9^{a}	32.6^{a}
	15	42.49^{ab}	38.4^{ab}	11.03	9.05^{a}	33.6^{a}
SE(±)		0.7	0.6	0.1	0.6	1.5
LSD0.05		2.3	2.1	NS	1.8	4.4
CV		6.4	6.3	5.8	27	17
p-value		0.02	0.01	0.43	0.02	<.001

LSD(5%)= Least significant at p=0.05,CV(%)= coefficient variation in percent , means with the same letter(s) or without letters are not significantly different at 5% level of significance , SE= standard error of means

4.3.13. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Bulb Dry Weight (BDW)

The effect of nitrogen fertilizer and its interaction with intra-row spacing on garlic bulb dry weight had no statistical difference (appendix 1). Coherently, it has been reported that overabundance of nitrogen application can lead to a decrease in the dry weight of garlic bulbs. This is linked with reports of Abdissa et al. (2011) who revealed that nitrogen rates exceeding 100 kg N ha^{-1} resulted in excessive vegetative growth; this, in turn, hindered bulb formation. Furthermore, Khokhar, (2019) reviewed that extremely high nitrogen concentrations caused a reduction in bulb dry weight, primarily because of nutrient imbalances and inefficient resource distribution. However, it is important to consider the broader implications of these findings. The lack of a significant effect in this study could be due to several factors, including the garlic variety reaching its optimal nitrogen uptake threshold, making further nitrogen increases ineffective.

The absence of a substantial impact from nitrogen fertilizer rates in this study could be attributed to the garlic variety had already attained optimal nitrogen uptake for its bulb dry matter accumulation. Thus, additional nitrogen may not yield further increases in growth; however, this can render subsequent nitrogen applications ineffective.

The influence of spacing between plants significantly affected garlic bulb dry weight whereby 10cm spacing gave the highest (12.5 g) bulb dry weight. The narrow intra row spacing of 5 cm gave the lowest (9.3 g) bulb dry weight which reduced by 34.4 % that shows the benefit of using wider spacing to enhance more bulb growth due to better water, fertilizer and light access. Indicating using wider spacing of garlic significantly increased the bulb dry weight primarily due to availability of more nutrients and less competition for light and space (Getaneh et al, 2020). Wider spacing enables greater room for root expansion and ensuring that plants are better equipped to absorb nutrients from the soil. Consequently, this leads to an increase in bulb size and dry weight.

With reduced competition, garlic plants can grow more vigorously, which in turn enhances photosynthetic efficiency, and boosts the storage of carbohydrates that directly contributes to a higher bulb dry weight.

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Table 4.6: Main effect different rate of nitrogen fertilizer and intra- row spacing on leaf dry weight, bulb dry weight, total bio mass, marketable yield and unmarketable yield

Factor	Treatment	LDW	BDW	TB	MY	UNMY
Nitrogen fertilizer kg/ha	0	2.4^{ab}	11.1	9.4	5.5^{b}	0.65
	46	2.7^{a}	12.2	10.9	6.6^{e}	0.47
	69	2.17^{b}	10.8	9.3	5.8^{ab}	0.54
	92	2.8^{a}	11.	9.1	5.7^{b}	0.49
SE(SE(±)		0.1	0.8	0.25	0.2	0.07
LSD0.05		0.5	NS	NS	0.78	NS
CV		20	22	14	13	40
p-value		0.04	0.69	0.06	0.04	0.4
Intra-row spacing	5	2.1^{b}	9.3^{b}	12.3^{a}	7^{a}	0.98^{a}
	10	2.8^{a}	12.5^{a}	10.3^{b}	6.5^{a}	0.35^{b}
	15	2.8^{a}	12.7^{a}	6.6^{c}	4.3^{b}	0.26^{b}
SE(±)		0.15	0.7	0.4	0.2	0.06
LSD0.05		0.4	2.1	1.2	0.63	0.18
CV		20	22	14	13	40
p- value		<.001	0.006	<.001	<.001	<.01

LDW= leaf dry weight, BDW= bulb dry weight, TB= total biomass, MY= marketable yield, UnMY= unmarketable yield, LSD (5%) = Least significant difference (5%), CV (%) = coefficient variation in percent, means with the same letter(s) or without letters are not significantly different at 5% level of significance

4.3.14. Effect of Nitrogen fertilizer rate and Intra row spacing on Bulb Diameter (BD)

The results showed that garlic bulb diameter was significantly affected by different intra-row spacing treatments, but not by the application of various nitrogen fertilizer levels (Table 4.7). The largest bulb diameter (39.7 mm) was observed at 15 cm and 10 cm spacing, while the smallest bulb diameter (36.5 mm) was recorded at 5 cm spacing (Table 4.7). There was a bulb diameter increment of about 8.8 % with an increase in intra-row spacing from 5cm to 15 (Table 4.7).This is consistent with the findings of Aliyu et al. (2008), who reported that wider intra-row spacing resulted in the largest bulb diameter. The smaller bulb diameter at narrower row spacing is likely due to increased competition between plants for nutrients, moisture, and sunlight. Therefore, garlic plants have better access to these resources, leading to more vigorous growth and enhanced photosynthetic activity. These results agreed with the findings of (Tadesse, and Dejene, (2018) who found that greater plant spacing significantly improved bulb diameter. This, in turn, increases the accumulation of carbohydrates and biomass, contributing to larger bulb size (Alem et al, 2010). Thus, wider intra-row spacing enhances garlic bulb diameter by reducing plant competition for resources, leading to better growth and increased bulb size.

Table 4.7: Main effect different rate of nitrogen fertilizer and intra- row spacing on total bulb yield, bulb diameter, clove number and bulb size

Factor	Treatment	Total bulb yield(t/ha)	Bulb diameter(mm)	Clove number	bulb size (mm)
Nitrogen fertilizer kg/ha	0	6.1	37	8.4	40.93
	46	7.1	39	8.35	41.4
	69	6.2	38	9.11	40.9
	92	6.3	39	8.8	40.22
SE(±)		0.2	0.9	0.4	1.0
$LSD_{0.05}$		NS	NS	NS	NS
CV (%)		11	7.2	15	7..3
p-value		0.062	0.483	0.59	0.859
intra-row spacing (cm)	5	7.9^{a}	36.5^{b}	8.3	38.8^{b}
	10	6.8^{b}	39.6^{a}	8.8	41.58^{a}
	15	4.5^{c}	39.7^{a}	8.8	42.19^{a}
SE(±)		0.2	0.8	0.3	0.8
$LSD_{0.05}$		0.6	2.3	NS	2.5
CV (%)		11	7.2	15	7.3
p- value		<.001	0.014	0.502	0.029

LSD (5%) = Least significant difference, CV (%) = coefficient of variation in percent, means with the same letter(s) or without letters are not significantly differed at 5% significant level.

4.3.15. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Clove Number

The results showed that there was no statistically significance difference among the nitrogen fertilizer means as well as intra-row spacing treatments, which indicates that nitrogen rates and intra row spacing had no effect on garlic clove number (Table 4.7). In line with this finding Kenea, and Gedamu, (2020) indicated that nitrogen fertilizer applications had no significant effect on number of cloves per bulb. Clove numbers tend to remain stable at higher nitrogen levels (92 kg/ha), indicating that further increases in nitrogen might not enhance clove production regardless of spacing.

The application of nitrogen has been shown to have a greater impact on bulb yield than on clove formation, as it primarily influences bulb size. In addition, Imtiaz Ahmed et al. (2017) discovered that increased nitrogen rates had minimal effects on the clove count; however, they did significantly enhance both bulb size and weight. In a similar vein, Singh et al. (2018) noted that, although intra-row spacing can influence the number of cloves, the application of nitrogen has a more substantial effect on the development of the bulb itself rather than on clove numbers.

This result indicates that nitrogen rates and intra-row spacing do not have a notable impact on the quantity of garlic cloves; this reinforces the notion that clove formation is less affected by these variables, especially when compared to other growth parameters such as bulb size and weight.

4.3.16. Effect of Nitrogen Fertilizer Rates and Intra-Row Spacing on Bulb Size

The result showed that nitrogen rates did not have a statistically significant impact on garlic bulb size, suggesting that variations in nitrogen application may not be a key factor influencing bulb development in garlic (Table 4.7).

This finding contrasts with some previous research where nitrogen levels were reported to enhance bulb size by promoting vigorous vegetative growth, as reported by Merga (2022) and Gessesew et al. (2015) who found positive correlations between higher nitrogen rates and increased bulb weight. However, in this case, the effect of intra-row spacing was more pronounced, with spacing treatments demonstrating a significant influence on bulb size. Narrow spacing of 5 cm resulted in the smallest bulbs, with a mean weight of 38.8 g, while garlic spaced at 10 and 15 cm produced larger bulbs, both reaching approximately 42 g. These findings agreed with the work of Shimelis et al. (2020) who observed that garlic plants with wider spacing had better access to nutrients, sunlight, and air circulation, leading to larger bulbs. Additionally, Khan et al. (2002) highlighted that optimal spacing can improve root expansion and overall plant growth, which may explain the observed differences in bulb size. Therefore, intra-row spacing may play a more significant role than nitrogen rates in determining garlic bulb size under the conditions of this experiment, further supporting the need to adjust spacing practices for optimal crop yield.

4.4. Correlation coefficient analysis among garlic growth, yield, and yield related parameters

Garlic plant height strong (r=0.98) positive correlated with leaf length, rust disease severity and clove numbers (Table 4. 8), indicating that taller plants generally have longer leaves, and more cloves which directly linked with higher chance of exposure to diseases. This is consistent with the findings of other studies where taller garlic plants had better leaf length and many cloves, which directly influences photosynthetic capacity and yield potential (Zakari, et al., 2017). The absence of significant correlation between plant height and leaf number suggested that leaf number may not be directly related to plant height in garlic. Similarly, it has been reported that leaf development is influenced by other growth parameters in garlic (Falaki, et al., 2006).

According to Schober et al. (2018), leaf fresh weight showed weak (r=0.32), positive correlations with bulb fresh weight (Table 4.8). Suggesting larger and healthier leaves can contribute to increased bulb growth. This is aligned with earlier studies showing that a higher leaf area correlates with increased photosynthetic capacity and thus better bulb development in garlic (Jia et al., 2023).

The correlation between total bulb yield, marketable and unmarketable yield was very strong (r=0.98). The negative (r= -0.5) correlation between unmarketable yield and bulb size further emphasized the significance of bulb size as a quality parameter in garlic production.

In addition, total biomass strongly positively (r=0.94) correlated with marketable yield and bulb fresh weight (r= 0.97), and bulb dry weight (r=0.89) respectively, suggesting biomass accumulation is closely linked to garlic yield and its components. Similarly, bulb dry weight, which is a key indicator of garlic quality, showed strong positive (r=0.88) correlations with both bulb fresh weight and leaf dry weight (r=0.56). This strengthens the idea that vigorous growths in both above-ground and below-ground biomass are essential for optimal yield and quality in garlic cultivation (Singh et al., 2013; Zakari et al., 2016).

Rust disease infestation and severity levels showed significant negative correlations with several garlic growth and yield parameters (Table 4.8). Besides, rust diseases severity was negatively correlated with bulb fresh weight (r=-0.7), bulb and leaf dry weight (r=-0.4), suggesting higher disease infestation levels can reduce garlic overall biomass and growth. In consistent with this, it has been reported that garlic diseases susceptibility level highly negatively correlated to its yield and quality reduction (Bal et al., 2019).

The correlation of harvest index with total biomass and disease infestation level was negative and strong (r= -0.5 and -0.3). However, its correlation with other parameters was generally weak indicating that garlic biomass allocation was not strongly influenced by these parameters. Harvest index was negatively correlated with disease severity, diseases infestation and leaf dry weight, suggesting sever disease could reduce leaf biomass and the efficiency of nutrient partitioning between vegetative and reproductive tissues, ultimately affecting the harvest index. This finding is in line with research by Ashok, et al. (2013), which indicated that disease stress and poor leaf growth can reduce the harvest index by limiting photosynthesis and nutrient allocation to the bulbs.

Generally, the correlation analysis indicated that, the critical role of plant height, leaf development, and biomass accumulation in determining garlic yield and quality.

Table 4.8: Correlation coefficient among growth, yield and yield components of garlic as influenced by nitrogen fertilizer rates and intra row spacing

	PH	**LFL**	**LN**	**TBY**	**MY**	**UNMY**	**TB**	**BFW**	**LFW**	**BD**	**BS**	**IL**	**DS**	**BDW**	**LDW**	**Clove N**	**HI**
PH	1																
LFL	0.98**	1															
LN	-0.03^{ns}	0.008^{ns}	1														
TBY	-0.01 ^{ns}	0.01 ^{ns}	0.35*	1													
MY	0.04 ^{ns}	0.09 ^{ns}	0.31*	0.98**	1												
UnMY	-0.26 ^{ns}	-0.03 ^{ns}	0.29 ^{ns}	0.57**	0.39*	1											
TB	-0.07 ^{ns}	-0.03 ^{ns}	0.35*	0.97**	0.94**	0.58**	1										
BFW	0.27 ^{ns}	0.32*	-0.14^{ns}	-0.32*	-0.19 ^{ns}	-0.7**	-0.35*	1									
LFW	0.11 ^{ns}	0.15 ^{ns}	0.25 ^{ns}	-0.04 ^{ns}	0.02	-0.29^{ns}	0.009^{ns}	0.52**	1								
BD	0.28 ^{ns}	0.32*	-0.12^{ns}	-0.24 ^{ns}	-0.12 ^{ns}	-0.6**	-0.25 ^{ns}	0.88**	0.53**	1							
BS	0.003 ^{ns}	0.04 ^{ns}	-0.16^{ns}	-0.28 ^{ns}	-0.18 ^{ns}	-0.5**	-0.29 ^{ns}	0.79**	0.6**	0.77**	1						
IL%	-0.02 ^{ns}	0.04 ^{ns}	0.1 ^{ns}	-0.48*	-0.44*	0.37*	-0.5**	-0.26^{ns}	-0.08^{ns}	-0.13^{ns}	-0.19^{ns}	1					
DS%	0.04*	0.03 ^{ns}	0.13 ^{ns}	-0.5**	-0.49*	0.5**	-0.5**	-0.49*	-0.32*	-0.42*	-0.59*	0.31*	1				
BDW	0.16 ^{ns}	0.2 ^{ns}	-0.23^{ns}	-0.25 ^{ns}	-0.13	-0.57*	0.26 ^{ns}	0.89**	0.56**	0.84**	0.75**	-0.1^{ns}	-0.4*	1			
LDW	0.26 ^{ns}	0.34*	0.10 ^{ns}	-0.19	-0.1 ^{ns}	-0.45*	-0.13 ^{ns}	0.6**	0.77**	0.56**	0.52**	0.0^{ns}	-0.4*	0.58**	1		
clove_N	0.3*	0.33*	0.09	-0.22 ^{ns}	-0.18	-0.23^{ns}	-0.19 ^{ns}	0.3*	0.12 ^{ns}	0.33*	0.15 ^{ns}	0.09^{ns}	-0.2^{ns}	0.3*	0.19 ^{ns}	1	
HI	0.21 ^{ns}	0.16 ^{ns}	-0.16^{ns}	-0.02 ^{ns}	-0.26 ^{ns}	-0.29^{ns}	-0.52*	0.29 ^{ns}	-0.17^{ns}	0.16 ^{ns}	0.19 ^{ns}	-0.3*	-0.2^{ns}	0.17 ^{ns}	-0.15 ^{ns}	-0.1 ^{ns}	1

Abbreviations: *PH= plant height (cm), LFL= leaf length (cm), LN= leaf number (count), TBY= total bulb yield (tons), MY= marketable yield (tons), UnMY= unmarketable yield (tons), TB=total biomass (tons), BFW=bulb fresh weight (gram), LFW= leaf fresh weight (gram), BD= bulb diameter (mm), BS= bulb size (mm), IL= diseases infestation level (%), DS= diseases severity level (%), BDW= bulb dry weight (gram), LDW= leaf dry weight (gram), CN_N= clove numbers (count), HI= harvest index (%).*

** Indicates very strong correlation (at 1% significant level) while * denotes a moderate correlation between the variables (at 5% significance level), and “NS” denoted none significant correlation.

4.5. Partial budget analysis of nitrogen rates and intra row spacing on garlic marketable bulb yields

The cost-benefit analysis of garlic yield at different levels of nitrogen fertilizer and intra-row spacing in the off-season of 2024 is highly varied (Tables 4.9 & 4.10). These results have figured out the application of nitrogen application and intra-row spacing had profound impact on garlic yield economic profitability with some exceptions like treatments received higher nitrogen rates of 69 and 92 kg ha^{-1} tended to have lower yields compared with the more moderate nitrogen treatments.

Benefit cost ratio is one of the most important determinants of economic efficiency. A high value of the ratio reflects reasonable cost control and higher marketable yields. The highest net benefit of ETB 2,134,200 was earned from plots treated with 10 cm intra row spacing and 46 kg N ha^{-1}, which had a profitable ratio of 10.84, reflecting in every investment of 1 ETB there would be a profit return of 10.84 ETB. The treatments with high rates of nitrogen application such as 92 kg ha^{-1}, combined with large intra-row spacing of 15 cm resulted about 9.32 and 3.81 benefit cost ratio respectively. This agrees with the findings of Liu et al. (2022), where optimal application of nitrogen coupled with spacing practices enhances profitability in garlic production.

Non-dominated treatments, such as plots treated with 10 cm intra row spacing and 46 kg N represent the best combination of nitrogen and intra-row spacing that yields high net benefits for which no other treatment has outperformed it. While dominated treatments like 1, 7, and 11, underperformed both in yield and profitability, especially as their spacing or nitrogen levels were compared to the same level spacing (Table 4.10). These dominant treatments reflect the possible inefficiencies of excessive nitrogen fertilization and inappropriate spacing of garlic under the particular off-season conditions. This agrees with Haque et al. (2015) who discussed cost inefficiency caused by excessive nitrogen. Excessive application of nitrogen fertilizers and wider spacing lead to diminishing returns and lower economic efficiency.

The analysis of marginal rate of return (MRR%) on garlic bulb yield revealed that, among the non-dominated treatments, application of 10 cm spacing and 46 kg N ha^{-1} showed the highest MRR of 8,690%, indicating that this treatment was very profitable. This result agreed with the finding that moderate nitrogen application, especially in combination with closer row spacing, significantly improves garlic yield and increases profitability (The MC of this treatment was relatively low at 4,300 ETB, while the MB stood at 373,700 ETB, hence a phenomenal MRR. Similarly high values of MRR with moderate application of nitrogen were reported from similar vegetable crops by Haque et al. (2015) in cabbage; Melese et al. (2018) in pepper who showed that optimum nitrogen levels upsurge yield and economic returns without crossing over the point of diminishing returns.

Table 4.9: Cost benefit analysis for the effect of nitrogen fertilizer rates and intra row spacings on garlic marketable bulb yield based on hectare and valued in ETB; during off season of 2024**.**

TRT	S	N	TVC (ETB)	MY	Adj.MY	SP_ton^{-1}	GB (ETB)	NB(ETB)	B:C	Dominance
9	15	0	122500.00	4.3	3.87	350,000	1354500	1232000.00	10.05	ND
10	15	46	126800.00	4.3	3.87	350,000	1354500	1227700.00	9.68	D
11	15	69	128966.66	4.1	3.69	350,000	1291500	1162533.34	9.01	D
12	15	92	131133.33	4.3	3.87	350,000	1354500	1223366.67	9.32	D
5	10	0	192500.00	6.2	5.58	350,000	1953000	1760500.00	9.14	ND
6	10	46	196800.00	7.4	6.66	350,000	2331000	2134200.00	10.84	ND
7	10	69	198966.67	5.4	4.86	350,000	1701000	1502033.33	7.54	D
8	10	92	201166.67	7.0	6.30	350,000	2205000	2003833.33	9.96	D
1	5	0	396666.67	6.0	5.40	350,000	1890000	1493333.34	3.76	D
3	5	69	403133.33	7.6	6.84	350,000	2394000	1990866.67	4.93	D
2	5	46	404666.67	8.1	7.29	350,000	2551500	2146833.34	5.30	ND
4	5	92	405300.00	6.2	5.58	350,000	1953000	1547700	3.81	D

Keys of abbreviations: *Trt=Treatments, S= intra row spacing(cm), N= nitrogen fertilizer (kg ha^{-1}), TVC= total variable cost, MY=marketable bulb yield (tone per hectare, SP= Selling price per ton, GB= gross benefit, NB= net benefit, ETB= Ethiopian birr, B:C = the ratio of net benefit to total variable cost , ND= none dominated, D = dominated , Adj. MY= adjusted marketable yield downed by 10%, t.ha^{-1} =yield ton per hectare.*

Table 4.10: Marginal rate of return for none dominated for the combinations of nitrogen fertilizer rates and intra row spacing treatments on garlic marketable bulb yield during off season, 2024**.**

TRT	S	N	Adj.MY	TVC	MC	NB	MB	MRR (%)
9	15	0	3.87	122500	0	1,232,000	0	-
5	10	0	5.58	192500	70000	1,760,500	528500	755
6	10	46	6.66	196800	4300	2,134,200	373700	8690
2	5	46	7.29	404666.7	207866.7	2146833	12633.34	6

Abbreviation keys:

Trt=Treatments, S= intra row spacing, N= nitrogen fertilizer rates, Adj. MY (ton per hectare adjusted by 10% down, TVC= total variable cost (ETB ha^{-1}), MC= marginal cost, NB= net benefit (ETB ha^{-1}), MB= marginal benefit, MRR (%) = marginal rate of return.

The calculated MRR from plots treated with a spacing of 10 cm with 46 kg N ha^{-1}, showed positive increase by a magnitude of 100%, implying that an increased investment from application of 46 kg N ha^{-1} accounted about ETB 4,300 marginal cost. However, the MRR was significantly lower at treatment 2, thus suggesting that spacing of 5 cm with 46 kg N ha^{-1} may not be economically efficient in comparison to 10 cm spacing with the same nitrogen rate. Similarly, the narrower row spacing enhances resource utilization, such as nutrient availability, thereby increasing returns (Kenea and Gedamu, 2020; Naruka & Dhaka, 2001).

On the other hand, plots treated with 10 cm spacing, and 0 kg N ha^{-1} revealed a reasonable net benefit of ETB 1,760,500, having a marginal return of 755%, demonstrating that the initial yield at higher spacing without nitrogen fertilization is so rewarding. However, its marginal cost for this treatment was very high (MC = ETB 70,000), reflecting the underlying consequence of diminishing returns after the initial increase in yield. This means that while there were no applications of nitrogen and the overall benefits were high, further increasing the yield using fertilizers was not as effectively returned.

Treatments like 5-cm spacing at 46 kg N ha^{-1}, showed minimum MRR (6%) indicating the lower use efficiency of nitrogen fertilizer when applied under very narrow spacing. The net benefit was positive but only ETB 2,146,833, whereas the marginal benefit was much smaller compared with the marginal cost, indicating the high input cost associated with closer spacing and the 46 kg N ha^{-1} rate was unjustified by the relatively small increase in returns. This agreed with the findings of Liu et al. (2023), who observed that excessive inputs in closely packed systems can lead to inefficiencies through root and nutrient availability.

5. CONCULISION AND RECOMMENDATION

5.1. Conclusion

Results from this experimental study on the effects of nitrogen fertilizer rates and intra row spacing on garlic growth, yield, yield components, rust disease infestation, and economic feasibility provide valuable information for improving garlic production. The application of nitrogen fertilizer positively affected several growth parameters such as plant height, leaf length, leaf dry weight, and marketable yield, indicating a very sensitive response of these garlic parameters to nitrogen fertilizer rates. Higher nitrogen rates were found to tend to give better growth for garlic in most treatments within the range of 69–92 kg N ha^{-1}.

Regarding intra-row spacing, garlic grown with 10 cm spacing recorded higher growth and maximum yield compared to the intra-row spacings of 5 and 15 cm. Generally, yields were reduced at the 15 cm spacing, indicating that this may not be appropriate for maximizing productivity in the area under study and other similar agro-ecological regions.

The best combination of nitrogen rate and intra-row spacing for maximizing garlic growth and yield was found to be 46–69 kg N ha^{-1} with 10 cm intra-row spacing. This suggests that wider intra-row spacing may not be optimal for maximizing garlic productivity in the studied agro-ecological region. Disease infestation and severity were less influenced by nitrogen rates but showed significant variations in terms of spacing, with narrower spacing (5 cm) showing higher levels of disease.

Furthermore, the combination of moderate to high nitrogen levels (46–69 kg N ha^{-1}) and 10 cm intra-row spacing resulted in the highest net benefits and the best benefit-cost ratio. These treatments proved to be the most cost-effective, providing the best return on investment for garlic producers by maximizing marketable yield while keeping input costs manageable

5.2. Recommendations

The results suggested the following recommendations:

- To optimize garlic growth and marketable bulb yield, nitrogen fertilizer application should be done at a rate of 46–69 kg N ha^{-1}.
- It is suggested that the garlic producers to use 10 cm intra row pacing as best arrangement for increasing garlic yield and reducing disease severity.
- It is recommended that, application of 46 kg N ha^{-1} at a spacing of 10 cm between rows to yield the best return on investment in terms of economic optimization as marketable yield and production costs are the main concerns, producers should take these treatments into account for the greatest net benefits.

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APPENDIX

Apendix1: Analysis of variance on growth, yield related parameters, and disease infestation levels of Garlic treated under different nitrogen fertilizer rates and intra row spacing's

SV	def	PH	LFL	LN	LFW	BFW	BDW	LDW	TB	MY	UNMY	TBY	BD	CN	BS	DS	DIL	HI
Replication	2	7.3	7.22	0.99	20.39	6.97	3.5	0.64	6.57	2.12	0.048	2.79	8.7	4.4	3.39	34.08	7	0.0006
Nitrogen (N)	3	525.8^{**}	248.2^{**}	0.18^{ns}	3.74^{ns}	18.03^{ns}	3.3^{ns}	0.87^{*}	5.7^{ns}	2.13^{*}	0.046^{ns}	1.68^{ns}	6.62^{ns}	1.13^{ns}	2.2^{ns}	92.58^{ns}	537^{ns}	0.0027^{ns}
Spacing (S)	2	34.7^{*}	66.39^{*}	0.3^{ns}	21.06^{*}	312.8^{**}	44.1^{*}	1.8^{*}	99.5^{**}	24.6^{**}	1.83^{**}	36.2^{**}	40.48^{*}	1.24^{ns}	37.39^{*}	833.49^{**}	3745^{*}	0.0046^{ns}
N*S	6	2.36^{ns}	7.87^{ns}	0.46^{ns}	5.9^{ns}	33.32^{ns}	7.3^{ns}	0.19^{ns}	4.8^{ns}	1.75^{*}	0.02^{ns}	1.65^{*}	9.6^{ns}	1.51^{ns}	1.59^{ns}	128.85^{ns}	279^{ns}	0.0036^{ns}
Error	22	7.4	129.4	0.46	4.9	28	6.7	0.27	2.01	0.65	0.04	0.65	7.8	1.74	8.9	56.93	698	0.002
Total	35																	

Abbreviations

SV= Sources of variation, DeF=degree of freedom, PH= plant height, LFL= Leaf length, LN=leaf number, LFW= leaf fresh weight, BFL= bulb fresh weight, LDW= leaf dry weight, TB= total biomass, MY= marketable yield, UNMY= unmarketable yield, TBY=total biomass yield, BD= bulb diameter, CN= clove numbers, BS=bulb size, DS= diseases severity, DIL= diseases infestation level, HI= harvest index

*and ** indicating significance difference at (5 and 1% confidence intervals) where as "ns" indicates none significance difference

Appendix 2.analysis of variance plant height (cm)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F probability
Replication	2	14.63	7.315	0.98	
Nitrogen	3	1577.525	525.842	70.28	<.001
Spacing	2	68.353	34.177	4.57	0.022
Nitrogen*spacing	6	14.216	2.369	0.32	0.921
Error	22	164.597	7.482		
Total	35	1839.322			

Appendix 3.analysis of variance leaf fresh weight (g)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	40.796	20.398	4.15	
Nitrogen	3	11.235	3.745	0.76	0.527
Spacing	2	42.13	21.065	4.29	0.027
Nitrogen*spacing	6	35.747	5.958	1.21	0.337
Error	22	108.093	4.913		
Total	35	238			

Appendix 4.analysis of variance of leaf length (cm)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability.
Replication	2	4.591	2.295	0.39	
Nitrogen	3	744.685	248.228	42.32	<.001
Spacing	2	66.394	33.197	5.66	0.01
Nitrogen*spacing	6	17.872	2.979	0.51	0.796
Error	22	129.042	5.866		
Total	35	962.584			

Appendix 5.analysis of variance of leaf dry weight (g)

Source of variation	Degree of freedom	Sum of square	Mean square	Variance ratio	F probability
Replication	2	1.2806	0.6403	2.32	
Nitrogen	3	2.6151	0.8717	3.15	0.045
Spacing	2	3.6093	1.8047	6.53	0.006
Nitrogen*spacing	6	1.1977	0.1996	0.72	0.637
Error	22	6.0845	0.2766		
Total	35	14.7873			

Appendix 6.analysis of variance of disease incidence level (%)

Source of variation	Degree of freedom	Sum of square	Mean square	Variance ratio	F probability
Replication	2	14	7	0.01	
Nitrogen	3	1617	539	0.77	0.522
Spacing	2	7490.2	3745.1	5.37	0.013
Nitrogen*spacing	6	1675.2	279.2	0.4	0.871
Error	22	15356.7	698		
Total	35	26153			

Appendix 7.analysis of variance of unmarketable yield (t/ha)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	0.09613	0.04806	1.02	
Nitrogen	3	0.14093	0.04698	1	0.413
Spacing	2	3.67742	1.83871	39.04	<.001
Nitrogen*spacing	6	0.14171	0.02362	0.5	0.8
Error	22	1.0361	0.0471		
Total	35	5.09228			

Appendix 8.analysis of variance of total biomass (t/ha)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	13.158	6.579	3.26	
Nitrogen	3	17.263	5.754	2.85	0.061
Spacing	2	198.115	99.058	49.07	<.001
Nitrogen*spacing	6	28.82	4.803	2.38	0.063
Error	22	44.414	2.019		
Total	35	301.77			

Appendix 9.analysis of variance of total bulb yield (t/ha)

Source of variation	Degree of freedom	Sum of square	Mean of square.	Variance ratio	F probability
Replication	2	5.5998	2.7999	4.7	
Nitrogen	3	5.0478	1.6826	2.82	0.062
Spacing	2	72.4424	36.2212	60.74	<.001
Nitrogen*spacing	6	9.949	1.6582	2.78	0.036
Error	22	13.1194	0.5963		
Total	35	106.1585			

Appendix 10.analysis of variance of marketable yield (t/ha)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability.
Replication	2	4.2591	2.1296	3.25	
Nitrogen	3	6.4082	2.1361	3.26	0.041
Spacing	2	49.3122	24.6561	37.65	<.001
Nitrogen*spacing	6	10.512	1.752	2.68	0.042
Error	22	14.4054	0.6548		
Total	35	84.897			

Appendix 11.analysis of variance of disease severity (%)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	68.17	34.08	0.6	
Nitrogen	3	277.74	92.58	1.63	0.212
Spacing	2	1666.99	833.49	14.64	<.001
Nitrogen*spacing	6	773.1	128.85	2.26	0.075
Error	22	1252.37	56.93		
Total	35	4038.36			

Appendix 12.analysis of variance bulb size (mm)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	6.784	3.392	0.38	
Nitrogen	3	6.799	2.266	0.25	0.859
Spacing	2	75.58	37.79	4.2	0.029
Nitrogen*spacing	6	9.58	1.597	0.18	0.98
Error	22	197.957	8.998		
Total	35	296.701			

Appendix 13.analysis of variance bulb fresh weight (g)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	13.93	6.97	0.25	
Nitrogen	3	54.08	18.03	0.64	0.595
Spacing	2	625.65	312.83	11.17	<.001
Nitrogen*spacing	6	199.93	33.32	1.19	0.348
Error	22	615.92	28		
Total	35	1509.52			

Appendix 14.analysis of variance bulb diameter (mm)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	17.414	8.707	1.11	
Nitrogen	3	19.864	6.621	0.85	0.483
Spacing	2	80.969	40.485	5.18	0.014
Nitrogen*spacing	6	57.747	9.624	1.23	0.329
Error	22	171.994	7.818		
Total	35	347.988			

Appendix 15.analysis of variance bulb dry weight (g)

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	7.074	3.537	0.53	
Nitrogen	3	9.902	3.301	0.49	0.692
Spacing	2	88.295	44.147	6.57	0.006
Nitrogen*spacing	6	43.854	7.309	1.09	0.4
Error	22	147.801	6.718		
Total	35	296.926			

Appendix16. Analysis of variance on leaf number

Source of variation	Degree of freedom	sum of square	Mean of square	variance ratio	f probability
replication	2	1.9905	0.9952	2.33	
Nitrogen	3	0.5521	0.184	0.43	0.733
Spacing	2	0.7352	0.3676	0.86	0.436
Nitrogen*Spacing	6	2.7786	0.4631	1.09	0.401
Error	22	9.3845	0.4266		
Total	35	15.441			

Appendix17. Analysis of variance clove number

Source of variation	Degree of freedom	Sum of square	Mean of square	Variance ratio	F probability
Replication	2	8.914	4.457	2.55	
Nitrogen	3	3.417	1.139	0.65	0.59
spacing	2	2.488	1.244	0.71	0.502
Nitrogen*spacing	6	9.093	1.515	0.87	0.534
Error	22	38.42	1.746		
Total	35	62.33			

Appendix18. Analysis of variance harvest index

Source of variation	Degree of freedom	sum of square	Mean square	variance ratio	f probability
Replication	2	0.001247	0.000623	0.3	
Nitrogen	3	0.008352	0.002784	1.35	0.285
spacing	2	0.009378	0.004689	2.27	0.127
Nitrogen*Spacing	6	0.021439	0.003573	1.73	0.162
error	22	0.04553	0.00207		
Total	35	0.085946			

Appendix 19: some growth stage of garlic in the growing season

Planting stage

Initial stage

Middle stage

Bulbing stage

Maturity stage

Harvesting