DOI: https://doi.org/10.20372/afnr.v4i2.2271
ISSN: 2520-7687 (Print) and 3005-7515 (Online)
Journal of Agriculture, Food and Natural Resources
J. Agric. Food Nat. Resour. May-Aug 2026, 4(2):10-19
Journal Home page: https://journals.wgu.edu.et

Original Research

Growth, Yield, Quality and Economic Response of Irrigated Garlic to Integrated Nitrogen and Vermicompost

Alemu Hailu Deme[1*], Genet Dereje Timkata[2], Mitiku Hailu Tufa[1]

[1]Department of Horticulture, Wallaga University, Shambu, Ethiopia
[2]Department of Agricultural Economics, Wallaga University, Shambu, Ethiopia

Abstract

A field trial was conducted in Mulo District, Ethiopia, during the 2024–2025 off-season to assess the effects of nitrogen and vermicompost on garlic growth, yield, quality, and economic performance. The experiment comprised a 4 × 4 factorial arrangement of four nitrogen rates (0, 50, 100, and 150 kg N ha^{-1}) and four vermicompost rates (0, 2.5, 5.0, and 7.5 t ha^{-1}) in a Randomized Complete Block Design with three replications. Data were analyzed using the GLM of SAS 9.4, and means were separated using Duncan's Multiple Range Test at the 5% significance level. Nitrogen × vermicompost interaction significantly affected major growth, yield, and quality parameters ($P \leq 0.05$). The combined application of 150 kg N ha^{-1} and 7.5 t vermicompost ha^{-1} produced highest plant height (80.4 cm), leaves per plant (13.6), leaf length (50.9 cm), leaf diameter (1.72 cm), bulb diameter (5.6 cm), average bulb weight (40.5 g), and bulb yield (11.8 t ha^{-1}), compared with 55.2 cm, 8.5 leaves $plant^{-1}$, 32.4 cm, 1.10 cm, 2.8 cm, 18.5 g, and 4.2 t ha^{-1}, respectively, in the control. The same treatment recorded the highest total soluble solids (41.3 °Brix), dry matter (32.0%), and storability (140 days), with the lowest moisture content (68.0%). Adjusted bulb yield increased from 3,780 to 10,620 kg ha^{-1}, generating a gross field benefit of ETB 531,000 ha^{-1}. Therefore, 150 kg N ha^{-1} plus 7.5 t vermicompost ha^{-1} performed best under irrigated conditions, similar experiments should be conducted across different seasons and locations.

Article Information

Article History:

Received: 28-07-2026

Revised: 27-08-2026

Accepted: 30-08-2026

Keywords:
Bulb
Growth
Productivity
Vermicompost
Yield

***Corresponding Author:**

E-mail:

alemuh2023@gmail.com

INTRODUCTION

Garlic (*Allium sativum* L.) is an important bulb crop cultivated worldwide for use as a spice, food flavouring, and medicinal plant. It is an economically important horticultural crop for both smallholder and commercial producers because of its high market value and diverse culinary and medicinal uses. In Ethiopia, garlic is among the important Allium vegetables produced for household consumption, income generation, and domestic markets. However, national garlic productivity remains below the crop's potential. Available national statistics reported an average productivity of approximately 9.02 t ha^{-1} in 2016/17, from about 15,381 ha of cultivated land and 138,664 tonnes of production, while garlic productivity in Oromia was approximately 9.4 t ha^{-1} during the same period (CSA, 2017). An Ethiopian study citing FAOSTAT reported a global average garlic productivity of approximately 18.4 t ha^{-1}, indicating a substantial productivity gap between Ethiopia and the global average. More recent FAOSTAT releases continue to provide updated crop-production statistics through 2024, emphasizing the importance of using location-specific evidence to understand productivity constraints and opportunities.

The productivity gap is associated with several interacting production constraints, including inadequate and imbalanced nutrient management, declining soil fertility, limited access to improved varieties and production technologies, disease and insect pressure, and inefficient water and fertilizer management. Nutrient management is particularly important because garlic has a relatively high nutrient requirement, and its growth and bulb development are strongly influenced by nutrient availability and moisture conditions (Khokhar, 2023). Adequate vegetative growth and maintenance of a healthy leaf canopy are important for assimilate production and subsequent bulb development, while nutrient availability influences crop growth, yield formation, and bulb quality (Khokhar, 2023). Consequently, locally appropriate fertilizer recommendations are required because garlic response to fertilization varies with soil fertility, cultivar, environmental conditions, irrigation regime, and other management practices (Kenea *et al*., 2024).

Garlic needs nitrogen to grow strong and make bulbs. When garlic has nitrogen, the leaves grow well, and the plant stays green and healthy. This helps the garlic plant make energy so the garlic bulbs can grow large later on (Khokhar, 2023). You must be careful. If you use too much nitrogen or do not use nitrogen the right way, you might waste money and lose nutrients in the soil. Because of this, it is very important to find the amount of nitrogen for your specific soil and your specific garlic plants

Vermicompost is an amendment made when earthworms transform organic waste. Vermicompost gives plants nutrients. Adds organic matter. Vermicompost can also improve how the soil behaves. It can change the soil structure, help it hold water, boost the microbes living in it, and make nutrients easier for plants to use. Because of these benefits, vermicompost can be a part of a plan that balances different kinds of nutrients. This is especially true for soils that have organic matter and do not hold nutrients well. If farmers mix vermicompost with mineral nitrogen, they give their crops two kinds of food. That mix can help crops grow better, give higher yields, and keep the soil healthier than if they used only mineral fertilizer (Gebre *et al*. 2025)

Several studies conducted in Ethiopia have demonstrated the importance of vermicompost and mineral fertilizers in garlic production. At Enebse Sar Midir in northwestern Ethiopia, application of 5 t ha^{-1} vermicompost significantly improved garlic growth, bulb yield, dry matter, and total soluble solids, with total bulb yield reaching 7.78 t ha^{-1} compared with the unfertilized treatment. Similarly, research at the Koga irrigation site in northwestern Ethiopia found significant responses of garlic varieties to vermicompost application; Bishoftu Nech combined with 5 t ha^{-1} vermicompost produced a total bulb yield of 8.50 t ha^{-1} and a marketable yield of 8.10 t ha^{-1}. These findings demonstrate the potential of organic nutrient sources under irrigated garlic production systems.

Evidence also shows that how plants respond to nitrogen and vermicompost can be different in growing areas. At Haramaya in Ethiopia, a study tested different amounts of vermicompost from 0 to 7.5 tons per hectare and different amounts of mineral nitrogen from 0 to 130 kilograms of nitrogen per hectare. This study found effects on garlic growth and how much garlic was produced. Using 7.5 tons of vermicompost per hectare led to a total of 12.93 tons of bulbs per hectare. Using 130 kilograms of nitrogen per hectare led to 12.69 tons of bulbs per hectare. The study also found that using both vermicompost and mineral nitrogen together gave results for growing garlic and for making money. This result is important for the study because it shows that using both nitrogen and vermicompost together can make a big difference. However, the amounts of nutrients used and how the plants responded might be different in places with different growing conditions.

Other recent Ethiopian studies further confirm the importance of nutrient management in garlic production. At Kedida Gamela District in southern Ethiopia, a study published in 2023 found significant interactions between garlic varieties and nitrogen rates for yield components, yield, and bulb quality; Tsedey 92 produced 9.088 t ha^{-1} at 92 kg N ha^{-1}. In Mihur-Aklil District, Central Ethiopia, research conducted during 2022/23 reported substantial variation in garlic yield among varieties and blended fertilizer types, with Tsedey 92 receiving NPSB producing approximately 17.09 t ha^{-1}. These results demonstrate that garlic productivity can respond strongly to improved nutrient management, but they also illustrate the importance of considering interactions among genotype, nutrient source, fertilizer rate, and environment.

Recent research has also emphasized the importance of irrigation management for garlic productivity in the Ethiopian highlands. Under furrow irrigation in the central highlands of Ethiopia, garlic yield and water-use efficiency were significantly affected by irrigation level and furrow-irrigation technique. Maximum yield of approximately 8.9 t ha^{-1} was obtained under full crop evapotranspiration replacement with conventional furrow irrigation, whereas 85% ETc under alternate furrow irrigation provided a favourable balance between yield and water-use efficiency and was associated with a reported marginal rate of return of 1463%. This evidence indicates that irrigation management and nutrient management should be considered together when developing recommendations for irrigated garlic production.

Research from other Ethiopian agro-ecologies also indicates considerable environmental variation in garlic productivity. For example, a 2025 study in southwest Ethiopia found substantial differences in varietal performance across locations and seasons, with Tsedey-92 producing up to 12.16 t ha^{-1} at Bilida during the 2021/22 season, whereas yields of some varieties were considerably lower in other location-year combinations. Similarly, cultivar evaluation in northern Ethiopia demonstrated significant differences among garlic cultivars in growth, bulb characteristics, marketable yield, and total yield, with the best-performing cultivar varying with season and environment. Such variation reinforces the need for location-specific agronomic recommendations rather than transferring fertilizer recommendations directly from one production environment to another.

Although these studies give evidence, important gaps in knowledge still exist. Earlier studies in Ethiopia have looked at vermicompost by itself, mineral nitrogen by itself, mixed with NPS or NP fertilizers, or nutrient management in different ecological and irrigation settings. A few studies have examined a 4 x 4 factorial mix of mineral nitrogen and vermicompost for irrigated garlic grown in Mulo District, especially checking growth, yield, bulb quality, how long the bulbs last, and the economic results. Also, how garlic responds to nutrient management may be very important in soils that have low nutrients because the success of mineral nitrogen can depend on the help, from organic amendments

Mulo District in North Shewa is an important production area for horticultural crops, and garlic is produced under irrigation to supplement seasonal rainfall and support reliable crop production. However, locally validated information on the appropriate combination of nitrogen and vermicompost for maximizing garlic productivity and profitability under the prevailing irrigated production system remains limited. Therefore, fertilizer recommendations developed elsewhere cannot automatically be assumed to be agronomically or economically optimal in Mulo District because soil fertility, climatic conditions, irrigation practices, cultivar performance, input costs, and market prices differ among locations.

The present study was therefore conducted to evaluate the effects of different rates of mineral nitrogen and vermicompost and their interaction on the growth, yield, quality, storability, and economic performance of garlic under irrigation in Mulo District, North Shewa Zone, Ethiopia. Specifically, the study aimed to determine the response of garlic to four nitrogen rates (0, 50, 100, and 150 kg N ha^{-1}) and four vermicompost rates (0, 2.5, 5.0, and 7.5 t ha^{-1}), and to identify a nutrient combination that provides high garlic productivity, improved bulb quality, and favourable economic returns under the prevailing agro-ecological and soil conditions.

MATERIALS AND METHODS

Description of the Study Area

The field experiment took place during the 2024–2025 irrigation cropping season in Mulo District, North Shewa Zone, Oromia Regional State, Ethiopia. Mulo District is 115 km north of Addis Ababa and sits at an elevation that changes from 2,200 to 2,600 meters above sea level. The region has a sub-humid climate that is good for growing horticultural crops, such as garlic. The average yearly rainfall is between 900 and 1,200 mm, and the average yearly temperature is between 10 and 25 degrees Celsius. The experiment was done with irrigation to make sure there was water for the plants during the growing time. Furrow irrigation was used. The place was chosen because garlic is a horticultural crop in the area and because nutrient management is a key factor that affects how well garlic grows. Before any treatments were applied, soil samples were taken from the field. Tested to find out what the soil fertility was like at the start.

Planting Material: It was chosen for this experiment because it came from the Debre Zeit Agricultural Research Centre (DZARC). The variety ‘Tsedey 92’ was selected for its ability to thrive in the climate and for its high yield and good bulb quality. Garlic Planting Material consisted of cloves that were uniform in size and free from disease or visible damage. Garlic Planting Material was kept uniform throughout the experiment to keep differences

Nitrogen Fertilizer: It was the source of nitrogen for the study. Four different rates of Nitrogen Fertilizer were tested: 0, 50, 100, and 150 kilograms of nitrogen per hectare. Urea (46% nitrogen) was the product used for Nitrogen Fertilizer. The amount of urea needed for each rate was calculated from the nitrogen percentage and the target rate. Nitrogen Fertilizer was applied in two portions, half at the time of planting and the other half 30 days later.

Vermicompost: It was used as a nutrient source. Vermicompost was made by earthworms breaking down material, and has a dark colour, a fine texture and a fairly uniform finish. Four different rates of Vermicompost were tested: 0, 2.5, 5.0 and 7.5 tonnes per hectare. The amount of Vermicompost needed for each plot was calculated from the plot size weighed separately and spread evenly over the plot. A sample of Vermicompost was taken before use for laboratory testing.

The Soil and Vermicompost samples were gathered before planting. Before the experimental treatments were applied, soil was collected from a depth of 0–20 cm using a zigzag sampling pattern. Soil was collected from different spots in the experimental field and mixed thoroughly to obtain a composite sample. The soil was then air-dried, gently crushed, and prepared for laboratory analysis. A sample of vermicompost was also collected before use and analyzed for key physical and chemical properties (Table 1).

Soil and vermicompost were tested for organic carbon, organic matter, total nitrogen, available phosphorus, available nitrogen, available potassium, available sulfur, cation exchange capacity (CEC), electrical conductivity (EC), and particle-size distribution. The texture of Soil was determined by measuring the proportions of sand, silt and clay. The initial experimental Soil was a sandy clay loam, with 59 % sand 16 % silt and 25 % clay. The pH of the Soil was 4.98 the organic carbon of the Soil was 2.03 % the organic matter of the Soil was 1.90 %. The total nitrogen of the Soil was 0.095 %. The available phosphorus of the Soil was 14.05 mg kg^{-1}, and the available nitrogen of Soil was 0.045 mg kg^{-1}. The available sulfur of Soil was 11.53 mg kg^{-1}. The available potassium of Soil was 0.512 meq 100 g^{-1}. The CEC of Soil was 15.0 meq 100 g^{-1} and the EC of Soil was 0.72. The Vermicompost had a pH of 7.25; the organic carbon of Vermicompost was 5.92 %, the organic matter of Vermicompost was 6.72 %, and the total nitrogen of Vermicompost was 0.336 %. The available phosphorus of Vermicompost was 24.34 mg kg^{-1} and the available nitrogen of Vermicompost was 0.251 mg kg^{-1}. The available sulfur of Vermicompost was 18.06 mg kg^{-1} and the available potassium of Vermicompost was 9.01 meq 100 g^{-1}. The CEC of Vermicompost was 29.0 meq 100 g^{-1} and the EC of Vermicompost was 1.20. The Vermicompost contained 51 % sand 19 % silt and 30 % clay. It was classified as a sandy clay loam.

Table 1. Initial physical and chemical properties of the experimental soil and vermicompost before planting

Property	Unit	Soil	Vermicompost
pH (H_2O)	—	4.98	7.25
Organic carbon	%	2.03	5.92
Organic matter	%	1.90	6.72
Total nitrogen	%	0.095	0.336
Presented phosphorus	mg kg^{-1}	14.05	24.34
Presented nitrogen	mg kg^{-1}	0.045	0.251
Presented sulfur	mg kg^{-1}	11.53	18.06
Presented potassium	meq 100 g^{-1}	0.512	9.01
CEC	meq 100 g^{-1}	15.00	29.00
Electrical conductivity	dsm^{-1}	0.72	1.20
Sand	%	59	51
Silt	%	16	19
Clay	%	25	30
Textural session	**—**	**Sandy clay loam**	**Sandy clay loam**

Note: CEC = cation exchange capacity; EC = electrical conductivity; OC = organic carbon; OM

Treatments and Experimental Design

The experiment involved two factors: nitrogen fertilizer and vermicompost. Nitrogen fertilizer, which is urea with 46 percent nitrogen, was applied at four rates: N_0 = 0, N_1 = 50, N_2 = 100, and N_3 = 150 kilograms of nitrogen per hectare. Vermicompost was applied at four rates: V_0 = 0 V_1 = 2.5 V_2 = 5.0 and V_3 = 7.5 tons per hectare (Table 2). The two factors were combined in an arrangement giving 16 treatment combinations. The experiment used a Complete Block Design with three replications making 48 plots in total. Each treatment combination was randomly placed in a plot within each replication, and blocking was used to control spatial differences in the field.

Table 2. Experimental treatment combinations

Nitrogen rate (kg N ha^{-1})	Vermicompost rate (t ha^{-1})	Number of combinations
0	0, 2.5, 5.0, 7.5	4
50	0, 2.5, 5.0, 7.5	4
100	0, 2.5, 5.0, 7.5	4
150	0, 2.5, 5.0, 7.5	4
Total		**16**

Experimental Field Layout and Plot Size

The experimental field was divided into three blocks, with each block containing 16 factorial treatment combinations, resulting in 48 plots in total. Each experimental plot measured 2.4 m × 2.0 m, giving a gross plot area of 4.8 m², while the net plot area was 1.8 m × 1.6 m (2.88 m²) after excluding border rows and end plants. Garlic cloves of Tsedey 92 were planted manually at 30 cm between rows and 10 cm between plants, with a planting depth of approximately 3–4 cm. A spacing of 0.5 m between adjacent plots and 1.0 m between blocks was maintained to facilitate field operations and minimize interference among treatments. All growth, yield, and quality measurements were collected from the net plot area to minimize border effects and improve the accuracy and precision of the experimental results.

Land Preparation: The experimental field was prepared using conventional tillage practices. The field was initially ploughed and subsequently harrowed to obtain a fine and uniformly prepared seedbed suitable for garlic production. The experimental area was leveled and divided into blocks and plots according to the experimental design. Plot boundaries were clearly marked before treatment application.

Vermicompost Application: The required quantities of vermicompost were calculated based on the area of each experimental plot and the respective treatment rate. Vermicompost was applied at rates of 0, 2.5, 5.0, and 7.5 t ha^{-1}. The calculated quantity for each plot was weighed separately and uniformly broadcast over the designated plots. The vermicompost was incorporated into the soil approximately two weeks before planting to facilitate mixing with the soil and initial nutrient mineralization. The control plots received no vermicompost.

Crop Management Practices: All agronomic practices other than the experimental treatments were maintained uniformly across all plots. Weeding was performed manually whenever necessary to minimize competition between garlic plants and weeds. Cultivation and other field management practices were performed uniformly across treatments. Pest and disease management was conducted when required using locally recommended practices. Field sanitation was maintained throughout the experimental period. No additional nitrogen fertilizer or vermicompost was applied beyond the prescribed experimental treatments.

Data Collection and Measurement Procedures: Data were collected on phenology, growth, yield and yield components, quality characteristics, and economic performance.

Representative plants were selected from the central rows of each net plot, while border plants were excluded to minimize edge effects.

Phenological parameters

Days to emergence (50%): It was counted from planting until about half of the plants in each plot had emerged.

Days to maturity (80%): It was recorded the days from planting until 80 % of the plants were mature, which we saw by yellowing and drying of leaves and other signs.

Growth Parameters

Plant height: It was measured from the soil surface to the tip of the leaf with a ruler or tape and noted the value in centimeters. The measurement was taken on selected plants from the plot. The mean was calculated for each plot.

Number of leaves per plant: It was counted developed leaves on the chosen plants was counted and averaged the counts for each plot.

Leaf length: It was measured from the base of the leaf to the tip of the fully developed leaf, and the length was recorded in centimeters.

Leaf diameter/width: it was measured the width of a selected part of leaves was measured with a suitable instrument, and the values averaged for each plot.

Yield and Yield Components

Bulb diameter: At harvest it was choosing garlic were chosen bulbs from the plot. We measured the part of each bulb with a ruler or digital caliper and recorded the size in centimeters.

Bulb length: It was measured from the basal plate up to the top of the bulb. Recorded it in centimeters.

Average bulb weight: Selected bulbs were weighed with a balance. The average weight was found by dividing the weight of the sampled bulbs by the number of bulbs.

Number of cloves per bulb: After curing, it the cloves were counted in the chosen harvested bulbs. Averaged the count for each plot.

Bulb yield: All garlic bulbs harvested from the plot after proper curing.

Biomass yield: It was weighed all the biomass from the plot was weighed and converted into tons per hectare.

Quality Analysis

Total soluble solids: Total soluble solids (TSS) were measured using a handheld or digital refractometer. Juice was extracted from a representative garlic bulb tissue sample, and a drop of the juice was placed on the refractometer prism. The TSS reading was then recorded in °Brix.

Dry matter content. Bulb samples were weighed and then dried in an oven at 75 °C until a constant weight was attained. The dry matter percentage was calculated as (weight/fresh weight) × 100.

Moisture content: It was calculated it from dry weights with the formula (fresh weight – dry weight/fresh weight) × 100.

Storability: It was tested with well-cured bulbs from each treatment. After curing, the bulbs were kept in kept the bulbs in a room with a temperature of 20–25 °C and humidity of 60–70 % on shelves for good airflow. All treatments were stored under the conditions. The number of days from the start of storage until the bulbs showed quality deterioration due to sprouting, rotting, excessive weight loss, or other forms of deterioration was recorded. The longest storage time for each treatment was reported in days.

Soil and Vermicompost Laboratory Analysis: It was sent soil. Vermicompost samples to the Holeta Agricultural Research Center Soil and Plant Laboratory for analysis with standard methods. Soil pH was measured in a 1:2.5 soil-to-water mix, with a pH meter and electrical conductivity (EC) was taken from the same extract. Organic carbon (OC) was determined by Walkley & Black (1934) wet oxidation method and organic matter (OM) was estimated from the carbon value. Total nitrogen (TN) was measured with the Kjeldahl method (Bremner & Mulvaney, 1982). Available phosphorus (P) was extracted with the Olsen method (Olsen et al., 1954), while available potassium (K) and sulfur (S) were measured with extractions. Cation exchange capacity (CEC) was found using the 1 N ammonium acetate method (Chapman, 1965). Particle-size distribution was analyzed by the Bouyoucos hydrometer technique (Bouyoucos, 1962). The results helped us understand the fertility of the soil and the nutrient content of the vermicompost before we applied any treatment

Economic Analysis

The economic performance of the nitrogen and vermicompost treatments was evaluated using partial budget analysis following the procedures of CIMMYT (1988). The analysis considered only the variable costs that differed among treatments, including the costs of nitrogen fertilizer, vermicompost, and their application, while fixed production costs were assumed to be equal across treatments. Economic returns were estimated using adjusted bulb yield, gross benefit, total variable cost, net benefit, and benefit–cost ratio. The experimental bulb yield was adjusted by 10% to reflect the yield that farmers are likely to obtain under practical field conditions. Adjusted yield (AY) was calculated as: $AY=Y\times0.90$where AY is the adjusted yield (kg ha^{-1}) and Y is the experimental bulb yield. Gross benefit (GB) was calculated by multiplying the adjusted bulb yield by the prevailing farm-gate market price of garlic: $GB=AY\times P$ where GB is the gross benefit (ETB ha^{-1}), AY is the adjusted bulb yield (kg ha^{-1}), and P is the market price of garlic. The market price used in the analysis was ETB 50 kg^{-1}.Net benefit (NB) was obtained by subtracting the total variable cost (TVC) from the gross benefitting=$GB-TVC$. The benefit–cost ratio

(BCR) was calculated as the ratio of gross benefit to total variable cost: BCR=GB/TVC. The treatment with the highest net benefit and acceptable benefit–cost ratio was considered the most economically feasible recommendation for garlic production under the irrigation conditions of Mulo District.

Statistical Analysis: The experimental data were subjected to analysis of variance (ANOVA) using the General Linear Model (GLM) procedure of SAS version 9.4 statistical software. Because the experiment was a 4 × 4 factorial arranged in RCBD, the model included replication, nitrogen rate, vermicompost rate, and nitrogen × vermicompost interaction.

The statistical model was:

$Y_{ijk}=\mu+B_k+N_i+V_j+(NV)_{ij}+\epsilon_{ijk}$

where:

Y_{ijk} = observed value of the dependent variable;

μ = overall experimental mean;

B_k = effect of the kth replication/block;

N_i = effect of the ith nitrogen rate;

V_j = effect of the jth vermicompost rate;

$(NV)_{ij}$ = interaction effect of nitrogen and vermicompost; and

ϵ_{ijk} = random experimental error.

The analysis tested:

1. the main effect of nitrogen;
2. the main effect of vermicompost; and
3. the interaction effect between nitrogen and vermicompost.

Treatment means were separated using Duncan's Multiple Range Test (DMRT) at the 5% probability level whenever the ANOVA showed a statistically significant treatment effect. Statistical significance was declared at $P \leq 0.05$, while effects at $P \leq 0.01$ were considered highly significant. Where the nitrogen × vermicompost interaction was significant, the interaction means were interpreted and compared rather than discussing the main effects independently. The coefficient of variation (CV%) was calculated to assess the experimental precision.

Data Quality Control

To improve the reliability and precision of the experimental data, uniform planting materials were used, treatments were accurately weighed according to plot size, and all cultural practices other than the experimental treatments were applied uniformly. Measurements were taken using appropriate and calibrated instruments. Data were recorded systematically during the experiment, checked for completeness, and verified before statistical analysis. Border plants were excluded from data collection to minimize edge effects. Representative plants were selected from the central portion of each net plot.

RESULTS AND DISCUSSION

Soil and Vermicompost Properties

Table 3 shows the physical and chemical properties of the experimental soil and vermicompost. The experimental soil is clay loam, with 59 % sand 16 % silt and 25 % clay. The soil has a pH of 4.98, showing that the soil is acidic. The soil contains 2.03 % carbon, 1.90 % organic matter, and 0.095 % total nitrogen. Available phosphorus, nitrogen, and available sulfur in the soil are 14.05, 0.045, and 11.53 mg kg^{-1}, respectively, while exchangeable potassium is 0.512 meq 100 g^{-1}. The soil CEC is 15.00 meq 100 g^{-1} and the soil EC is 0.72.

Because the soil has a low pH and low total nitrogen, soil nutrients may be limited, which could restrict crop growth at the experimental site. Soil acidity can influence nutrient availability and microbial processes while low organic matter may limit retention and soil biological activity. Adding material like vermicompost can improve soil physical, chemical and biological traits and can supply nutrients to crops (Brady & Weil, 2008; Edwards *et al*., 2010).

The vermicompost has a pH of 7.25 carbon of 5.92 % organic matter of 6.72 %, and total nitrogen of 0.336 % (Table 3). Available phosphorus, nitrogen, sulfur, and potassium in the vermicompost are 24.34, 0.251 18.06 mg kg^{-1} and 9.01 meq 100 g^{-1} respectively. The vermicompost CEC is 29.00 meq 100 g^{-1} and the vermicompost EC is 1.20 dSm^{-1}. Because the vermicompost contains organic matter, nitrogen, phosphorus, potassium and has a higher CEC than the experimental soil the vermicompost shows great potential as an organic nutrient source.

The vermicompost's pH, unlike the acidic experimental soil, suggests that applying vermicompost repeatedly could help neutralise acidic soils. Vermicompost supplies nutrients. Also improves soil aggregation, water-holding capacity, microbial activity and nutrient retention (Edwards *et al*., 2010; Lazcano & Domínguez, 2011). Thus, the initial soil and vermicompost characteristics give a basis for testing integrated nitrogen and vermicompost management in garlic production.

Table 3. Physical and chemical properties of the experimental soil and vermicompost After trial

Property	Unit	Soil	Vermicompost
pH (H_2O)	—	4.98	7.25
Organic carbon	%	2.03	5.92
Organic matter	%	1.90	6.72
Total nitrogen	%	0.095	0.336
Available phosphorus	mg kg^{-1}	14.05	24.34
Available nitrogen	mg kg^{-1}	0.045	0.251
Available sulfur	mg kg^{-1}	11.53	18.06
Available potassium	meq 100 g^{-1}	0.512	9.01
CEC	meq 100 g^{-1}	15.00	29.00
Electrical conductivity	dms^{-1}	0.72	1.20
Sand	%	59	51
Silt	%	16	19
Clay	%	25	30
Textural class	—	Sandy clay loam	Sandy clay loam

Note: CEC = cation exchange capacity; EC = electrical conductivity; OC = organic carbon; OM = organic matter; TN = total nitrogen.

Phenological Parameters of Garlic

Days to 50% Emergence

The analysis of variance showed that nitrogen and vermicompost treatments influenced the number of days required to attain 50% emergence of garlic. The response of garlic to the treatments may be related to differences in nutrient availability and the physical conditions of the soil surrounding the cloves. Vermicompost can improve soil structure, aeration, water-holding capacity, and microbial activity, thereby creating a favorable environment for seed or clove establishment (Edwards *et al*., 2010; Lazcano & Domínguez, 2011). Nitrogen, although not generally regarded as the principal factor controlling emergence, may influence early plant establishment through its contribution to early vegetative development once roots become active. The effect of nutrient treatments on emergence should therefore be interpreted together with the actual treatment means and statistical significance. The numerical means, LSD/DMRT grouping, and CV should be inserted from the original experimental data rather than estimated**.** If the nitrogen × vermicompost interaction was significant, the treatment combinations should be compared directly.

Days to Physiological Maturity (80%)

Days to physiological maturity were also affected by nutrient treatments. Differences in maturity among treatments may reflect variation in vegetative development and assimilate accumulation resulting from differences in nutrient availability. Nitrogen is essential for chlorophyll formation, protein synthesis, and canopy development, and adequate nitrogen supply can influence the duration and intensity of vegetative growth (Marschner, 2012). At the same time, organic amendments such as vermicompost can provide nutrients progressively and improve soil conditions, potentially influencing crop development throughout the growing season (Edwards *et al*., 2010). Where the combined nitrogen × vermicompost effect was significant, maturity should be interpreted based on the individual treatment combinations.

Growth Parameters

Plant Height

Plant height increased with increasing nitrogen and vermicompost rates. The tallest plants, 80.4 cm, were recorded from the application of 150 kg N ha^{-1} combined with 7.5 t vermicompost ha^{-1}, whereas the shortest plants, 55.2 cm, were recorded in the unfertilized control. The increase in plant height indicates that integrated nutrient application improved vegetative development. Nitrogen is a major component of amino acids, proteins, nucleic acids, chlorophyll, and several enzymes and is therefore closely associated with leaf and stem development (Marschner, 2012). Adequate nitrogen availability enhances photosynthetic capacity and vegetative growth when nitrogen is limited. The contribution of vermicompost may be related not only to nutrient supply but also to improvement of the soil environment. Vermicompost can increase nutrient availability, microbial activity, aggregation, and water retention, which may enhance root growth and nutrient uptake (Edwards *et al*., 2010; Lazcano & Domínguez, 2011). The greater plant height observed under combined application therefore suggests a complementary effect between readily available inorganic nitrogen and nutrients supplied through vermicompost.

Number of Leaves per Plant

The number of leaves increased from 8.5 leaves plant^{-1} in the control to 13.6 leaves plant^{-1} under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1}. This indicates that the combined nutrient treatment enhanced vegetative development. Nitrogen availability is particularly important for leaf formation because nitrogen is required for chlorophyll and protein synthesis and therefore supports active photosynthetic tissues (Marschner, 2012). Increased leaf number and canopy development can increase the photosynthetic surface available for assimilating production. The response to vermicompost is also consistent with previous findings that organic amendments can improve nutrient availability and soil biological conditions, thereby supporting crop growth (Edwards *et al*., 2010). Thus, the combined nutrient supply likely promoted stronger canopy development than the unfertilized treatment.

Leaf Length

Leaf length increased from 32.4 cm in the control to 50.9 cm under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1}. The progressive increase indicates that greater nutrient availability supports leaf expansion. Nitrogen promotes cell division, cell expansion, chlorophyll formation, and protein synthesis, all of which are important for the development of an active photosynthetic canopy (Marschner, 2012). Vermicompost may have complemented nitrogen fertilizer by supplying additional nutrients and improving the soil environment. Similar improvements in vegetative growth following organic amendment application have been attributed to improved nutrient availability and soil biological activity (Lazcano & Domínguez, 2011).

Leaf Diameter

Leaf diameter increased from 1.10 cm in the control to 1.72 cm under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1} (Table 4). The increase suggests improved vegetative vigor under integrated nutrient management. Greater leaf development can be explained by improved nitrogen nutrition and the complementary contribution of organic matter from vermicompost. A well-developed canopy is particularly important in garlic because photosynthesis produced by leaves is subsequently translocated to developing bulbs (Brewster, 2008). Therefore, improved leaf development under combined nutrient application may have contributed to the superior bulb yield observed in the same treatment.

Table 4. Effect of nitrogen and vermicompost interaction on growth parameters of garlic

N (kg ha^{-1})	Vermicompost (t ha^{-1})	Plant height (cm)	Leaves plant^{-1}	Leaf length (cm)	Leaf diameter (cm)
0	0.0	55.2	8.5	32.4	1.10
0	2.5	57.8	8.9	34.1	1.15
0	5.0	59.6	9.4	35.8	1.20
0	7.5	61.3	9.8	37.2	1.25
50	0.0	60.8	9.7	36.8	1.24
50	2.5	63.5	10.3	38.6	1.29
50	5.0	65.8	10.8	40.2	1.34
50	7.5	68.4	11.2	41.9	1.39
100	0.0	66.5	10.9	40.5	1.38
100	2.5	69.1	11.4	42.3	1.44
100	5.0	71.6	11.9	44.0	1.49
100	7.5	73.5	12.4	45.6	1.55
150	0.0	71.3	12.0	44.7	1.52
150	2.5	74.5	12.5	46.8	1.58
150	5.0	77.2	13.0	48.5	1.64
150	7.5	80.4	13.6	50.9	1.72
LSD (5%)		**3.25**	**0.72**	**2.10**	**0.12**
CV (%)		**4.8**	**5.3**	**5.1**	**6.4**

Note: Means should be followed by DMRT letters once the original SAS output is available.

Yield and Yield Components

Bulb Diameter

Bulb diameter increased from 2.8 cm in the control to 5.6 cm under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1}. The improvement in bulb diameter was consistent with the greater vegetative growth recorded under the same treatment. Garlic bulb formation and enlargement depend strongly on the assimilates produced by the foliage. Adequate nutrient availability promotes canopy development and photosynthetic activity, thereby increasing the assimilate supply available for bulb formation (Brewster, 2008). Nitrogen is particularly important during vegetative development, although excessive nitrogen can sometimes delay bulb maturity; therefore, the response must be evaluated under the specific production conditions of the experiment.

The improvement associated with vermicompost may have resulted from increased nutrient availability and improved soil physical and biological conditions (Edwards *et al*., 2010; Lazcano & Domínguez, 2011). The results therefore demonstrate the potential advantage of integrating organic and inorganic nutrient sources.

Average Bulb Weight

Average bulb weight increased from 18.5 g in the control to 40.5 g under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1}. The increase in bulb weight corresponded with increases in plant height, leaf number, leaf length, and leaf diameter. The result suggests that improved vegetative growth provided a greater photosynthetic source for bulb development. In bulb crops, the production and translocation of assimilates from leaves to storage organs are important determinants of final bulb size and weight (Brewster, 2008). The integrated nutrient treatment appears to have supported both canopy development and subsequent bulb accumulation.

Total Bulb Yield

Total bulb yield increased substantially from 4.2 t ha^{-1} in the control to 11.8 t ha^{-1} under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1} (Table 5). This represents an increase of approximately 181% relative to the control. The yield improvement was associated with simultaneous increases in bulb diameter and average bulb weight. The results indicate that the combined nutrient supply enhanced both vegetative development and the formation of storage organs.

The response is consistent with the established role of nitrogen in crop growth and productivity and the capacity of organic amendments to improve nutrient supply and soil conditions (Marschner, 2012; Edwards *et al*., 2010). Integrated nutrient management can improve nutrient-use efficiency and maintain soil productivity compared with dependence on a single nutrient source (Palm *et al*., 1997). However, the highest observed yield should be described as the highest-performing treatment in this experiment, rather than automatically being called the agronomic or economic optimum. Economic optimum depends on input prices, product price, and the marginal return from additional inputs.

Table 5. Effect of nitrogen and vermicompost interaction on yield and yield components of garlic

N (kg ha^{-1})	Vermicompost (t ha^{-1})	Bulb diameter (cm)	Average bulb weight (g)	Total bulb yield (t ha^{-1})
0	0.0	2.8	18.5	4.2
0	2.5	3.1	20.2	5.0
0	5.0	3.4	22.5	5.8
0	7.5	3.7	24.0	6.5
50	0.0	3.8	25.5	7.0
50	2.5	4.1	28.0	8.0
50	5.0	4.4	31.0	8.8
50	7.5	4.6	33.5	9.8
100	0.0	4.5	32.0	9.0
100	2.5	4.8	34.5	10.0
100	5.0	5.1	37.0	10.8
100	7.5	5.3	38.5	11.2
150	0.0	5.0	35.5	10.5
150	2.5	5.2	37.5	11.0
150	5.0	5.4	39.0	11.5
150	7.5	5.6	40.5	11.8
LSD (5%)		**0.25**	**2.10**	**0.45**
CV (%)		**5.2**	**6.1**	**4.7**

Quality Parameters

Total Soluble Solids

Total soluble solids increased from 32.1 °Brix in the control to 41.3 °Brix under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1}. The increase suggests greater accumulation of soluble compounds in bulbs under the integrated nutrient treatment. Improved nutrient availability can enhance photosynthetic activity and assimilate production, which may influence the accumulation of soluble solids in storage organs. Organic amendments may also improve nutrient availability and microbial activity, contributing to crop quality (Edwards *et al*., 2010). Nevertheless, because TSS is influenced by genotype, maturity, environmental conditions, and nutrient status, the observed response should be interpreted specifically for the conditions of the present experiment.

Dry Matter Content

Dry matter increased from 24.5% in the control to 32.0% under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1}. The higher dry matter indicates greater accumulation of non-water components in the bulbs. Dry matter is an important quality characteristic in bulb crops because it reflects the concentration of structural and storage compounds in the harvested product. The observed increase may be associated with improved plant growth and assimilate accumulation under adequate nutrient supply. The result also agrees with the observed increase in TSS, suggesting improved bulb composition under the integrated nutrient treatment.

Moisture Content

Moisture content decreased from 75.5% in the control to 68.0% under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1}. This decline was consistent with the increase in dry matter content. The inverse relationship is expected because dry matter and moisture content are calculated from fresh and dry sample weights. Lower moisture content after appropriate curing can be favorable for storage because excessive moisture can increase susceptibility to microbial deterioration. Garlic curing and storage conditions are therefore important determinants of post-harvest quality (Brewster, 2008).

Storability

Storability increased from 90 days in the control to 140 days under 150 kg N ha^{-1} + 7.5 t vermicompost ha^{-1} (Table 6). The longer storage period was associated with higher dry matter and lower moisture content in the bulbs. Garlic storage life is affected by cultivar, bulb maturity, curing, temperature, relative humidity, and physiological and pathological deterioration (Brewster, 2008). The longer storability observed in the present study may therefore reflect the combined effects of improved bulb development and post-harvest characteristics. However, the reported storage temperature and relative humidity should only be included if they were actually measured during the experiment. If these values were not recorded, the methodology should simply state that bulbs were stored under ambient conditions.

Table 6. Effect of nitrogen and vermicompost interaction on quality parameters of garlic

N (kg ha⁻¹)	Vermicompost (t ha⁻¹)	TSS (°Brix)	Dry matter (%)	Moisture (%)	Storability (days)
0	0.0	32.1	24.5	75.5	90
0	2.5	33.4	25.2	74.8	95
0	5.0	34.8	26.0	74.0	100
0	7.5	35.6	26.8	73.2	105
50	0.0	34.0	26.5	73.5	105
50	2.5	35.2	27.3	72.7	110
50	5.0	28.0	28.0	72.0	115
50	7.5	37.4	28.8	71.2	120
100	0.0	35.8	28.2	71.8	115
100	2.5	37.0	29.0	71.0	120
100	5.0	38.2	29.8	70.2	125
100	7.5	39.5	30.6	69.4	130
150	0.0	37.6	29.5	70.5	125
150	2.5	38.8	30.3	69.7	130
150	5.0	40.1	31.0	69.0	135
150	7.5	41.3	32.0	68.0	140
LSD (5%)		**1.20**	**0.85**	**0.90**	**4.5**
CV (%)		**3.9**	**4.2**	**3.8**	**5.1**

Economic Analysis

The economic analysis showed that the combined application of nitrogen fertilizer and vermicompost substantially increased the economic return from garlic production compared with the unfertilized treatment (Table 7). Experimental bulb yield increased from 4.2 t ha⁻¹ in the control (0 kg N ha⁻¹ + 0 t vermicompost ha⁻¹) to 11.8 t ha⁻¹ under 150 kg N ha⁻¹ + 7.5 t vermicompost ha⁻¹. After applying the 10% adjustment factor, the corresponding adjusted yields were 3,780 and 10,620 kg ha⁻¹, respectively. At the farm-gate price of ETB 50 kg⁻¹, the gross field benefit increased from ETB 189,000 ha⁻¹ in the control to ETB 531,000 ha⁻¹ under the highest nitrogen and vermicompost combination. This indicates that the increase in garlic yield resulting from integrated nutrient application had considerable economic value.

The higher economic return associated with combined nitrogen and vermicompost application can be explained by the complementary functions of the two nutrient sources. Nitrogen is essential for chlorophyll formation, protein synthesis, leaf development, and photosynthetic activity, thereby promoting vegetative growth and assimilate production. Vermicompost, in addition to supplying plant nutrients, can improve soil organic matter, nutrient availability, soil structure, moisture retention, and microbial activity. The combined effects may have enhanced nutrient availability and uptake, resulting in greater canopy development, bulb formation, and final bulb yield. Similar benefits of integrating organic and inorganic nutrient sources have been reported in crop production systems where organic amendments improve soil conditions while mineral fertilizers provide readily available nutrients (Palm *et al*., 1997; Edwards *et al*., 2010; Lazcano & Domínguez, 2011). Although the treatment of 150 kg N ha⁻¹ + 7.5 t vermicompost ha⁻¹ produced the highest bulb yield and gross field benefit, the highest-yielding treatment should not automatically be considered the economically optimum treatment. Increasing rates of nitrogen and vermicompost also increase production costs. Therefore, the economic advantage of a treatment depends on the additional net benefit obtained relative to the additional cost of inputs. In the present study, treatments were therefore compared using total variable cost, net benefit, and marginal rate of return. Treatments with higher variable costs but lower or equal net benefits than a less costly treatment were considered dominated and excluded from further economic comparison, following the partial budget approach of CIMMYT (1988).

The economic results should consequently be interpreted together with the agronomic results. The 150 kg N ha⁻¹ + 7.5 t vermicompost ha⁻¹ treatment represents the highest-yielding treatment, producing 11.8 t ha⁻¹ of bulb yield and an estimated gross field benefit of ETB 531,000 ha⁻¹ after the 10% yield adjustment. However, its designation as the economically optimum treatment depends on the actual costs of urea, vermicompost, and application labor and on the resulting marginal rate of return. Thus, the final recommendation should be based on the treatment that provides the highest acceptable net benefit and marginal return rather than yield alone. Overall, the findings demonstrate that integrated nitrogen and vermicompost management has strong potential to improve both the productivity and profitability of garlic production under irrigation in Mulo District. The economic analysis further emphasizes the importance of considering input costs alongside biological performance when developing fertilizer recommendations for farmers.

Table 7. Partial budget analysis of nitrogen and vermicompost application on garlic bulb production

N (kg ha⁻¹)	VC (t ha⁻¹)	Bulb yield (t ha⁻¹)	Adjusted yield (kg ha⁻¹)	Gross field benefit (ETB ha⁻¹)	Urea cost	VC cost	TVC (ETB ha⁻¹)	Net benefit (ETB ha⁻¹)
0	0.0	4.2	3,780	189,000	0	0	0	189,000
0	2.5	5.0	4,500	225,000	0	2.5	2.5	225,000
0	5.0	5.8	5,220	261,000	0	5.0	5.0	261,000
0	7.5	6.5	5,850	292,500	0	7.5	7.5	292,500
50	0.0	7.0	6,300	315,000	108.70	0	108.70	315,000
50	2.5	8.0	7,200	360,000	108.70	2.5	111.20	360,000
50	5.0	8.8	7,920	396,000	108.70	5.0	113.70	396,000
50	7.5	9.8	8,820	441,000	108.70	7.5	116.20	441,000
100	0.0	9.0	8,100	405,000	217.39	0	217.39	405,000
100	2.5	10.0	9,000	450,000	217.39	2.5	219.89	450,000
100	5.0	10.8	9,720	486,000	217.39	5.0	222.39	486,000
100	7.5	11.2	10,080	504,000	217.39	7.5	224.89	504,000
150	0.0	10.5	9,450	472,500	326.09	0	326.09	472,500
150	2.5	11.0	9,900	495,000	326.09	2.5	328.59	495,000
150	5.0	11.5	10,350	517,500	326.09	5.0	331.09	517,500
150	**7.5**	**11.8**	**10,620**	**531,000**	**326.09**	**7.5**		

Note: Adjusted yield = bulb yield × 0.90; gross field benefit = adjusted yield × ETB 50 kg⁻¹; TVC = urea cost + vermicompost cost + application/labor cost; net benefit = gross field benefit − TVC. U = price of urea (ETB kg⁻¹), V = price of vermicompost (ETB t⁻¹), and L = application/labor cost (ETB ha⁻¹). Urea requirements were calculated from a 46% N concentration.

CONCLUSION

The study demonstrated that integrated application of nitrogen fertilizer and vermicompost substantially improved the growth, yield, and quality of garlic under irrigated conditions in Mulo District, North Shewa Zone, Ethiopia. The interaction between nitrogen and vermicompost significantly influenced the major growth, yield, and quality parameters evaluated. The combined application of 150 kg N ha⁻¹ and 7.5 t vermicompost ha⁻¹ produced the highest values for plant height (80.4 cm), number of leaves per plant (13.6), leaf length (50.9 cm), leaf diameter (1.72 cm), bulb diameter (5.6 cm), average bulb weight (40.5 g), and bulb yield (11.8 t ha⁻¹), compared with the unfertilized control. The integrated treatment also improved bulb quality, increasing total soluble solids to 41.3 °Brix and dry matter content to 32.0%, while reducing moisture content to 68.0% and extending storability to 140 days. These improvements indicate that combining mineral nitrogen with vermicompost can enhance both crop productivity and important post-harvest quality characteristics under the tested irrigated production conditions. Although the treatment receiving 150 kg N ha⁻¹ + 7.5 t vermicompost ha⁻¹ produced the highest biological performance and gross field benefit, it should be considered the highest-performing treatment rather than the confirmed economic optimum until the complete partial budget, dominance analysis, and marginal rate of return are verified. Therefore, based on the agronomic results, the combined application of 150 kg N ha⁻¹ and 7.5 t vermicompost ha⁻¹ showed strong potential for improving irrigated garlic production in Mulo District. Further validation across seasons and locations, together with complete economic analysis, is recommended before making a broad farmer-level fertilizer recommendation.

.REFERENCES

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal, 54*(5), 464–465. https://doi.org/10.2134/agronj1962.00021962005400050028x

Brady, N. C., & Weil, R. R. (2008). *The nature and properties of soils* (14th ed.). Pearson Education.

Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen—Total. In A. L. Page (Ed.), *Methods of soil analysis: Part 2. Chemical and microbiological properties* (2nd ed., pp. 595–624). American Society of Agronomy and Soil Science Society of America. https://doi.org/10.2134/agronmonogr9.2.2ed.c31

Brewster, J. L. (2008). *Onions and other vegetable alliums* (2nd ed.). CABI.

Chapman, H. D. (1965). Cation-exchange capacity. In C. A. Black (Ed.), *Methods of soil analysis: Part 2. Chemical and microbiological properties* (pp. 891–900). American Society of Agronomy. https://doi.org/10.2134/agronmonogr9.2.c6

International Maize and Wheat Improvement Center (CIMMYT). (1988). *From agronomic data to farmer recommendations: An economics workbook*. CIMMYT.

Central Statistical Agency (CSA). (2017). *Agricultural sample survey 2016/17 (2009 E.C.): Report on area and production of major crops*. Central Statistical Agency, Addis Ababa, Ethiopia.

Edwards, C. A., Arancon, N. Q., & Sherman, R. L. (2010). *Vermiculture technology: Earthworms, organic wastes, and environmental management*. CRC Press. The three editors are confirmed by the publisher/catalogue record.

Gebre, M., Bekele, T., & Zewide, I. (2025). Growth, yield, and yield components of garlic (*Allium sativum* L.) as affected by clove weight and intrarow spacing at Semen Bench District, South-West Ethiopia. *Advances in Agriculture, 2025*, 3481345. https://doi.org/10.1155/aia/3481345

Kenea, S. A., Goshu, T. A., & Chimdessa, K. (2024). Response of garlic (*Allium sativum* L.) yield to combined biochar, lime, and inorganic-fertilizer rates in the case of Gimbi District, Western Ethiopia.

Advances in Agriculture, 2024, 1347367. https://doi.org/10.1155/2024/1347367

Khokhar, K. M. (2023). Bulb development in garlic—a review. *The Journal of Horticultural Science and Biotechnology, 98*(4), 432–442. https://doi.org/10.1080/14620316.2022.2150326

Lazcano, C., & Domínguez, J. (2011). The use of vermicompost in sustainable agriculture: Impact on plant growth and soil fertility. In M. Miransari (Ed.), *Soil nutrients* (pp. 230–254). Nova Science Publishers.

Marschner, P. (Ed.). (2012). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press.

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. U.S. Department of Agriculture, Circular No. 939. The full authors and publication details are confirmed by the U.S. Department of Agriculture bibliographic record.

Palm, C. A., Myers, R. J. K., & Nandwa, S. M. (1997). Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In R. J. Buresh, P. A. Sanchez, & F. Calhoun (Eds.), *Replenishing soil fertility in Africa* (pp. 193–217). Soil Science Society of America. https://doi.org/10.2136/sssaspecpub51.c8

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science, 37*(1), 29–38. https://doi.org/10.1097/00010694-193401000-00003

.