DOI: https://doi.org/10.20372/afnr.v3i3.1523
ISSN: 2520-7687 (Print) and 3005-7515 (Online)
Journal of Agriculture, Food and Natural Resources
J. Agric. Food Nat. Resour. Sep-Dec 2025, 3(3):08-16
Journal Home page: https://journals.wgu.edu.et

Original Research

The Effect of Nitrogen Fertilizer Rates and Intra-row Spacing on Yield Components and Qualities of Shallot (*Allium ascalonium* L.) at Mulo District, Ethiopia

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Abstract

The leafy vegetable shallot (Allium ascalonium L.) is grown in many tropical locations, including Ethiopia. Due to insufficient soil fertility, a lack of better planting materials, improper plant density, and a lack of agronomy research, the study area's shallot yield is low. Thus, this experiment was carried out during the 2021–2022 off-season in Mulo District, Oromia Regional State, Ethiopia. The primary goal of this study was to assess intra-row spacing and nitrogen fertilizer rates affected shallot growth, yield, and quality. Four intra-row spacings (5, 10, 15, and 20 cm) and four nitrogen fertilizer rates (0, 50, 100, and 150 kg N ha $^{-1}$*) were set up in a 4 × 4 factorial experiment utilizing a randomized full block design with three replications. Data were collected on yield components, yield, and quality parameters of shallots. Both the main effects and their interaction exhibited a substantial (* $p < 0.05$*) impact on yield and quality parameters, according to analysis of variance. The maximum marketable and total bulb yields were obtained from the interaction of 150 kg N ha* $^{-1}$ *nitrogen fertilizer with 15 cm intra-row spacing, while the lowest yields 16.79tha* $^{-1}$ *were recorded from the zero kg N and at the narrowest spacing. Therefore, the use of 150 kg N ha* $^{-1}$ *nitrogen fertilizer with 15 cm intra-row spacing can be recommended for improved shallot production under the conditions of the study area. However, further studies across different seasons would be to validate these findings.*

Article Information

Article History:

Received: 07-04- 2025
Revised: 16-12-2025
Accepted: 20-12-2025

Keywords:
Agronomic practices
Intra-row spacing
Nitrogen Fertilizer
Quality

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INTRODUCTION

Shallot (*Allium ascalonicum* L.) is a member of the Alliaceae family, which also includes onion, garlic, leek, and chives. Common onions are believed to have originated in Central Asia, whereas shallots are regarded to be native to Asia Minor and southwest Asia (Afrin and Okudo, 1996). Morphologically, shallots resemble common onions, but instead of forming a single large bulb, they produce clusters of 2–20 smaller bulblets. Farmers prefer cultivating shallots because they mature faster, exhibit better drought and disease tolerance than common onions, and retain a distinctive flavor even after cooking (Etana *et al*., 2019). Shallot is a high-value spice crop that is widely farmed in Ethiopia and is important for household nutrition, generating revenue, and preparing traditional foods like wot (Getahun, 2003). Globally, shallot and onion productivity under best management practices ranged between 15-30 t ha^{-1}. However, in Ethiopia, the average national yield of shallot under smallholder farmers is much lower, often below 10 t ha^{-1}, despite the crop's high yield potential. Under research and improved management conditions, yields exceeding 25–35 t ha^{-1} have been reported. Yield variation is largely influenced by the availability of improved planting materials, time and rates of fertilizer application, improper plant density, and pest and disease management. Shallot performs best in cool to mild climates, well-drained, fertile soils, and altitudes ranging approximately from 1,800 to 2,200 m above sea level (Zeleke, 2023). Nitrogen is the most important component for shallot growth and bulb development. It directly affects vegetative growth, photosynthetic capacity, bulb size, dry matter accumulation, and final yield (Akhter *et al*., 2020).

However, both insufficient and excessive nitrogen application negatively affect yield and quality. Nitrogen deficiency leads to poor vegetative growth, small bulbs, and low yield, while excessive nitrogen promotes excessive vegetative growth, delays maturity, increases storage losses, and reduces bulb quality. In addition, plant spacing strongly influences competition for light, nutrients, moisture, and air circulation. Very narrow spacing increases competition, disease incidence, and unmarketable yield, whereas very wide spacing reduces plant population per unit area and limits total yield. Therefore, optimum yield and quality of shallot depend not only on nitrogen rate or spacing alone, but on their combined interaction (Tesfaye, 2019). Although farmers in many shallot-producing areas traditionally apply little or no fertilizer and use very close plant spacing, research conducted on shallot and related Allium crops has clearly demonstrated that yield and bulb quality respond strongly to both nitrogen fertilizer and plant spacing. Previous studies have shown that moderate to high nitrogen rates significantly increase bulb weight, diameter, dry matter content, total soluble solids, and marketable yield when combined with appropriate spacing. Similarly, factorial experiments involving nitrogen and spacing are widely used to identify optimum combinations because main effects alone often do not explain yield response patterns. Therefore, it is scientifically appropriate to include a control (0 kg N ha^{-1}), increasing nitrogen levels (50, 100, and 150 kg N ha^{-1}), and narrow to broad intra-row spacing (5–20 cm) in order to clearly evaluate crop response under both traditional and better management approaches (Tesfaye, 2019).

In many production areas, farmers continue to cultivate shallot using traditional practices characterized by poor soil fertility management, minimal or zero fertilizer application, use of low-quality planting materials, and very narrow plant spacing. These practices result in severe nutrient deficiency, intense crop competition, high disease pressure, poor bulb development, and ultimately low marketable yield and poor bulb quality (Islam *et al.*, 2016).

Most previous studies focused either on nitrogen or spacing individually, while very few considered their interaction on growth, yield, and quality traits. Furthermore, growth parameters that explain physiological response to these management factors are often under-reported. This lack of integrated, location-specific research makes it difficult to formulate reliable recommendations for farmers in the study area. Therefore, the main objective of this study was to determine the effects of nitrogen fertilizer rates and intra-row spacing on shallot production components and quality.

MATERIALS AND METHODS

Study Site:

The field experiment was carried out in the Mulo District of North Shewa Zone, Oromia Regional State, Ethiopia, during the one-season off-season cropping period of 2021–2022. With an elevation of 2,315 meters above sea level, the research area is situated roughly 31 kilometers north of Addis Ababa at latitude 9°04′60′ N and longitude 38°13′00′ E. The area is characterized by a minimum temperature ranging from 6–10°C and a maximum temperature between 18–23°C. The mean annual temperature is about 15.36°C, with the lowest average temperature (8°C) recorded in December and the highest (22.9°C) in February and May. The experimental soil is characterized as clay loam (Source).

Description of Experimental Materials: An improved shallot variety known as 'DZSHT-005' was used as the planting material.. The variety was obtained from the Debre Zeit Agricultural Research Center (DZARC) and was officially released in 2019. It is known for its high yield potential and good adaptability to the agro-ecological conditions of the central highlands of Ethiopia, including the study area. For all treatments, nitrogen fertilizer was derived from urea (46% N).

Treatments and Experimental Design:

A 4 x 4 factorial combination of a Randomized Complete Block Design (RCBD) with three replications was used to set up four intra-row spacing levels (5, 10, 15, and 20 cm) and four nitrogen fertilizer dosages (0, 50, 100, and 150 kg N ha^{-1}).

Experimental Procedure: Oxen plowing was used to prepare the experimental field, which was then manually cleaned and leveled. Individual plots were properly leveled before planting. Shallot bulbs of uniform size were planted in January 2022 in well-prepared rows according to the assigned intra-row spacing treatments. During planting, urea, a nitrogen fertilizer, was applied as a side dressing in compliance with the approved treatment levels. Every plot received consistent application of all other agronomic practices, including irrigation, weeding, and pest management, as recommended for shallot production in the area.

Soil tests

Method of Soil Sampling: To determine the experimental field's initial fertility level, soil samples were taken prior to planting. In a zigzag pattern throughout the experimental site, composite soil samples were collected at depths ranging from 0 to 30 cm. After properly mixing and air-drying the soil, it was sieved through a 2 mm sieve for the majority of analyses and a 0.5 mm screen for the measurements of organic carbon and total nitrogen.

Soil Physico-Chemical Analysis: In order to determine baseline fertility and evaluate crop responses to nitrogen and spacing treatments, soil characteristics were examined. A glass electrode pH meter was used to measure the pH of the soil in a 1:2.5 soil-to-water solution. The sedimentation (hydrometer) method was used to determine the texture of the soil. The organic carbon content was measured using Walkley and Black's (1934) method, and the organic matter was calculated by multiplying the percentage of organic carbon by 1.724. According to Olsen et al. (1954), available phosphorus was removed using 0.5 M $NaHCO_3$, and total nitrogen was calculated using the Kjeldahl digestion and distillation method. **Exchangeable potassium** was measured with a flame photometer after ammonium acetate extraction, and **electrical conductivity** was determined to assess the salinity status of the soil.

Data Collected

Growth, yield components, yield, and bulb quality metrics were measured. For each plot, five representative plants were randomly selected and tagged. The study evaluated various **yield components, yield, and bulb quality parameters of** shallot**.** Bulb diameter (cm), bulb length (cm), average bulb weight (g), and the quantity of bulblets per plant were among the yield component characteristics recorded. Marketable bulb yield (t ha^{-1}), unmarketable bulb yield (t ha^{-1}), and total bulb yield (t ha^{-1}) were the yield characteristics. Dry matter content (%), total soluble solids (°Brix), shelf life (days), and bulb weight loss (%) during storage were the bulb quality characteristics evaluated. All data were collected 110 days after planting**,** except for shelf life and weight loss, which were recorded during storage**.**

Statistical methods

Gomez and Gomez (1984) used SAS 9.3 version software to perform statistical operations on the gathered data. to examine how intra-row spacing, nitrogen fertilizer levels, and their combination affect shallot growth, production, and quality. The Least Significant Difference (LSD) test at the 5% probability level ($P \le 0.05$) was used to separate the treatment means when the annova revealed a significant difference.

The factorial RCBD model was:

$$Yijk = \mu + Bi + Nj + Sk + (NS)jk + \varepsilon ijk$$

Where:

Y_{ijk} = observed value (response variable) for
i = block (replication)
j = nitrogen level
k = spacing level
μ = overall mean of all treatments
B_i = effect of the *i-th block* (replication effect)
N_j = effect of the *j-th nitrogen treatment level*
S_k = effect of the *k-th spacing treatment level*
$(NS)_{jk}$ = interaction effect between nitrogen (N) and spacing (S)
ε_{ijk} = Experimental error

RESULTS AND DISCUSSION

The Physical and Chemical Properties of the Experimental Soil: An essential measure of soil water retention, aeration, and nutrient availability is the soil's particle size distribution. The laboratory analysis

(Table 1) showed that the soil consisted of 77% sand, 15.64% silt, and 6.72% clay, which classifies the soil as sandy loam according to the USDA soil textural classification system. This texture is generally suitable for shallot production due to its good drainage and aeration properties. At the testing location, the pH of the soil was 5.89, which is considered to be mildly acidic. According to Murphy (1968), soils with pH between 5.5 and 6.5 are classified as slightly acidic, a condition that is favorable for shallot production.

The soil's organic matter content (0.86%) and organic carbon content (0.5%) were both assessed as low to extremely low, suggesting poor organic matter status. The total nitrogen content (0.24%) was rated as moderate (Table 1). However, the low organic carbon content suggests weak biological activity and low potential for natural nitrogen mineralization. This demonstrates that the best shallot production in the study area requires external nitrogen application. The soil was found to be very low in available phosphorus (0.29 mg kg^{-1}), which further limits crop productivity and indicates the importance of phosphorus fertilization for sustainable production. The exchangeable potassium content (0.25 cmol (+)/kg) (Table 1) was rated as low, suggesting possible potassium limitation. The electrical conductivity value (0.10 dS m^{-1}) showed that the soil is non-saline and therefore suitable for shallot cultivation.

Table 1. The experimental soil's physicochemical characteristics

Soil Parameter	Value	Rating	Reference
Distribution of particle sizes			
Sand (%)	77	–	–
Silt (%)	15.64	–	–
Clay (%)	6.72	–	–
Textural class	Sandy loam	–	USDA (1987)
Soil pH (H_2O)	5.89	Slightly acidic	Murphy (1968)
Organic carbon (%)	0.50	Low	Gessesew *et al*. (2015)
Organic matter (%)	0.86	Very low	Tekalign (1991)
Total nitrogen (%)	0.24	Moderate	
Available phosphorus (mg kg^{-1})	0.29	Very low	
Exchangeable potassium (cmol(+)/kg)	0.25	Low	Murphy (2007)
Electrical conductivity (dS m^{-1})	0.10	Non-saline	

Note: N stands for nitrogen, P for phosphorus, K for potassium, pH for hydrogen potential, and dS m^{-1} for decisiemens per meter.

Yield of Shallot Bulbs and Yield Components

Bulb Length: Nitrogen rates and intra-row spacing interacted to significantly affect bulb length ($p < 0.001$). Although this was statistically comparable to the combination of 150 kg N ha^{-1} with 15 cm spacing, the greatest bulb length (5.41 cm) was obtained at 150 kg N ha^{-1} with 20 cm spacing (Table 2). Wider spacing increases bulb length because there is less rivalry between plants, which improves access to sunlight, water, and nutrients. Additionally, higher nitrogen levels promote cell elongation, vegetative growth, and chlorophyll synthesis, resulting in enhanced photosynthetic activity and assimilate translocation to the bulbs. In contrast, the shortest bulb length (2.95 cm) was measured at zero nitrogen and 5 cm spacing, likely due to limited nutrient availability and intense competition. These results corroborate those of Hordofa et al. (2020), who found that higher nitrogen rates greatly improve the growth of onion bulbs.

Bulb Diameter: Additionally, the combined application of nitrogen rates and spacing had a highly significant impact on bulb diameter ($p < 0.001$). At 150 kg N ha^{-1} and 15 cm spacing, the maximum bulb diameter was measured; this was statistically comparable to 150 kg N ha^{-1} at 20 cm. Plants were able to accumulate more carbohydrates in their bulbs and improve bulb expansion at wider intrarow spacing and greater nitrogen levels. Conversely, the smallest bulb diameter was recorded at zero nitrogen and 5 cm spacing, were intense competition restricted leaf growth and photosynthetic area. These findings are in line with those of Etana et al. (2019), who discovered that onion bulb weight was significantly boosted by nitrogen injection up to 136 kg ha^{-1}.

Average Bulb Weight: The average bulb weight was shown to be significantly impacted ($p < 0.001$) by the interaction between nitrogen rates and spacing. At 150 kg N ha^{-1} and 15 cm apart, the heaviest bulbs (72 g per plant) were measured. Reduced competition at wider spacing and sufficient nitrogen availability promoted dry matter accumulation in bulbs. On the other hand, at zero nitrogen and 5 cm spacing, the lowest bulb weight (24.85 g per bulb) occurred , probably as a result of competition for few a resources. Tekle (2015) reported that higher nitrogen and wider spacing increased onion bulb weight.

Bulb Fresh Weight: The interaction between nitrogen rates and spacing had a substantial ($p < 0.001$) impact on bulb fresh weight. The highest fresh weight was obtained with 150 kg N ha^{-1} spaced 15 cm apart. Wider spacing improves access to sunlight, moisture, and nutrients, while nitrogen promotes vegetative growth and carbohydrate translocate carbohydrate to bulbs. The lowest fresh weight (26 g per plant) was recorded under zero nitrogen and 5 cm spacing, statistically comparable to 0 kg N ha^{-1} at 10 cm spacing. This trend aligns with Singh *et al*. (2018), who reported higher fresh weights with increased nitrogen and wider spacing.

Bulb Dry Weight: The nitrogen × spacing interaction has a highly significant ($p < 0.01$) effect on bulb dry weight. Although it was statistically comparable to 150 kg N ha^{-1} at 15 cm and 20 cm spacing, the maximum dry weight (11.08 g) was obtained at 150 kg N ha^{-1} with 20 cm spacing. Higher nitrogen and wider spacing enhance photosynthetic area and assimilate production, increasing dry matter storage in bulbs. The lowest dry weight (5.7 g) was recorded at zero nitrogen and 5 cm spacing, comparable to 0 kg N ha^{-1} at 10 and 15 cm spacing.

Percentage of Dry Matter Content: The bulb dry matter content was strongly impacted ($p < 0.01$) by the interaction between nitrogen rates and spacing. The lowest percentage (5.1%) was found at zero nitrogen and 5 cm spacing, which was statistically comparable to the same nitrogen rate at 10 and 15 cm(Table 2). The highest percentage (10.73%) was found at 150 kg N ha^{-1} with 20 cm spacing. Higher nitrogen and wider spacing likely improved nutrient translocation from leaves to bulbs, enhancing dry matter accumulation.

Table 2. Interaction effects of nitrogen fertilizer rates and intra-row spacing on shallot yield and its components.

Treatment		Yield Components					
Spacing	Nitrogen	BL	BD	ABW	BFW	BDW	BDM (%)
5	0	2.95^{i}	3.07^{k}	24.85^{m}	26.00^{i}	5.70^{f}	5.10^{i}
5	50	3.12^{h}	3.19^{j}	36.16^{k}	36.00^{h}	6.16^{ef}	6.76^{h}
5	100	3.38^{g}	3.42^{i}	46.13^{i}	48.00^{g}	6.25^{ef}	7.48^{gh}
5	150	3.54^{f}	3.56^{h}	51.21^{g}	52.67^{f}	6.30^{ef}	9.32^{cd}
10	0	3.03^{hi}	3.13^{jk}	30.95^{l}	28.00^{i}	5.71^{f}	5.14^{i}
10	50	3.61^{f}	3.23^{j}	48.83^{h}	48.00^{g}	6.16^{ef}	7.54^{fgh}
10	100	4.01^{e}	4.58^{e}	64.86^{e}	71.67^{e}	6.26^{ef}	8.89^{de}
10	150	5.17^{b}	4.73^{d}	67.85^{c}	113.33^{bc}	8.48^{c}	10.62^{ab}
15	0	3.11^{h}	3.36^{i}	34.95^{k}	33.67^{h}	5.78^{f}	5.25^{i}
15	50	3.540^{f}	3.60^{gh}	52.01^{g}	55.00^{f}	6.65^{e}	7.95^{fg}
15	100	4.83^{c}	4.88^{c}	66.21^{de}	103.00^{d}	9.88^{b}	9.55^{cd}
15	150	5.40^{a}	5.45^{a}	72.00^{a}	118.67^{a}	11.05^{a}	10.46^{ab}
20	0	3.12^{h}	3.68^{g}	38.37^{j}	36.00^{h}	5.92^{ef}	6.98^{h}
20	50	3.51^{f}	4.06^{f}	56.11^{f}	69.33^{e}	7.57^{d}	8.31^{ef}
20	100	4.67^{d}	5.22^{b}	66.56^{cd}	110.33^{c}	10.58^{a}	9.85^{bc}
20	150	5.41^{a}	5.45^{a}	69.86^{b}	117.67^{ab}	11.08^{a}	10.73^{a}
CV (%)		2.00	1.50	1.80	4.20	6.50	6.10
LSD (5%)		0.13	0.10	1.51	4.65	0.81	0.82

Note: At p<0.05 probability levels, there was no discernible difference between the mean and the identical letters. HI stands for harvest index. BL stands for bulb length, BD for bulb diameter, ABW for average bulb weight, BDW for bulb dry weight, and BDM for bulb dry matter.

Harvest Index: The harvest index of shallot plants was significantly impacted ($p < 0.001$) by the interaction between nitrogen rate and intra-row spacing. As nitrogen levels and intra-row spacing rose, the harvest index significantly increased. The combination of 150 kg N ha^{-1} with 15 cm spacing had the best harvest index, followed by 150 kg N ha^{-1} with 10 cm spacing (Table 3). The superior harvest index at 150 kg N ha^{-1} and 15 cm spacing may be attributed to the production of more and broader leaves, thicker pseudostems, and taller plants, all of which contribute to greater photosynthetic activity and assimilate translocation to the bulbs. Higher above-ground biomass and marketable output were the outcome of this combination. In contrast, plants grown at spacing of (5 cm, 10 cm, and 20 cm) without nitrogen fertilizer had the lowest harvest indixs (Table 3). The reduced harvest indix under these conditions could be due to limited vegetative growth and reduced photosynthetic capacity caused by intense inter-plant competition. Smaller leaf size, thinner leaf diameters, and shorter plant height under low nitrogen and close spacing likely restricted biomass production, resulting in lower marketable bulb yield and, consequently, a reduced harvest index.

Biomass (Bulb Weight): The dry total biomass yield was significantly ($p < 0.001$) affected by the interaction between nitrogen rates and intra-row spacing. The biomass output increased significantly with wider spacing and greater nitrogen levels. Plants planted at 150 kg N ha^{-1} and 20 cm spacing produced the highest total biomass, followed by plants grown at 150 kg N ha^{-1} and 15 cm spacing (Table 3). On the other hand, at 10 cm spacing and zero nitrogen, the lowest dry biomass output was observed.

Higher nitrogen rates and wider spacing were associated with the highest biomass yields, which may be explained by improved vegetative growth, which includes increased plant height, leaf number, length, and diameter. These factors all work together to improve photosynthetic efficiency and assimilate accumulation in plant tissues (Sharma, 1992). Wider spacing also improves overall plant performance and increases dry matter accumulation by reducing competition for vital growth resources like light, water, and nutrients.

Marketable Bulb Yield: The combination of intra-row spacing and nitrogen fertilizer rates had a substantial ($p < 0.001$) effect on marketable bulb output. The greatest commercial bulb yield of 34.06 t ha^{-1} was achieved with 150 kg N ha^{-1} and 15 cm spacing. Increasing spacing beyond 15 cm, however, did not result in further yield improvement (Table 3). The higher yield under these conditions can be attributed to greater plant height, increased leaf number, and longer leaves, which collectively enhance photosynthetic capacity and assimilate production. Adequate nitrogen availability also promotes protein synthesis and hormonal activity, leading to improved bulb formation and higher marketable yield.

Conversely, marketable bulb production was lowest in plants cultivated without nitrogen at 5 cm spacing (14.58 t ha^{-1}), which was statistically equivalent to 0 kg N ha^{-1} at 10 cm spacing. The reduction in yield under these treatments was likely due to shorter plants, fewer leaves per plant, and restricted growth from severe inter-plant competition. According to Latif et al. (2010), marketable bulb yield depends not only on individual plant performance but also on the total number of plants per unit area and other yield-contributing factors. The current findings are corroborated by Atalay's (2019) claim that onion output peaked at a nitrogen rate of 82 kg N ha^{-1}.

Unmarketable Bulb Yield: For unmarketable bulb yield, there was also a significant interaction ($p < 0.001$) between nitrogen rate and intra-row spacing. The treatment with 0 kg N ha^{-1} and 5 cm spacing had the highest unmarketable yield (2.21 t ha^{-1}) (Table 3). Increased competition for resources from closer plant spacing led to a higher percentage of undersized bulbs and, consequently, a higher unmarketable yield.

On the other hand, the combination of 150 kg N ha^{-1} and 15 cm spacing produced the lowest unmarketable yield (0.45 t ha^{-1}) (Table 3). Improved nutrient availability and less competition may have contributed to the decrease in unmarketable bulbs at higher nitrogen rates by encouraging the growth of larger, commercially viable bulbs. Nitrogen deficiency and overcrowding likely weakened plant growth, making plants more susceptible to environmental stress and limiting assimilate production, which led to smaller bulbs. In a similar vein, Demisie (2018) found that closer plant spacing produced the largest unmarketable yields and the lowest total yields.

Total Bulb Yield: The interaction between intra-row spacing and nitrogen fertilizer rate had a substantial impact ($p < 0.001$) on shallot bulb yield overall. Up to a certain point, stronger nitrogen application and wider spacing significantly enhanced total yield (Table 3). 150 kg N ha^{-1} with 15 cm spacing produced the highest total bulb production (34.51 t ha^{-1}), which was statistically equivalent to 150 kg N ha^{-1} with 20 cm spacing. Even though individual plant performance improved, overall output somewhat decreased after 15 cm spacing, perhaps as a result of fewer plants per unit area. With 5 cm spacing and no nitrogen injection, the lowest overall yield (16.79 t ha^{-1}) was observed (Table 3). This suggests that both nitrogen deficiency and excessive competition limit bulb development.

Overall, the results indicate that moderate spacing combined with an adequate nitrogen rate optimizes both vegetative and bulb growth, leading to maximum yield. These findings are consistent with those of Nasir and Akkasa (2018), who reported that low bulb yield was recorded at excessively wide spacing.

Table 3. Interactions between intra-row spacing and nitrogen on shallot biomass and yield.

Spacing (cm)	N (kg ha^{-1})	HI (%)	Bulb weight (t ha^{-1})	Marketable bulb yield (t ha^{-1})	Unmarketable bulb yield (t ha^{-1})	Total bulb Yield (t ha^{-1})
5	0	57.77^{k}	25.24^{m}	14.58^{j}	2.21^{a}	16.79^{i}
5	50	63.68^{h}	28.62^{k}	18.23^{h}	1.94^{c}	20.16^{g}
5	100	70.92^{e}	31.25^{i}	22.16^{g}	1.85^{d}	24.00^{f}
5	150	77.76^{bc}	34.17^{g}	26.57^{e}	1.09^{e}	27.65^{d}
10	0	59.65^{j}	24.83^{m}	14.81^{j}	2.13^{b}	16.93^{i}
10	50	67.35^{g}	32.75^{h}	22.06^{g}	1.80^{d}	23.86^{f}
10	100	77.14^{c}	35.38^{f}	27.29^{e}	0.96^{f}	28.25^{d}
10	150	78.83^{b}	39.33^{c}	31.00^{c}	0.63^{i}	31.63^{b}
15	0	62.34^{i}	26.36^{l}	16.43^{i}	1.98^{c}	18.41^{h}
15	50	70.05^{ef}	36.30^{f}	25.20^{f}	1.13^{e}	26.33^{e}
15	100	78.22^{bc}	38.38^{d}	30.02^{cd}	0.85^{g}	30.87^{bc}
15	150	80.45^{a}	42.34^{b}	34.06^{a}	0.45^{j}	34.51^{a}
20	0	63.17^{hi}	30.19^{j}	19.07^{h}	1.95^{c}	21.02^{g}
20	50	68.88^{f}	35.26^{f}	24.29^{f}	1.09^{e}	25.38^{e}
20	100	75.05^{d}	39.15^{c}	29.38^{d}	0.73^{h}	30.11^{c}
20	150	74.51^{d}	44.02^{a}	32.80^{b}	0.57^{i}	33.37^{a}
CV (%)		1.14	0.80	3.10	2.90	2.90
LSD (5%)		1.33	0.43	1.23	0.65	1.25

Note: HI for harvest index (%). At $p < 0.05$, means that are followed by the same superscript letter or letters within a column do not differ substantially.

Quality Parameters

Bulb Dry Weight: The bulb dry weight was significantly impacted ($p < 0.01$) by the interaction between nitrogen rate and intra-row spacing. The combination of 150 kg N ha^{-1} and 15 cm intra-row spacing produced the maximum bulb dry weight (17.90 g) (Table 4). On the other hand, plants that got 5 cm (0 kg N ha^{-1}) had the lowest bulb dry weight (15.42 g) Table 4). The increased photosynthetic area, which enables more assimilate production and effective transfer of photosynthates to the bulbs, is responsible for the rise in bulb dry weight at higher nitrogen levels and wider spacing. Adequate nitrogen availability promotes vigorous vegetative growth, improving nutrient uptake and photosynthetic efficiency, ultimately resulting in higher dry matter accumulation. In a similar vein, shallot bulbs grown at wider intra-row spacing yielded higher bulb dry weight per plant than those grown at closer spacing, according to Dereje et al. (2012).

Total Soluble Solids (TSS): the interaction of Nitrogen fertilizer rates and intra-row spacing had a highly significant ($p < 0.001$) influence on the total soluble solids (TSS). When 100 and 150 kg N ha^{-1} were combined with a 5 cm intra-row spacing, the highest TSS value (14.15%) was observed (Table 4). Increasing nitrogen fertilizer rates consistently enhanced the TSS of the bulbs; however, TSS values tended to decline as intra-row spacing widened. Plants grown without nitrogen fertilizer (0 kg N ha^{-1}) at 20 cm and 15 cm intra-row spacing, respectively, had the lowest TSS levels (11.29% and 11.88%) (Table 4). The development of larger bulbs with a higher water content, which dilutes soluble materials, may be the cause of this decrease in TSS at wider spacing. This conclusion is consistent with the findings of Mallor et al. (2011), who found that larger bulbs with lower TSS concentration were produced by wider plant spacing because of increased moisture content. Similarly, Tekle (2015) found that maximum TSS values were achieved at higher nitrogen rates combined with narrower intra-row spacing.

Table 4. Interaction effect of intra-row spacing and nitrogen on quality parameters of shallot

Treatment		**Quality Parameter**	
Intra-row Spacing	Nitrogen rate	TSS	BDW(70^{0}C)
5	0	13.69^{bc}	15.42^{f}
5	50	13.68^{bc}	16.28^{d}
5	100	13.89^{ab}	16.88^{c}
5	150	14.15^{a}	17.29^{b}
10	0	13.61^{cd}	15.51^{f}
10	50	13.02^{f}	16.30^{d}
10	100	12.03^{h}	17.14^{b}
10	150	11.91^{h}	17.72^{a}
15	0	11.88^{h}	15.75^{e}
15	50	13.69^{bc}	16.77^{c}
15	100	13.40^{de}	17.80^{a}
15	150	12.40^{g}	17.90^{a}
20	0	11.29^{i}	15.92^{e}
20	50	13.32^{e}	16.90^{c}
20	100	12.82^{f}	17.84^{a}
20	150	12.75^{f}	17.81^{a}
CV (%)		1.26	0.77
LSD (5%)		0.27	0.22

Note: *TSS=total soluble solid, BDW=bulb dry weight*

Bulb Size Distribution and Weight Loss

Small Bulb Size (14.32–20.31 g): The weight loss of stored shallot bulbs in the small size category (14.32–20.31 g) was significantly impacted ($p < 0.001$) by the interaction between nitrogen fertilizer rate and intra-row spacing. During the first two weeks of storage, nitrogen fertilizer and spacing had no noticeable influence on bulb weight loss. However, significant weight loss was observed beginning from the third week and continued through the fourth and fifth weeks of the storage period (Table 5). These results are in line with those of Tesfa et al. (2015), who found that until the third week of storage, nitrogen fertilizer had no discernible effect on the cumulative weight loss of shallots. As the storage period advanced, weight loss progressively increased, likely due to the evaporation of water and dry matter from the bulbs (Tesfa *et al*., 2015). Bulb weight losses of 2.90 g and 3.27 g between the third and fourth weeks of storage, and 2.94 g and 3.27 g between the fourth and fifth weeks of storage, were recorded at the nitrogen rate of 150 kg ha^{-1} combined with intra-row spacing of 15 cm and 20 cm (Table 5). The increased weight loss under higher nitrogen rates and wider spacing may be attributed to the formation of larger bulbs that exhibit higher respiration rates during storage, leading to greater moisture loss.

Jilani *et al*. (2004) similarly found that larger onion bulbs stored under ambient conditions for 120 days experienced greater weight loss compared to small and medium-sized bulbs. On the other hand, bulbs produced under zero nitrogen application and closer spacing (5 cm) exhibited the lowest weight losses of 1.67 g and 2.13 g, respectively, across the same storage intervals (Table 5). This minimal weight loss could be due to the formation of smaller bulbs, which typically have lower respiration rates and, consequently, reduced moisture loss during storage. Tekalign *et al*. (2012) also reported that onion bulb weight loss tends to increase with higher nitrogen application, and that significant deterioration occurs after about 15 days of storage.

Table 5. interactions between nitrogen and intrarow space on the weight loss of small bulbs.

		Bulb Weight Loss				
Treatment		**three week**	**four week**	**five week**	**Differences**	
S	N	S1	S2	S3	S1-S2	S2-3
5	0	14.42^{h}	12.32^{i}	10.06^{i}	1.67^{f}	2.13^{f}
5	50	15.05^{fg}	12.85^{gh}	10.60^{gh}	2.12^{e}	2.25^{e}
5	100	15.79^{de}	13.34^{def}	10.80^{fgh}	2.52^{b}	2.54^{c}
5	150	17.16^{c}	14.68^{c}	12.13^{c}	2.55^{b}	2.55^{c}
10	0	14.62^{gh}	12.52^{hi}	10.38^{hi}	1.74^{f}	2.14
10	50	15.51^{ef}	13.00^{fgh}	10.40^{hi}	2.51^{b}	2.60^{bc}
10	100	16.15^{d}	13.58^{de}	10.94^{efg}	2.57^{b}	2.64^{b}
10	150	17.34^{c}	14.45^{c}	11.18^{ef}	2.89^{a}	3.26^{a}
15	0	14.96^{g}	12.69^{ghi}	10.39^{hi}	2.27^{de}	2.30^{de}
15	50	15.85^{de}	13.54^{de}	11.19^{ef}	2.45^{b}	2.32^{d}
15	100	16.17^{d}	13.80^{d}	11.40^{de}	2.59^{b}	2.64^{b}
15	150	17.95^{b}	15.48^{b}	12.94^{b}	2.90^{a}	3.27^{a}
20	0	14.97^{g}	12.67^{hi}	10.34^{hi}	2.31^{cd}	2.33^{d}
20	50	15.63^{e}	13.17^{efg}	10.63^{gh}	2.46^{bc}	2.54^{c}
20	100	16.99^{c}	14.44^{c}	11.80^{cd}	2.54^{b}	2.64^{b}
20	150	19.72^{a}	16.84^{a}	13.82^{a}	2.94^{a}	3.27^{a}
CV (%)		1.80	2.10	2.60	4.60	1.50
LSD (5%)		0.48	0.48	1.17	0.19	0.06

Note: LSD=Least significant difference, CV= Coefficient of variation N=Nitrogen =spacing, S1, S2, S3=small bulb size represents.

Medium Bulb Size (25.1–44.54 g): The weight loss of stored shallot bulbs in the medium size category (25.1–44.54 g) was significantly impacted ($p< 0.001$) by the interaction between nitrogen fertilizer rates and intra-row spacing. During the initial storage period, nitrogen application and intra-row spacing had no observable effect on weight loss up to the third week. However, from the third week onward, specifically during the third, fourth, and fifth storage assessment periods, a notable increase in bulb weight loss was recorded (Table 5). The bulbs' loss of moisture and dry material explains the progressive increase in weight loss as the storage period increased. The most bulb weight loss was seen when the intra-row distance was 20 cm, and the nitrogen delivery rate was 150 kg ha^{-1}. The corresponding weight losses were approximately 3.45 g and 3.58 g between the third and fourth, and fourth and fifth weeks of storage, respectively (Table 5). The higher weight loss with higher nitrogen rates and wider spacing may be due to the formation of somewhat larger bulbs within the medium size class, which typically exhibit higher respiration rates and consequently more moisture loss during storage.

Conversely, the lowest bulb weight losses (2.2 g and 2.3 g) were recorded under zero nitrogen application and a closer intra-row spacing of 5 cm, measured between the third and fourth, and fourth and fifth weeks of storage, respectively (Table 5). The reduced weight loss under these conditions may be attributed to the formation of smaller bulbs within the medium category, which generally have lower respiration rates and therefore experience less moisture loss. Similarly, higher nitrogen fertilizer treatment rates significantly increased onion bulb weight loss, according to Tekalign et al. (2012).

Table 6. Nitrogen fertilizer and intra-row spacing interactions on medium-sized bulb weight loss.

		Bulb Weight Loss				
Treatment		**three week**	**four week**	**five week**	**Differences**	
S	N	M1	M2	M3	M1-2	M2-3
5	0	26.25^{j}	24.05^{j}	21.75^{l}	2.20^{h}	2.30^{j}
5	50	28.73^{gh}	26.27 ^{gh}	23.77^{hij}	2.46^{ef}	2.50^{ghi}
5	100	30.77^{e}	27.68^{f}	24.52 ^{gh}	2.47^{ef}	3.16^{d}
5	150	33.68^{d}	30.27^{d}	26.69^{e}	3.29^{b}	3.45^{b}
10	0	27.40^{i}	24.94^{ij}	22.50 ^{kl}	2.29^{gh}	2.44^{i}
10	50	31.43^{e}	28.98^{e}	26.46 ^{ef}	2.45^{ef}	2.52^{gh}
10	100	33.37^{d}	30.27^{d}	26.91^{e}	2.53^{e}	3.36^{c}
10	150	34.13^{d}	30.71^{d}	27.23 ^{de}	3.39^{ab}	3.45^{b}
15	0	27.66 ^{hi}	25.27 ^{hi}	22.82 ^{jkl}	2.35^{fg}	2.45^{hi}
15	50	30.42^{ef}	27.95 ^{ef}	25.40 ^{fg}	2.46^{ef}	2.56^{g}
15	100	33.32^{d}	30.80^{d}	28.14^{d}	2.86^{d}	2.66^{f}
15	150	36.72^{c}	33.47^{c}	30.02^{c}	3.41^{ab}	3.46^{b}
20	0	28.10 ^{hi}	25.68 ^{hi}	23.15 ^{ijk}	2.39^{efg}	2.51^{ghi}
20	50	29.43^{fg}	26.96 ^{fg}	24.25 ^{ghi}	2.48^{ef}	2.70^{f}
20	100	39.13^{b}	36.27^{b}	33.28^{b}	3.10^{c}	2.99^{e}
20	150	44.03^{a}	40.84^{a}	37.38^{a}	3.45^{a}	3.58^{a}
CV (%)		2.10	2.30	2.60	3.20	1.60
LSD (5%)		1.14	1.15	1.17	0.15	0.08

Note: N=Nitrogen, S =spacing, M1, M2, M3=medium bulb size represents

Large Bulb Size (55.12g-98.67g): At large bulb sizes, the interaction between nitrogen fertilizer rates and intra-row spacing had a highly significant ($p<0.01$) impact on bulb weight loss. The weight loss of the stored shallot bulbs during the one-month storage and one-week period (Table 7). Nitrogen fertilizer and intra-row spacing did not increase shallot weight loss until the third week of the storage evaluation period; however, they did cause weight loss during the third, fourth, and fifth weeks of the storage assessment periods (Table 7). The bulb weight loss was highest within an application of nitrogen fertilizer of 150 kgha-1 and intra row spacing of 20cm at the difference between the 3rd and 4th and 4th with 5th weeks under storage assessment periods, result was obtained 3.54 and 4.03g, respectively(Table 7). Weight loss increased with the length of storage, which may have been caused by dry matter and water loss from bulbs. The development of larger bulbs with higher respiration rates may be the cause of the greatest bulb weight loss with increased nitrogen fertilizer rates and intra row spacing.

However, the lowest with application of nil nitrogen fertilizer and intra row spacing of 5cm at the 3rd, 4th and 5th weeks under storage assessment periods in which weight losses he differences between 3rd with 4th and 4th with 5th about 2.24 and 2.54g respectively(Table 7). The development of lower bulbs with lower respiration rates may be the cause of the lowest bulb weight loss at zero nitrogen fertilizer rates and smaller intra-row spacing. As the rate of nitrogen administration increased, Tekalign et al. (2012) similarly observed significant weight losses in onion bulbs.

Table 7. .Interaction effects of spacing and nitrogen on weight loss on large bulb size

		Bulb Weight Loss				
Treatment		**three week**	**four week**	**five week**	**Differences**	
N	S	L1	L2	L3	L1-L2	L2-L3
5	0	56.13^{f}	52.68^{g}	50.42^{g}	2.24^{h}	2.56^{h}
5	50	58.33^{ef}	55.40^{fg}	52.44^{fg}	2.93^{e}	2.98^{efg}
5	100	60.99^{de}	57.85^{def}	54.61 ^{def}	3.14^{cd}	3.243^{bcd}
5	150	64.62^{d}	61.47^{d}	58.17^{d}	3.15^{cd}	3.30^{bc}
10	0	56.12^{f}	53.70^{fg}	50.76^{fg}	2.42^{g}	2.74^{gh}
10	50	59.48^{ef}	56.84^{efg}	53.85 ^{efg}	2.64^{f}	3.04^{def}
10	100	63.74^{d}	60.61^{de}	57.39 ^{de}	3.13^{d}	3.30^{bc}
10	150	64.53^{d}	61.34^{d}	58.03^{d}	3.26^{b}	3.39^{b}
15	0	56.98 ^{ef}	54.74 ^{fg}	51.78^{fg}	2.24^{h}	2.95^{fg}
15	50	60.87 ^{de}	57.76^{def}	54.62 ^{def}	3.11d	3.13^{cdef}
15	100	72.47^{c}	69.24^{c}	65.95^{c}	3.23^{bc}	3.36^{bc}
15	150	87.41^{b}	84.16^{b}	80.77^{b}	3.48^{a}	3.82^{a}
20	0	57.35 ^{ef}	55.08 ^{fg}	52.11^{fg}	2.27^{h}	2.97^{fg}
20	50	59.05 ^{ef}	55.90 ^{fg}	52.60 ^{fg}	3.12^{d}	3.22^{bcde}
20	100	89.22^{b}	85.74^{b}	81.92^{b}	3.26^{b}	3.31^{bc}
20	150	96.80^{a}	93.26^{a}	89.30^{a}	3.54^{a}	4.03^{a}
CV (%)		3.70	3.90	4.10	1.80	4.80
LSD (5%)		4.11	4.17	4.12	0.09	0.26

Note: N stands for nitrogen, S for spacing, L1, L2, and L3 for large bulb size.

Shelf Bulb Life: Throughout the storage periods, the proportion of sprouted bulbs was significantly ($p<0.01$) impacted by the interaction between nitrogen fertilizer and intra-row spacing. Nitrogen has a significant influence on the percentage of sprouted bulbs beginning at twenty-two days after storage and continuing forward. Throughout the storage periods, nitrogen fertilizer and intra-row spacing had a significant interaction effect on sprouted bulbs. When comparing the nil nitrogen fertilizer application and closer intra row spacing with higher nitrogen fertilizer application at 150kgha^{-1} and intra row spacing of 20cm, which increased the sprouted bulbs about 6.1, 9.9, 14.7, 25.2, and 51.3% after storage periods of 22, 30, 37, 45 and 52 days, respectively (Table 8).This is the reason for maximum high nitrogen and in wider intra row spacing produced bulbs with increased sprouting in storage due to increased oxygen and moisture access at the central growing point While, the nil application of nitrogen fertilizer application and intra row spacing of 5cm, which was increased within sprouted bulbs from three to seven weeks 2.6, 6.4, 11.5, 13.6, and 25.9% respectively (Table 8). Due to a lack of oxygen and moisture at the central growing point, this is the cause of minimal shallot sprouting (Table 8). Etana *et al*. (2019) found that the lowest number of onion sprouts was observed in unfertilized plots.

Table 8. Impact of intra-row spacing and nitrogen fertilizer rate on shelf life %

Shelf life analysis						
Treatment		**Period of storage bulbs in seven weeks(wks)**				
N	S	3 wks	4wks	5 wks	6 wks	7wks
5	0	2.6^{k}	6.4^{i}	11.5^{j}	13.6^{l}	25.9^{h}
5	50	3.5^{hi}	7.3^{h}	12.4^{h}	15.8^{ij}	29.6^{g}
5	100	3.8^{f}	8.6^{ef}	13.5^{de}	17.9^{gh}	33.5^{f}
5	150	4.3^{d}	9.6^{cd}	14.0^{b}	19.4^{ef}	38.8^{d}
10	0	3.0^{j}	6.4^{i}	11.8^{i}	14.4^{kl}	27.5^{gh}
10	50	3.5^{gh}	8.4^{fg}	12.6^{g}	16.2^{i}	33.7^{f}
10	100	4.1^{e}	9.4^{d}	13.6^{de}	18.7^{fg}	42.8^{c}
10	150	5.1^{c}	9.7^{bc}	14.1^{b}	20.6^{cd}	47.6^{b}
15	0	3.3^{i}	8.3^{g}	12.2^{h}	14.8^{k}	28.1^{gh}
15	50	3.6^{gh}	8.5^{efg}	13.1^{f}	17.2^{h}	34.4^{ef}
15	100	4.1^{e}	9.5^{d}	13.7^{cd}	20.1^{de}	43.7^{c}
15	150	5.8^{b}	9.8^{ab}	14.6^{a}	21.9^{b}	48.9^{b}
20	0	3.3^{i}	8.4^{fg}	12.3^{h}	15.24^{jk}	28.6^{g}
20	50	3.7^{fg}	8.6^{e}	13.4^{e}	18.2^{g}	36.2^{e}
20	100	5.1^{c}	9.7^{bc}	13.9^{bc}	21.1^{bc}	44.8^{c}
20	150	6.1^{a}	9.9^{a}	14.7^{a}	25.2^{a}	51.4^{a}
CV (%)		2.60	1.00	0.90	2.90	3.60
LSD (5%)		0.17	0.20	0.20	0.87	2.23

N**ote:** N=Nitrogen, S =Spacing

CONCLUSION

The current study's findings unequivocally showed that intra-row spacing and nitrogen fertilizer rates had a major impact on shallot growth, yield, and bulb quality. The combination of 15 cm intra-row spacing and 150 kg N ha^{-1} nitrogen application yielded the highest production and best quality attributes among the studied treatments. The interaction effect of nitrogen and spacing was measured for all significant parameters, indicating that these two factors must be managed together rather than independently.

Even though the treatment of 150 kg N ha^{-1} with 15 cm spacing demonstrated superior shallot yields and quality parameters, the study as a whole confirms that, under the specified conditions, proper management of nitrogen fertilizer and intra-row spacing is essential for improving shallot productivity and bulb quality. However, integrating agronomic recommendations with economic evaluation is necessary to ensure sustainable and profitable shallot production for smallholder farmers.

Acknowledgments: The authors gratefully acknowledge the Mulo District Agriculture Office for providing labor support and nitrogen fertilizer for the experiment. Special thanks are also extended to the Beshoftu Agricultural Research Center for supplying the shallot planting material used in the study. The authors also acknowledge Wollega University, Shambu Campus, for providing ICT (computer and related technical) support during data processing and report preparation. The authors further appreciate all individuals who contributed directly or indirectly to the successful completion of this research.

Conflict of interest; The author states that the research described in this article was not impacted by any known competing financial interests.

Funding: No funding received for this research.

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