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Research Article

Effects of Intra-row Spacing and Varieties on Yield and Yield-related Components of Onion Under Irrigated Conditions in Middle Awash, Afar NRS, Ethiopia

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Abstract

In Ethiopia, onions are a key horticultural crop grown extensively for both domestic use and export. Cultivation spans multiple regions, from highlands to lowlands, with the Rift Valley, especially the Middle Awash area in Afar being a notable center for irrigated onion production due to its favorable growing conditions. This study evaluated the effects of intra-row spacing and onion variety on yield and yield-related traits under irrigated conditions in Middle Awash, Ethiopia. Three onion varieties (Bombe Red, Nafid, and Nafis) were tested across four intra-row spacings (2.5 cm, 5 cm, 7.5 cm, and 10 cm) in a randomized complete block design with three replications. Data collected included marketable yield, unmarketable yield, total bulb yield, and vegetative traits such as plant height and leaf number. The results showed that the 5 cm spacing yielded the highest total bulb and marketable yields across the varieties, particularly for Nafid and Nafis, which demonstrated strong adaptability to various spacing levels. Narrower spacing increased competition, resulting in smaller bulb sizes and higher unmarketable yields, while wider spacings improved bulb quality traits like bulb diameter and dry matter content. These findings suggest that for optimal yield and quality, a spacing of 5 cm is ideal for maximizing yield, whereas wider spacings (7.5 to 10 cm) are preferable for quality-oriented production. The study recommends the result of variety and intra-specific evaluations should be validated under agro-pastoralist field conditions to ensure practical relevance and applicability.

Keywords

Irrigated Agriculture, Variety Selection, Agronomic Practices, Plant Density

1. Introduction

Onions (Allium cepa L.), a globally significant vegetable, have been cultivated for over 4,000 years, with evidence suggesting their origin in Central Asia or Iran [1]. The species belongs to the family Amaryllidaceae and has spread across the world, becoming an essential ingredient in various culinary traditions and a key component of global food systems due to its flavor, versatility, and nutritional benefits. Globally, onions are grown in over 170 countries, with China, India, and the United States leading production [2]. The crop is highly valued not only for fresh consumption but also for processing into products such as dried onions, onion powder, and pickles, further enhancing its economic importance.

In Ethiopia, onions are one of the most important horticultural crops, cultivated both for domestic consumption and

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export. The crop is widely grown in several regions, including the highlands and lowlands, with the Rift Valley region, particularly the Middle Awash area in Afar, recognized for its irrigated onion production potential. The Middle Awash area, characterized by its semi-arid climate and reliance on irrigation, has seen significant growth in onion production over the past decades, contributing substantially to the national economy [3]. Despite the increasing production, challenges related to productivity and quality persist, with factors such as inadequate spacing, variety selection, and resource management affecting overall yield and marketability. Recent studies indicate that the productivity of onions in Ethiopia, particularly in regions like Afar, is still far below its potential, and improvements in agronomic practices could significantly enhance production [4].

The release of improved onion varieties in Ethiopia has also contributed to advancing production. Varieties such as Nafid, Nafis, Adama Red, Melkam, and Bombe Red have been developed and registered by the Ethiopian Institute of Agricultural Research (EIAR) and are being adopted by producer across the country. These varieties are known for their higher yield potential, disease resistance, and superior bulb quality [5]. However, the optimal intra-row spacing for these varieties remains a critical factor in maximizing yield and bulb quality under different agro-ecological conditions. Previous studies have explored the effects of spacing on onion productivity, but there remains a gap in understanding the combined effects of spacing and variety in specific regions such as the Middle Awash, where water availability and environmental factors present unique challenges to production.

Intra-row spacing is an important agronomic practice that directly impacts plant competition, resource allocation, and ultimately yield. Narrow spacing has been associated with higher plant density but may result in competition-induced stress, affecting bulb size and marketability [6]. Conversely, wider spacing may reduce competition and enhance bulb size and quality but could potentially lead to lower overall yields. In the Middle Awash area, where water availability is managed through irrigation, finding the optimal intra-row spacing for various onion varieties is crucial to balance high yield with desirable bulb characteristics such as size, shape, and marketability.

Despite the growing interest in improving onion production practices, research on the combined effects of intra-row spacing and variety in regions like the Middle Awash remains limited. Research gaps exist in understanding how different varieties respond to varying spacing conditions under irrigated environments, particularly in relation to yield and quality traits. Addressing these gaps could provide valuable insights for optimizing agronomic practices in the region, promoting sustainable farming, and improving food security. Therefore, this activity was designed to investigate the combined effects of intra-row spacing and onion variety on yield and yield components under irrigated conditions in the Middle Awash, Afar, Ethiopia.

2. Materials and Methods

2.1. Study Site

The study was conducted at the Werer Agricultural Research Center, located in the Gebiresu Zone of Afar Regional State in Ethiopia. This area lies on a broad alluvial plain along the right bank of the Awash River, at an elevation of approximately 740 meters above sea level (masl), and is positioned at 9°20’31" N latitude and 40°10’11" E longitude in the Middle Awash Rift Valley. Werer Agricultural Research Center is situated 260 km from the Ethiopian capital, Addis Ababa, along the main highway connecting Addis Ababa to Djibouti.

The climate of the area is classified as semi-arid, characterized by bimodal rainfall, with an annual precipitation of about 533 mm. Temperatures fluctuate with a mean minimum of 15.2 ℃ and a mean maximum of 38 ℃. Relative humidity averages between 36% in June (the lowest) and 58% in August (the highest). The region experiences approximately 8.5 hours of daily sunshine, with an average solar radiation of 536 calories per square centimeter per day [7].

The Amibara district, is characterized by predominantly alluvial and clay soils, largely a result of the river systems and seasonal flooding in the area. These soil types are known for their fertility and are well-suited for agricultural activities, especially for crops that require moist soil conditions. In addition to the alluvial and clay soils, certain areas within the district contain sandy soils, influenced by the region’s arid environment. This variation in soil types provides diverse agricultural potential across the district, supporting both moisture-loving crops and those adapted to drier conditions.

2.2. Experimental Design and Treatments

The experiment was conducted using a factorial arrangements of randomized complete block design (RCBD) with three replications. The study involved two primary factors: onion variety and intra-row spacing, each designed to investigate their individual and interactive effects on onion yield, and yield related traits.

Factor 1: Varieties

Three distinct onion varieties were selected for the study: Bombe Red, Nafid, and Nafis. These varieties were chosen based on their agronomic potential, adaptability to the local environment, and contrasting traits, such as growth habit, bulb size, and yield potential. Examining multiple varieties provides insights into how different genetic backgrounds may respond to varying spacing treatments, thus identifying optimal combinations for specific varieties. Bombe Red is a medium-to-large bulb onion variety appreciated for its bright red color, firm texture, and high marketability; Nafid is known for its vigorous growth, uniform bulb shape, and resistance to diseases, while Nafis, a high-yielding variety, produces larger bulbs when grown with wider spacing due to its preference for lower plant densities.

Factor 2: Intra-row Spacing

Intra-row spacing, a critical factor in plant density and yield quality for onions, was assessed at four levels in this study: 2.5 cm, offering the highest density with potential trade-offs in bulb size due to competition; 5 cm, a moderate spacing for balanced competition and space utilization; 7.5 cm, reducing competition to encourage larger bulbs and minimize unmarketable yield; and 10 cm, the widest spacing, designed to maximize bulb growth through minimal competition but potentially reducing overall yield per area.

2.3. Treatment Structure and Layout

Each experimental plot contained a combination of one variety and one spacing level, forming a total of twelve unique treatments (3 varieties × 4 spacings). This factorial design allowed for the examination of both the main effects of each factor (variety and spacing) and their potential interactions. For each variety-spacing combination, treatments were randomly assigned within each block to reduce bias and account for environmental heterogeneity. Each treatment was replicated across three blocks, enhancing the robustness of the experiment by providing additional data points for statistical analysis. Standardized agronomic practices, such as irrigation, fertilization, and pest control, were uniformly applied across all treatments to ensure that observed differences in yield, and yield related traits were attributable to the treatments rather than external factors.

2.4. Data Collection Procedures

1) Marketable Yield (MY) refers to the weight of bulbs that meet quality standards, including proper size (3–7 cm diameter), uniform shape, appropriate color, intact texture, and absence of disease or pest damage. Bulbs that meet these criteria are separated and weighed, with the total recorded in kilograms (kg) and converted to a per-hectare basis.
2) Unmarketable Yield (UMY) includes bulbs that do not meet market standards due to factors like poor size, deformities, color issues, physical damage, pest or disease damage, or other defects. These bulbs are separated, weighed, and the total weight is recorded in kilograms, also converted to a per-hectare basis. Unmarketable yield can be reported as a percentage of the total bulb yield.
3) Total Bulb Yield (TBY): The total bulb yield (TBY) was calculated as the sum of marketable and unmarketable yields and was expressed in quintals per hectare (q/ha).
4) Number of Marketable Bulbs (MN) and Unmarketable Bulbs (UMN): After sorting the harvested bulbs, the number of marketable bulbs (MN) and unmarketable bulbs (UMN) were counted separately for each plot. The bulbs were counted by hand, and the counts were recorded as the total number of bulbs in each category.
5) Percent of Marketable Bulb Number (PMN): The percentage of marketable bulbs in each plot was calculated using the formula:

$$PMN = \left(\frac{\text{Marketable Numbers}}{\text{Marketable Numbers+Unmarketable Numbers}}\right) * 100 \quad (1)$$

6) Plant Height (PH): The plant height (PH) was measured in centimeters (cm) from the soil surface to the tip of the highest leaf on five randomly selected plants per plot. The average plant height for each plot was calculated by averaging the heights of the selected plants.
7) Number of Leaves per Plant (NL): The number of leaves per plant was recorded by counting the leaves on five randomly selected plants per plot. Only fully developed leaves were counted, and the average number of leaves per plant was computed.
8) Leaf Diameter (LD): The leaf diameter was measured in centimeters (cm) at the widest point of the second fully developed leaf from the top of five randomly selected plants per plot. A caliper was used to measure the leaf diameter, and the average was calculated for each plot.
9) Leaf Length (LL): The leaf length was measured in centimeters from the base to the tip of the longest leaf on five randomly selected plants per plot. The average leaf length for each plot was determined.
10) Neck Diameter (ND): The neck diameter was measured in centimeters (cm) at the base of the bulb, where the bulb meets the neck, for five randomly selected plants per plot. A caliper was used to measure the neck diameter, and the average was calculated.
11) Bulb Diameter (BD): The bulb diameter was measured in centimeters (cm) at the widest point of the bulb for five randomly selected bulbs per plot. The average bulb diameter was determined.
12) Bulb Length (BL): The bulb length was measured in centimeters (cm) from the base to the tip of the bulb for five randomly selected bulbs per plot. The average bulb length was calculated.
13) Leaf Dry Matter (LDM): To determine leaf dry matter the leaves from five randomly selected plants were harvested and dried in a forced-air oven at 65 ℃ for 48 hours until a constant weight was achieved. After drying, the leaf dry weight was recorded, and the percentage of dry matter was calculated as follows:

$$LDM = \left(\frac{\text{Dry Leaf Weight}}{\text{Fresh Leaf Weight}}\right) * 100 \quad (2)$$

14) Bulb Dry Matter (BDM): To determine bulb dry matter five randomly selected bulbs were cleaned, peeled, and sliced, and then dried in the same forced-air oven at 65 ℃ for 48 hours until a constant weight was reached.

The dry weight of the bulbs was recorded, and the dry matter percentage was calculated as:

$$BDM = \left(\frac{\text{Dry Bulb Weight}}{\text{Fresh Bulb Weight}}\right) * 100 \quad (3)$$

2.5. Statistical Analysis

Analysis of variance (ANOVA) was conducted using SAS software to assess the significance of effects due to variety, spacing, and their interactions. Mean comparisons were performed using the Least Significant Difference (LSD) test at a 5% significance level. The correlation analysis was performed by calculating a correlation coefficient. This coefficient provides a quantitative measure of the strength and direction of association between two or more variables. In this experiment, Pearson's correlation coefficient (r) was used due to its suitability in assessing linear relationships. Pearson's rrr-value ranges from -1 to +1 from -1 to +1, where values near +1 indicate a strong positive relationship, values near -1 indicate a strong negative relationship, and values near 0 indicate no linear correlation. Pearson's r is calculated using the formula:

$$r = \frac{\sum (x-\bar{x})(y-y)}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \quad (4)$$

3. Results and Discussion

3.1. Results

The Analysis of Variance (ANOVA) results presented in Table 1 provide a detailed overview of the effects of onion variety, intra-row plant spacing, and their interactions on various yield and growth traits of onions cultivated under irrigated conditions in the Middle Awash area over the 2023 and 2024 growing seasons.

For the 2023 season, the ANOVA results reveal highly significant varietal differences ($p < 0.01$) for multiple traits, including the number of marketable bulbs (MN), unmarketable bulbs (UMN), percent marketable bulbs (PMN), plant height (PH), number of leaves (NL), leaf diameter (LD), leaf length (LL), neck diameter (ND), and bulb length (BL). These findings suggest that variety selection strongly influences yield-related characteristics and morphological traits in this specific growing season, making varietal choice critical for optimizing yield and quality in the Middle Awash region.

In terms of intra-row spacing, the 2023 data indicate highly significant effects ($p < 0.01$) on marketable yield (MY), MN, UMN, PMN, leaf dry matter (LDM), and bulb dry matter (BDM). There are also significant differences ($p < 0.05$) for unmarketable yield (UMY), highlighting the importance of plant density in impacting not only yield but also the proportion of unmarketable bulbs, a key quality metric. Additionally, significant variety-by-spacing interaction effects were observed, with highly significant differences in LDM ($p < 0.01$) and significant effects ($p < 0.05$) on MN and UMN. These interaction effects suggest that optimal intra-row spacing may vary by variety, with potential for enhanced leaf and bulb dry matter production in certain variety-spacing combinations.

For the 2024 growing season, the ANOVA results indicate similarly strong varietal influences on traits such as MY, total bulb yield (TBY), MN, UMN, PMN, and bulb diameter (BD) ($p < 0.01$). Intra-row spacing effects were also highly significant ($p < 0.01$) across several traits, including MY, TBY, MN, UMN, PMN, BD, LDM, and BDM. These findings are consistent with the 2023 results, suggesting that spacing consistently affects yield and quality traits across years. Additionally, significant variety-by-spacing interaction effects ($p < 0.01$) for MN, UMN, and BDM further highlight the importance of optimizing specific variety-spacing combinations for improving productivity and quality.

The combined ANOVA (Table 2) across the 2023 and 2024 seasons offers insight into year-to-year stability and general trends. The results show that year is a significant factor ($p < 0.01$) influencing MY, UMY, TBY, MN, UMN, PMN, LD, LL, ND, BD, BL, and BDM, indicating that seasonal conditions significantly impact both yield and morphological traits. This effect underscores the variability introduced by environmental factors in yield performance and bulb quality, suggesting that management strategies may need adjustment based on seasonal conditions.

Variety effects in the combined analysis were significant ($p < 0.01$) for MY, TBY, MN, UMN, PMN, PH, ND, and BL, with additional significant impacts ($p < 0.05$) on NL, LL, and BD, underscoring the consistent role of variety in determining both yield and growth traits across multiple seasons. The significant year-by-variety interaction effects for PH and NL ($p < 0.05$) and ND ($p < 0.01$) suggest that varietal responses may vary between growing seasons, which could be due to differing environmental pressures or adaptability traits in each variety.

For intra-row spacing, the combined data reveal highly significant differences ($p < 0.01$) in MY, TBY, MN, UMN, PMN, BD, dry matter (DM), and BDM, underscoring the importance of spacing in influencing yield and quality over time. There were also significant year-by-spacing interaction effects ($p < 0.05$) for MN, UMN, and BDM, suggesting that optimal spacing may vary annually, likely influenced by year-specific climatic factors. Moreover, significant variety-by-spacing interactions ($p < 0.01$) for MN, UMN, and BDM, as well as additional effects ($p < 0.05$) on PMN, highlight the potential benefits of adjusting spacing according to variety characteristics to optimize yield and quality.

The ANOVA findings emphasize the complex interactions between variety, spacing, and environmental conditions on yield and quality traits in onions. The highly significant effects of variety and spacing, along with the interaction effects, suggest that targeted management strategies, such as selecting optimal spacing for specific varieties, may enhance productivity and quality in the Middle Awash region. Additionally, the year-to-year variability implies that adaptive management practices that account for seasonal conditions are likely essential for maximizing onion production in semi-arid environments. These results provide a foundation for future research focused on fine-tuning agronomic practices for improved yield stability and quality in onion cultivation.

Table 1. *Analysis of Variance for mean of squares of Onion traits grown under irrigated condition of Middle Awash during growing seasons of 2023 and 2024.*

Source of Variations	Parameters							
	DF	MY	UMY	TBY	MN	UMN	PMN	PH
Year 1 (2023)								
Varieties	2	1.51ns	0.04ns	3285.33ns	397.69**	397.69**	193.69**	131.75**
Spacing	3	9.22**	0.45*	9582.16ns	44159.30**	5692.55**	485.67**	3.39ns
Variety*Spacing	6	0.49ns	0.26ns	961.20ns	47.77*	47.77*	9.58ns	19.06ns
Block	2	1.80ns	0.57*	5403.58ns	34.36ns	34.36ns	16.61ns	1.92**
Error	22	1.26	0.14	3317.15	18.69	18.69	6.34	3.62
Mean		6.53	0.96	334.74	127.06	18.19	91	37.69
CV (%)		17.18	38.96	17.21	3.4	23.76	2.77	5.05
R2		0.57	0.58	0.42	1	0.98	0.93	0.8
Year 2 (2024)								
Varieties	2	8.24**	0.53ns	21458.42**	608.36**	608.36**	214.62**	1.87ns
Spacing	3	8.25**	0.79ns	11619.59**	50151.00**	3755.58**	351.85**	19.66ns
Variety*Spacing	6	0.76ns	0.28ns	1844.76ns	133.03**	133.03**	12.16ns	8.77ns
Block	2	2.20ns	2.36**	5948.85ns	42.36ns	42.36ns	10.80ns	1.74ns
Error	22	1.29	0.39	3271.76	28.3	28.3	5.93	12.65
Mean		5.65	2.02	290.94	131.28	13.97	93.39	37.91
CV (%)		20.08	30.83	19.66	4.05	38.07	2.61	9.38
R2		0.64	0.54	0.58	1	0.96	0.92	0.3

Table 1. *Continued.*

Source of Variations	Parameters							
	NL	LD	LL	ND	BD	BL	LDM	BDM
Year 1 (2023)								
Varieties	32.37**	0.07**	52.05**	0.49**	0.24ns	0.92**	14.97ns	1.46ns
Spacing	3.90ns	0.00ns	1.43ns	0.02ns	0.58ns	0.11ns	395.28**	66.56**
Variety*Spacing	3.94ns	0.01ns	2.06ns	0.00ns	0.17ns	0.06ns	19.26**	6.89ns
Block	8.28ns	0.00ns	3.60ns	0.06*	1.73**	0.48**	17.73ns	17.73ns
Error	3.43	0	5.4	0.02	0.25	0.09	7.07	6.52
Mean	12.88	0.58	26.81	1	4.84	4.43	17.23	19.99
CV (%)	14.38	11.14	8.67	12.44	10.34	6.86	15.43	12.78

Source of Variations	Parameters							
	NL	LD	LL	ND	BD	BL	LDM	BDM
R2	0.61	0.68	0.52	0.78	0.55	0.63	0.9	0.66
Year 2 (2024)								
Varieties	0.52ns	0.04ns	4.28ns	0.03ns	1.20**	0.27ns	8.39ns	6.63ns
Spacing	3.56ns	0.07ns	10.98ns	0.01ns	2.70**	0.08ns	296.32**	288.27**
Variety*Spacing	1.93ns	0.08ns	14.17ns	0.03ns	0.09ns	0.11ns	3.20ns	23.18**
Block	5.97ns	0.03ns	11.33ns	0.05ns	0.53**	0.49ns	6.66ns	14.33ns
Error	4.02	0.07	11.65	0.03	0.08	0.16	10.99	5.2
Mean	11.75	0.8	29.92	1.24	3.74	4.13	18.12	17.21
CV (%)	17.06	33.08	11.41	13.87	7.45	9.76	18.3	13.24
R2	0.29	0.35	0.37	0.35	0.88	0.4	0.8	0.9

Note: *, **, and ns indicate significance at the 0.05 and 0.01 probability levels and non-significance, respectively. DF = Degrees of freedom; CV = coefficient of variation. MY = Marketable Yield (kg), UMY = Unmarketable Yield (kg), TBY = Total Bulb Yield (q/ha), MN = Number of Marketable Bulbs (count per plot), UMN = Number of Unmarketable Bulbs (count per plot), PMN = Percent of Marketable Bulb Number, PH = Plant Height (cm), NL = Number of Leaves per Plant, LD = Leaf Diameter (cm), LL = Leaf Length (cm), ND = Neck Diameter (cm), BD = Bulb Diameter (cm), BL = Bulb Length (cm), LDM = Leaf Dry Matter (%), and BDM = Bulb Dry Matter (%)

Table 1. *Combined Analysis of Variance for mean of squares of Onion traits under irrigated condition of Middle Awash (2023 and 2024).*

Source of Variations	Parameters							
	DF	MY	UMY	TBY	MN	UMN	PMN	PH
Year	1	10.73**	20.25**	26560.68**	341.80**	341.80**	106.15**	0.98ns
Varieties	2	10.53**	0.24ns	26183.29**	999.34**	999.34**	401.85**	61.03**
Variety*Year	2	0.59ns	0.29ns	1717.22ns	9.86ns	9.86ns	1.26ns	70.77**
Spacing	3	16.05**	1.00ns	19548.56**	89019.65**	8943.31**	798.66**	8.12ns
Spacing*Year	3	0.23ns	0.17ns	404.70ns	109.88**	109.88**	6.77ns	14.19ns
Variety*Spacing	6	0.88ns	0.30ns	1988.60ns	161.89**	161.89**	18.04*	7.21ns
Variety*Spacing*Year	6	1.00ns	0.27ns	2198.53ns	14.54ns	14.54ns	2.55ns	3.66ns
Error	47	1.18	0.37	3109.18	24.66	24.66	6.83	8.49
Mean		6.05	1.49	311.02	127.89	15.46	92.39	37.86
CV (%)		17.94	40.74	17.93	3.88	32.11	2.83	7.7
R2		0.63	0.62	0.54	1	0.96	0.91	0.49

Table 2. *Continued.*

Source of Variations	Parameters							
	NL	LD	LL	ND	BD	BL	LDM	BDM
Year	26.13ns	0.88**	163.13**	0.99**	21.69**	1.57**	11.67ns	161.42**

Source of Variations	Parameters							
	NL	LD	LL	ND	BD	BL	LDM	BDM
Varieties	17.01*	0.01ns	35.45*	0.35**	1.08*	1.01**	19.21ns	4.43ns
Variety*Year	9.76*	0.10ns	12.76ns	0.12*	0.27ns	0.15ns	2.00ns	2.88ns
Spacing	6.71ns	0.03ns	8.80ns	0.00ns	2.50**	0.09ns	640.50**	265.63**
Spacing*Year	0.35ns	0.04ns	4.35ns	0.03ns	0.67ns	0.10ns	2.96ns	68.13**
Variety*Spacing	2.74ns	0.03ns	9.61ns	0.01ns	0.10ns	0.11ns	12.18ns	25.68**
Variety*Spacing*Year	4.34ns	0.05ns	7.22ns	0.02ns	0.16ns	0.06ns	11.82ns	7.23ns
Error	3.97	0.04	8.51	0.03	0.25	0.16	9.38	5.69
Mean	12.35	0.69	28.43	1.13	4.29	4.28	17.81	18.69
CV (%)	16.13	27.54	10.26	14.17	11.63	9.35	17.19	12.76
R2	0.44	0.52	0.5	0.65	0.76	0.42	0.83	0.84

Note: *, **, and ns indicate significance at the 0.05 and 0.01 probability levels and non-significance, respectively. DF = Degrees of freedom; CV = coefficient of variation. MY = Marketable Yield (kg), UMY = Unmarketable Yield (kg), TBY = Total Bulb Yield (q/ha), MN = Number of Marketable Bulbs (count per plot), UMN = Number of Unmarketable Bulbs (count per plot), PMN = Percent of Marketable Bulb Number, PH = Plant Height (cm), NL = Number of Leaves per Plant, LD = Leaf Diameter (cm), LL = Leaf Length (cm), ND = Neck Diameter (cm), BD = Bulb Diameter (cm), BL = Bulb Length (cm), LDM = Leaf Dry Matter (%), and BDM = Bulb Dry Matter (%)

3.2. Discussion

Main Effects of Variety and Intra-row Spacing on Yield Components

The analysis of variance in Table 4 underscores the main effects of onion variety and intra-row spacing on yield and yield components under irrigated conditions in the Middle Awash area, revealing significant differences in yield, quality, and vegetative traits across varieties and intra-row spacing levels.

Varietal Performance

Marketable Yield (MY) and Total Bulb Yield (TBY)

The observed high yields of the Nafid variety, with a marketable yield (MY) of 6.49 kg per plot and total bulb yield (TBY) of 333.91 quintals per hectare, indicate its promising adaptability and productivity in the Middle Awash region. This performance suggests that Nafid's genetic attributes may confer an advantage in terms of efficient resource use and tolerance to the regional climate, which is essential for achieving high productivity under irrigated conditions [8, 9]. The similarly strong yield potential of Nafis, which closely follows Nafid, further confirms its suitability for this agro-ecological zone, likely due to similar genetic traits that favor robust growth and bulb development under the local environmental conditions.

Bombe Red, on the other hand, yielded significantly lower (5.41 kg per plot and 279.23 quintals per hectare), which aligns with findings by [10], who observed that genetic diversity among onion varieties can significantly influence their adaptability and yield potential in specific environments. The comparatively lower yield of Bombe Red indicates its reduced genetic compatibility with the conditions in Middle Awash, possibly due to differences in nutrient uptake efficiency or sensitivity to climate variations. Research by [11] suggests that well-adapted varieties like Nafid and Nafis exhibit physiological traits that optimize nutrient absorption and bulb growth, which may explain their superior yield performance.

The implications of these findings underscore the critical need for targeted variety selection in the Middle Awash region, where environmental factors, soil characteristics, and irrigation practices collectively shape crop outcomes. Selecting high-yielding, well-adapted varieties not only maximize productivity but also enhances resource efficiency, a crucial factor given the resource constraints in many agricultural areas in Ethiopia [12]. By focusing on varieties like Nafid and Nafis, which demonstrate both high yield and adaptability, producer can improve the economic sustainability of onion production in the region. The data further support the recommendation for site-specific variety selection as a means to achieve sustainable intensification of onion production, which is integral to the agricultural economy in areas.

Number of Marketable Bulbs (MN)

The high number of marketable bulbs (MN) observed in the Nafid variety, with 134.71 bulbs per plot, underscores its effective conversion of vegetative growth into commercially valuable yield components, a critical attribute for optimizing market returns in onion production. This is closely followed by the Nafis variety with 130.67 bulbs per plot, both of which significantly outperform Bombe Red, which only achieved

122.13 bulbs per plot. The enhanced MN in Nafid and Nafis is directly correlated with their higher marketable yield (MY), supporting findings by Ethiopian researchers that suggest a strong link between marketable bulb count and overall productivity in onion crops [8, 9].

This greater efficiency in producing marketable bulbs likely reflects genetic factors in Nafid and Nafis that promote balanced vegetative and reproductive growth, leading to optimal bulb size and weight that meet market standards. [13] suggest that such varieties possess physiological traits that facilitate efficient nutrient assimilation and water use, enabling higher photosynthate allocation towards bulb formation. This trait is particularly advantageous in regions like Middle Awash, where irrigation practices and soil nutrient management are crucial for sustaining high yield levels. The significantly lower MN in Bombe Red, as well as its lower yield performance, suggests limited genetic adaptability, potentially due to a reduced capacity to partition resources effectively into marketable bulb output [1, 14, 15].

Moreover, the superior MN in Nafid and Nafis not only enhances marketability but also contributes to yield stability across varying environmental conditions, which is essential for consistent commercial production. These findings reinforce the importance of selecting varieties like Nafid and Nafis for their ability to convert vegetative growth into marketable yield efficiently. This trait ensures that producer in the Middle Awash region can achieve high economic returns while maintaining stable yield outcomes, which is vital for the sustainability and competitiveness of onion production in Ethiopia [16]. Such insights underscore the broader need for targeted breeding programs that prioritize marketable yield components alongside total yield potential, as emphasized by [17].

Percent of Marketable Bulbs (PMN)

The percentage of marketable bulbs (PMN) achieved by the Nafid variety, at 95.60%, significantly outpaced both Nafis (93.37%) and Bombe Red (87.62%). This high PMN in Nafid and Nafis is an indicator of their superior quality and adaptability, ensuring that a greater proportion of the bulbs produced meet market standards. According to studies by Ethiopian researchers, high PMN is a valuable attribute in onion production, as it maximizes economic returns by minimizing the proportion of bulbs that are unmarketable due to size, shape, or other quality-related factors [17, 18]. The significantly lower PMN in Bombe Red suggests it may be less suited to the environmental conditions and management practices in Middle Awash, leading to a higher incidence of unmarketable yield.

This outcome aligns with research by [8, 19], who emphasized that differences in genetic adaptability among onion varieties can influence PMN, especially under specific agro-climatic conditions. High PMN is often associated with varieties that exhibit efficient resource use, reduced susceptibility to environmental stresses, and stable development of desirable bulb traits, including size, shape, and firmness [13, 20]. Studies by [21] further support this observation, suggesting that onion varieties with stable morphological traits and efficient nutrient partitioning into bulb formation are more likely to maintain high PMN under variable growing conditions.

The comparatively low PMN in Bombe Red may result from its lower genetic plasticity, which limits its capacity to maintain bulb quality in the Middle Awash environment. Lower PMN can also result from increased sensitivity to environmental stresses, such as temperature fluctuations and nutrient availability, which may impact bulb uniformity and structural integrity [22]. Thus, the high PMN in Nafid and Nafis not only reflects their yield potential but also indicates that these varieties can consistently produce bulbs that meet market requirements. This adaptability is essential for enhancing the efficiency and profitability of onion production, as high PMN reduces post-harvest losses and maximizes the portion of the crop that can be sold [23-25].

Therefore, these findings highlight the need for producer in the Middle Awash region to select varieties with high PMN, such as Nafid and Nafis, to optimize their commercial yield. By choosing varieties with higher PMN, producers can minimize the costs associated with unmarketable yield, increase labor efficiency, and ensure a more stable return on investment in onion production [10, 16, 26-28]. This study supports the broader agricultural strategy of focusing on marketable yield components as a key determinant of variety selection, which is essential for sustaining onion production in Ethiopia's commercial farming sector.

Vegetative Traits (PH, NL, LL)

The robust vegetative growth observed in Nafid and Nafis, with plant heights of 38.83 cm and 38.62 cm respectively, along with a high leaf count, suggests their enhanced photosynthetic capacity and overall growth vigor, which supports high bulb yields. Studies by [24, 29-31] confirm that greater leaf area and plant height correlate with increased photosynthate production and allocation to bulbs, leading to better marketable yields. This superior growth in Nafid and Nafis is likely due to their genetic adaptability to the Middle Awash environment, facilitating efficient nutrient uptake and resilience in irrigated conditions. International research supports this link between vegetative growth and yield potential, noting that increased plant height and leaf production improve biomass and yield [21, 32]. In contrast, Bombe Red's lower height and leaf count suggest reduced photosynthetic capacity and adaptability, highlighting Nafid and Nafis as more suitable options for high-yield onion production in regions requiring optimal photosynthetic efficiency.

Bulb Quality Traits (ND, BD, BL, and BDM)

Nafid and Nafis exhibited superior quality traits, such as larger neck diameter (ND), bulb diameter (BD), and bulb length (BL), enhancing their potential for producing high-quality bulbs preferred for fresh consumption and processing. Studies by [8, 33-35] underscore the economic importance of larger bulb sizes, which meet market demands and yield higher returns. Additionally, [36-38] note that traits like ND, BD, and BL are largely heritable, making variety selection pivotal in quality improvement.

In contrast, leaf dry matter (LDM) and bulb dry matter (BDM) showed no significant varietal differences, suggesting these traits are less genetically determined and more influenced by environmental factors and management practices. [20, 21] corroborate this, reporting that dry matter content in onions is sensitive to conditions such as soil type and irrigation. Thus, while selecting varieties like Nafid and Nafis with desirable genetic traits enhances bulb quality, optimized management practices are essential for improving LDM and BDM, supporting a dual strategy in onion production for quality and yield stability [39, 40].

Intra-Row Spacing Effects

Yield Components (MY, TBY, MN, UMN):

The 5 cm intra-row spacing achieved the highest marketable yield (MY) at 7.10 kg per plot and total bulb yield (TBY) at 354.93 quintals per hectare, making it the most effective spacing for onion production under irrigated conditions. These results suggest that a 5 cm spacing optimally balances plant competition and resource use, leading to higher yields without compromising bulb quality. Similar findings are reported by [17], who observed that moderate spacing supports effective resource allocation, reducing excessive plant competition while maximizing productivity.

In contrast, while the narrower 2.5 cm spacing produced relatively high yields, it also resulted in a significant increase in unmarketable bulb count (UMN = 50.056), likely due to overcrowding, which limited each plant's access to essential nutrients and water. Excessive plant density often leads to competition stress, resulting in smaller or misshapen bulbs that lack marketability. This phenomenon aligns with [41, 42] in Ethiopian studies, which indicated that dense planting can increase unmarketable yield due to resource limitations affecting bulb size and shape.

These findings support the conclusion that moderate spacing, such as 5 cm, is ideal for achieving high marketable yields while minimizing unmarketable output. Internationally, [21] similarly highlights the importance of spacing in bulb crops, noting that optimal plant spacing improves bulb size and quality by reducing intra-row competition. As such, selecting the right spacing is essential in maximizing both the quantity and quality of yield in onion production, particularly in regions where resource-efficient, high-yield production is a priority [20].

Marketable and Unmarketable Bulbs

The findings indicate that a 5 cm intra-row spacing achieved the highest marketable bulb counts, while maintaining a lower count of unmarketable bulbs. This outcome reinforces the conclusion that moderate plant density effectively balances competition among plants, promoting the development of marketable bulbs. In denser planting configurations, such as the 2.5 cm spacing, overcrowding occurs, which leads to higher unmarketable bulb counts due to increased competition for light, water, and nutrients. Similar observations were made by [43], who found that excessive plant density reduces bulb marketability as competition limits each plant's access to essential resources.

Wider spacing arrangements, like the 7.5 cm and 10 cm configurations, significantly reduced unmarketable bulb counts, suggesting that lower plant densities improve bulb quality by reducing competitive stress. Research, such as the studies by [44-46], confirms that wider spacing promotes better bulb quality, as the lower density provides plants with more room for optimal growth, enhancing their ability to produce larger, well-formed bulbs suited for market demand.

This spacing effect aligns with conclusions on allium crops, which underscore that spacing adjustments can reduce the incidence of unmarketable bulbs by improving resource distribution per plant. Similarly, [20] highlighted that wider spacing arrangements generally result in superior bulb quality, attributing the effect to reduced competition, which enables efficient nutrient uptake and better photosynthetic performance. These findings underscore the importance of choosing the appropriate plant spacing to maximize both yield and marketability in onion production, with moderate densities like 5 cm achieving a favorable balance between bulb yield and quality in irrigated environments.

Bulb Quality Traits (BD, BDM)

The findings from the study highlight the significant influence of intra-row spacing on bulb quality, with wider spacings such as 10 cm resulting in larger bulb diameters (4.82 cm) and higher bulb dry matter (BDM = 22.00%). This indicates that lower plant density allows each plant to access more resources, which promotes the development [21] of larger, more robust bulbs. These results are consistent with previous studies by [47, 48], who found that wider spacings improve individual bulb size and dry matter content by reducing intra-plant competition for nutrients, water, and light. Additionally, [16] noted that wider spacing in onions enhances the ability of plants to accumulate dry matter, which is crucial for bulb storage and processing quality.

The relationship between spacing and bulb quality suggests that wider plant arrangements are particularly beneficial when the emphasis is on producing high-quality bulbs rather than maximizing total yield. This aligns with the findings of [9], who demonstrated that wider spacing in onions results in better bulb shape and size, qualities that are highly valued in both local and international markets. Furthermore, studies by [20, 21] also support the idea that wider spacing can enhance bulb quality, especially in environments where maximizing bulb size and dry matter content is more important than simply increasing yield.

In contrast, narrower spacings, such as 2.5 cm, led to higher unmarketable bulb counts due to excessive plant competition, as observed in this study. This finding is consistent with the work of [49], who emphasized that high-density planting often leads to smaller, misshapen bulbs, which are less likely to meet market standards.

Table 3. *Mean performances of onion varieties and intra-row spacing for Yield and Yield related components.*

Treatments	**MY**	**TBY**	**MN**	**UMN**	**PMN**	**PH**	**NL**	**LL**	**ND**	**BD**	**BL**	**LDM**	**BDM**
Variety													
Bombe Red	5.41 b	279.23 b	122.13 c	23.13 a	87.62 c	35.95 b	11.31 b	26.86 b	0.97 b	4.04 b	4.04 b	17.31	18.19
Nafid	6.49 a	333.91 a	134.71 a	10.54 c	95.60 a	38.83 a	12.52 a	29.06 a	1.19 a	4.37 a	4.38 a	17.00	18.39
Nafis	6.37 a	325.38 a	130.67 b	14.58 b	93.37 b	38.62 a	13.13 a	29.18 a	1.20 a	4.46 a	4.42 a	18.72	19.21
Grand Mean	6.09	312.84	129.17	16.08	94.09	37.80	12.32	28.36	1.12	4.29	4.28	17.68	18.60
LSD	0.64	32.69	2.98	2.98	1.36	1.84	1.17	1.69	0.10	0.29	0.21	ns	ns
Spacing													
2.5	6.49 ab	321.54 ab	229.94 a	50.056 a	82.12 c	38.72	11.96	29.20	1.12	3.91 c	4.30	9.39 d	14.18 b
5	7.10 a	354.93 a	131.72 b	8.28 b	94.09 b	37.80	11.74	28.34	1.11	4.19 bc	4.30	16.71 c	16.10 b
7.5	5.96 b	297.94 bc	87.50 c	3.50 c	96.15 a	37.68	12.38	28.30	1.10	4.24 b	4.18	21.29 b	22.12 a
10	4.82 c	276.95 c	67.50 d	2.50 c	96.43 a	37.00	13.19	27.61	1.14	4.82 a	4.35	23.32 a	22.00 a
Grand Mean	6.09	312.84	129.17	16.08	16.08	37.80	12.32	28.36	1.12	4.29	4.28	17.68	18.60
LSD	0.74	37.75	3.44	3.44	1.57	ns	ns	ns	ns	0.33	ns	1.95	1.95

Note: Means followed by the same letter within the same column are not significantly different at 5% level of significance, ns = non-significance, MY = Marketable Yield (kg per plot), TBY = Total Bulb Yield (q/ha), MN = Number of Marketable Bulbs (count per plot), UMN = Number of Unmarketable Bulbs (count per plot), PMN = Percent of Marketable Bulb Number (%), PH = Plant Height (cm), NL = Number of Leaves per Plant, LL = Leaf Length (cm), ND = Neck Diameter (cm), BD = Bulb Diameter (cm), BL = Bulb Length (cm), LDM = Leaf Dry Matter (%), BDM = Bulb Dry Matter (%) and LSD = Least Significance Difference

Interaction Effects of Variety and Intra-row Spacing on Yield and Yield Components of Onion

The interaction effects between onion variety and intra-row spacing, shown in Table 5, revealing that optimal spacing configurations vary by variety and influence yield and quality traits such as the number of marketable bulbs (MN), unmarketable bulbs (UMN), percentage of marketable bulbs (PMN), and bulb dry matter (BDM). These results highlight the importance of variety-specific spacing to maximize yield and bulb quality in onion production under irrigated conditions.

Number of Marketable Bulbs (MN)

The results of the study indicate that Nafid exhibited superior performance in terms of marketable bulb counts (MN) at the narrowest intra-row spacing of 2.5 cm (241.83 bulbs), outperforming both Bombe Red (217.00 bulbs) and Nafis (231.00 bulbs). This suggests that Nafid is particularly well-adapted to higher planting densities, likely due to its genetic traits that allow it to better tolerate competition for resources such as light, water, and nutrients. This observation aligns with [50, 51], who found that certain onion varieties, particularly those with a higher degree of competitive ability, are better suited for high-density planting configurations. Such varieties typically exhibit greater resilience under conditions of high plant density, which translates into increased yield potential.

However, as spacing increased across all varieties, there was a noticeable decrease in marketable bulb counts. This decrease was consistent across varieties, suggesting that lower plant densities (wider spacing) may reduce the overall competitive pressure, thereby affecting the plants' ability to maximize their full potential for bulb production. Despite this, Nafid consistently outperformed Bombe Red and Nafis at all spacing levels. For instance, at a 5 cm spacing, Nafid produced 138.33 bulbs compared to Bombe Red's 121.67 bulbs, indicating that Nafid maintains its competitive advantage in denser plantings but does not benefit as much from reduced competition in wider spacings.

This trend suggests that Nafid may be better suited for intensive planting systems, where high planting density is prioritized to maximize yield, while varieties like Bombe Red and Nafis may exhibit more consistent performance across different spacing levels. [52] similarly reported that certain varieties exhibit steadier yield responses across varying intra-row spacings, with Bombe Red and Nafis demonstrating more stable marketable bulb counts under reduced competition.

Number of Unmarketable Bulbs (UMN)

The results of this study indicate that narrow intra-row spacing of 2.5 cm led to the highest unmarketable bulb counts (UMN) across all onion varieties, with Bombe Red having the highest count (63.00), followed by Nafis (49.00) and Nafid (38.17). The increased number of unmarketable bulbs at such tight planting densities can be attributed to competition-induced stress, where plants struggle for essential resources like light, water, and nutrients, which can negatively impact bulb development, size, and overall quality. [9] have similarly found that high planting densities often lead to increased competition among plants, resulting in smaller, less uniform bulbs that fail to meet market standards.

On the other hand, wider spacings, such as 7.5 cm and 10 cm, significantly reduced the number of unmarketable bulbs in all varieties. At a 10 cm spacing, both Nafid and Nafis showed minimal unmarketable bulb counts (0.67 and 1.83, respectively), indicating that reducing plant density alleviates competitive stress and promotes better growth conditions. This reduction in unmarketable bulbs in wider spacings supports the idea that lower plant densities facilitate better resource allocation, enabling bulbs to grow larger and more uniformly, which enhances their quality and marketability. This finding is in agreement with [8], who reported that reduced competition in onions, resulting from wider spacing, improves the overall quality of the bulbs, leading to higher percentages of marketable yields.

Percentage of Marketable Bulbs (PMN)

The findings from this study reveal that Nafid and Nafis achieved the highest percentage of marketable bulbs (PMN), with values ranging from 98.81% to 99.05%, across various intra-row spacing configurations of 5 cm, 7.5 cm, and 10 cm. This consistent high PMN across multiple spacing levels indicates the robustness of these varieties in producing marketable bulbs, irrespective of the plant density. This performance suggests that Nafid and Nafis possess inherent characteristics that enable them to perform well under a variety of spacing regimes, likely due to their efficient use of resources such as light, water, and nutrients. This aligns with the findings of [53], who suggested that some onion varieties exhibit a high degree of adaptability to different intra-row spacings, thus ensuring high marketability and overall yield stability across different growing conditions.

In contrast, Bombe Red demonstrated a PMN of 93.22% at 7.5 cm spacing, but its marketability decreased significantly under narrower spacing conditions (e.g., 2.5 cm), indicating that this variety is more suited to moderate to wider spacings. The lower PMN observed at tighter spacings suggests that Bombe Red may experience competition stress at high densities, limiting its ability to produce uniform and high-quality bulbs. These findings support the concept that certain onion varieties require tailored spacing to optimize their marketable yield, as different genetic backgrounds influence how plants respond to competition and resource allocation [53].

For Nafid and Nafis, spacings of 5 cm or more appear to be optimal for maximizing their marketable bulb percentage. These varieties maintain high PMN values across various spacings, suggesting they can adapt well to both moderate and wider planting densities. This versatility in responding to different spacings further supports their suitability for high-performance onion production in diverse conditions.

Bulb Dry Matter (BDM)

Wider spacings, such as 7.5 cm and 10 cm, significantly increased BDM, particularly in Bombe Red (23.16–23.27%) and Nafis (21.91%). This trend suggests that reduced plant competition at wider spacings enhances the plants' ability to accumulate dry matter in bulbs, a factor associated with superior bulb quality [6].

Among the varieties, Bombe Red exhibited the highest BDM at wider spacings, suggesting it efficiently converts resources into dry matter when plant density is reduced. This characteristic may make Bombe Red particularly suitable for quality-focused production, such as for longer storage or processing applications where dry matter is critical [54].

The interaction effects between variety and intra-row spacing reveal that spacing configurations must be tailored to specific varieties to optimize yield and bulb quality. Key findings include: Nafid performs well under high-density planting (2.5–5 cm spacing), achieving high marketable yields with minimal compromise in bulb quality. Similarly, Nafis responds well at these spacing levels, balancing yield with quality. In contrast, Bombe Red benefits most from moderate to wider spacings (7.5 cm or more), achieving higher marketable bulb percentages and BDM under these conditions [55].

For yield-oriented production, Nafid and Nafis are suitable for narrower spacings (2.5–5 cm) to maximize marketable yield. However, where quality attributes such as high BDM are prioritized, especially for storage or processing, wider spacings (7.5–10 cm) are recommended, particularly for Bombe Red. These insights align with findings by [56], who emphasize variety-specific management for optimized performance under irrigated conditions.

Table 4. *Interaction Effects of Variety and Intra-row Spacing on Yield and yield Components.*

Variety	Intra-row Spacing (cm)	MN	UMN	PMN	BDM
Bombe Red	2.5	217.00 c	63.00 a	77.50 e	13.56 c
	5	121.67 e	18.33 d	86.90 c	12.79 c
	7.5	84.83 f	6.17 e	93.22 b	23.27 a
	10	65.00 g	5.00 e	92.86 b	23.16 a
Nafid	2.5	241.83 a	38.17 c	86.37 c	14.92 c

Variety	Intra-row Spacing (cm)	MN	UMN	PMN	BDM
	5	138.33 d	1.67 e	98.81 a	16.03 c
	7.5	89.33 f	1.67 e	98.17 a	21.18 ab
	10	69.33 f	0.67 e	99.05 a	21.45 ab
Nafis	2.5	231.00 b	49.00 b	82.50 d	14.06 c
	5	135.17 d	4.83 e	96.55 a	19.48 b
	7.5	88.33 f	2.67 e	97.07 a	21.91 ab
	10	68.17 g	1.83 e	97.38 a	21.40 ab
Grand Mean		129.17	16.08	92.20	18.60
LSD		6.05	6.05	2.76	3.33

Note: Means followed by the same letter within the same column are not significantly different at 5% level of significance, ns = non-significance, MN = Number of Marketable Bulbs (count per plot), UMN = Number of Unmarketable Bulbs (count per plot), PMN = Percent of Marketable Bulb Number (%), BDM = Bulb Dry Matter (%) and LSD = Least Significance Difference

Correlation of the Onion Parameters

The Pearson correlation analysis of onion agronomic traits provides valuable insights into how various plant characteristics influence yield and yield-related parameters. Positive correlations were found between traits such as plant height (PH), leaf width (BL), neck diameter (ND), and bulb-related weights, including fresh weight above ground (FWAG) and bulb dry weight (BDW). These traits collectively contributed positively to both marketable yield (MY) and total bulb yield (TBY), suggesting that plant structure and biomass allocation play essential roles in improving onion productivity. This highlights the importance of selecting varieties with strong morphological traits that enhance overall yield performance.

Plant height (PH) exhibited a significant positive correlation with both marketable yield (MY) and total bulb yield (TBY), indicating that taller plants can optimize light capture and photosynthesis, leading to higher yields. This finding is consistent with previous studies by [12, 16, 57], which emphasized the role of taller plants in improving yield by maximizing carbohydrate production. Similarly, leaf length (BL) was positively correlated with MY and TBY, suggesting that wider leaves contribute to better photosynthetic efficiency and resource utilization, thereby supporting increased yield outcomes, as observed by [10].

Marketable number (MN) was strongly correlated with marketable yield (MY), which underscores the importance of neck diameter (ND) and other structural traits in boosting yield efficiency. [58, 59] reported similar findings, indicating that morphological traits such as ND are key to improving the marketability of onion bulbs. This highlights the role of structural features in optimizing both yield and quality of onions, with particular emphasis on traits that influence bulb uniformity and marketability.

The analysis also revealed negative correlations, particularly with unmarketable numbers (UMN), which were negatively correlated with both MY and TBY. This suggests that the production of unmarketable bulbs often caused by factors such as size inconsistency or nutrient allocation imbalances detracts from total yield. High planting densities, for example, were found to lead to smaller and less marketable bulbs due to competition-induced stress, as noted by [60]. This emphasizes the need to minimize unmarketable yield to optimize total productivity.

Leaf diameter (LD) showed a weak negative correlation with total bulb yield (TBY), suggesting that larger leaves could potentially reduce yield due to shading effects that limit photosynthesis and light penetration. This finding aligns with observations by [20], who noted that excessive leaf size could impede optimal bulb growth by reducing light availability within the plant canopy.

Conversely, traits such as bulb diameter (BD), dry weight above ground (DWAG), and leaf length (LL) showed minimal influence on both MY and TBY, suggesting that these traits are less critical in optimizing yield. This implies that breeding programs focused on improving onion yield should prioritize traits that have a stronger and more direct impact on productivity, such as plant height, leaf width, and neck diameter, while less emphasis should be placed on traits like bulb diameter or leaf length, which exhibit weak or neutral correlations with yield outcomes.

Table 5. *Correlation of the Onion Yield with Yield related Parameters.*

Traits	*PH*	*NL*	*LD*	*LL*	*ND*	*BD*	*BL*	*FWAG*	*DWAG*	*LDM*
PH	1.00									
NL	0.26*	1.00								
LD	0.21	0.00	1.00							
LL	0.66**	0.14	0.34**	1.00						
ND	0.49**	0.36**	0.41**	0.65**	1.00					
BD	0.03	0.22	-0.17	-0.15	-0.09	1.00				
BL	0.37**	0.44**	-0.05	0.21	0.27*	0.51**	1.00			
FWAG	0.16	0.48**	-0.32*	-0.22	-0.17	0.40**	0.48**	1.00		
DWAG	0.16	0.53**	-0.26*	-0.20	-0.12	0.38**	0.45**	0.94**	1.00	
LDM	-0.06	0.34**	0.07	-0.04	0.18	-0.10	0.01	0.07	0.31*	1.00
ABW	-0.08	0.28*	-0.37**	-0.35**	-0.37**	0.47**	0.50**	0.66**	0.62**	0.05
BFW	-0.04	0.28*	-0.40**	-0.38**	-0.39**	0.47**	0.49**	0.74**	0.65**	-0.05
BDW	-0.07	0.37**	-0.40**	-0.38**	-0.34**	0.40**	0.44**	0.77**	0.71**	0.16
BDMP	-0.20	0.32*	-0.22	-0.21	-0.11	-0.13	-0.03	0.32*	0.34**	0.58**
MN	0.12	0.07	-0.37**	-0.20	-0.37**	0.44**	0.44**	0.60**	0.43**	-0.34
UMN	0.00	-0.32*	0.40**	0.22	0.24*	-0.39**	-0.45**	-0.57**	-0.56**	-0.11
MY	0.34**	0.03	-0.05	0.08	-0.09	0.05	0.26*	0.18	0.10	-0.34**
UMY	-0.03	-0.39**	0.42**	0.28*	0.28*	-0.37**	-0.34**	-0.58**	-0.55**	-0.25*
TBY	0.34**	0.09	-0.07	0.05	-0.09	0.05	0.30*	0.22	0.17	-0.23*

Table 5. *Continued.*

Traits	*ABW*	*BFW*	*BDW*	*BDMP*	*MN*	*UMN*	*MY*	*UMY*	*TBY*
PH									
NL									
LD									
LL									
ND									
BD									
BL									
FWAG									
DWAG									
LDM									
ABW	1.00								
BFW	0.86**	1.00							
BDW	0.84**	0.94**	1.00						
BDMP	0.23	0.21	0.49**	1.00					

Traits	ABW	BFW	BDW	BDMP	MN	UMN	MY	UMY	TBY
MN	0.48**	0.67**	0.55**	-0.07	1.00				
UMN	-0.54**	-0.54**	-0.57**	-0.33**	-0.45**	1.00			
MY	0.15	0.25*	0.10	-0.28*	0.42**	-0.10	1.00		
UMY	-0.51**	-0.53**	-0.59**	-0.44**	-0.50**	0.75**	-0.04	1.00	
TBY	0.21	0.28*	0.15	-0.22	0.40**	-0.17	0.97**	-0.10	1.00

Note: * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively. PH = Plant Height (cm), NL = Number of Leaves per Plant, LD = Leaf Diameter (cm), LL = Leaf Length (cm), ND = Neck Diameter (cm), BD = Bulb Diameter (cm), BL = Bulb Length (cm), FWAG = Fresh Weight Above Ground (g), DWAG = Dry Weight Above Ground (g), LDM = Leaf Dry Matter (%), ABW = Average Bulb Weight (g), BFW = Bulb Fresh Weight (g), BDW = Bulb Dry Weight (g), BDMP = Bulb Dry Matter (%), MN = Number of Marketable Bulbs (count per plot), UMN = Number of Unmarketable Bulbs (count per plot), PMN = Percent of Marketable Bulb Number, MY = Marketable Yield (kg), UMY = Unmarketable Yield (kg), TBY = Total Bulb Yield (q/ha).

4. Conclusion and Recommendations

4.1. Conclusions

This study highlights the critical role of onion variety, intra-row spacing, and their interactions in influencing both the yield and quality of onions grown under irrigated conditions in the Middle Awash, Afar National Regional State, Ethiopia. The results demonstrate that high yielding varieties such as Nafid and Nafis exhibit strong adaptability to varying intra row spacing, with the 5 cm spacing providing the highest marketable yield (MY) and total bulb yield (TBY) while maintaining acceptable bulb quality. On the other hand, wider spacings (7.5 cm and 10 cm) were found to improve bulb quality, reflected by larger bulb diameters and higher dry matter content, which are crucial for storage and processing purposes. However, the narrowest intra-row spacing (2.5 cm) resulted in higher levels of unmarketable yield, primarily due to increased plant competition. This study underscores the importance of selecting the appropriate intra-row spacing to achieve an optimal balance between yield quantity and quality. These findings can guide producer in the region to make informed decisions for maximizing onion production, whether the focus is on higher yield or improved bulb quality for post-harvest handling. Therefore, a targeted approach to spacing, considering both the variety and the intended market, is essential for efficient and sustainable onion farming in the Middle Awash area.

4.2. Recommendations

Varietal Selection: To enhance yield and bulb quality, it is recommended that producer in semi-arid areas, such as the Middle Awash, prioritize the adoption of high performing onion varieties like Nafid and Nafis. These varieties have shown strong adaptability to different intra-row spacing levels and display high yield potential and marketable bulb quality. Selecting these varieties can improve productivity and income for producer, as they produce consistently well in varied spacing arrangements. When paired with optimal spacing, Nafid and Nafis can maximize both yield and quality, providing reliable results across diverse environmental conditions.

Optimal Spacing: Intra-row spacing plays a key role in onion yield and quality, and spacing should be carefully managed based on production goals. For a balanced approach that maximizes yield while maintaining quality, a 5 cm intra-row spacing is recommended. This spacing allows for higher plant density, which increases overall yield without sacrificing bulb size or marketability. However, when bulb quality is a primary objective such as for onions intended for extended storage, processing, or specific market standards a wider spacing of 7.5 cm to 10 cm should be implemented. Wider spacing reduces plant competition, resulting in larger bulbs with higher dry matter content, which are more suitable for long term storage and processing. Tailoring spacing practices to the intended market or storage goals can significantly improve outcomes for producer and agro-pastoralists.

Validating Onion Varieties with Intra-row spacing: The result of variety and intra-specific evaluations should be validated under agro-pastoralist field conditions to ensure practical relevance and applicability. Conducting on-farm trials with the active involvement of agro-pastoralists will provide valuable insights into the performance of the evaluated varieties under local conditions and encourage the adoption of high-performing options. This participatory approach not only strengthens the credibility of the results but also enhances the capacity of agro-pastoralists to implement adaptive management practices effectively. By combining scientific recommendations with local knowledge, this strategy can improve production stability, enhance bulb quality, and promote sustainable onion production in agro-pastoral systems.

Abbreviations

Afar NRS	Afar National Regional State
ANOVA	Analysis of Variance
WARC	Werer Agricultural Research Center
EIAR	Ethiopian Institute of Agricultural Research

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Author Contributions

Yitages Kuma Beji: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing

Nardos Mulugeta: Validation, Visualization, Writing – original draft, Writing – review & editing

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Yitages Kuma Beji, a dedicated horticultural researcher at the Ethiopian Institute of Agricultural Research (EIAR), holds a B.Sc. in Plant Sciences from Ambo University (Jun. 24, 2010) and an M.Sc. in Horticulture from Hawassa University (Feb. 20, 2017). With over a decade of experience, he has advanced from Junior Researcher to Researcher-I and Crop Research Process Head at the Werer Agricultural Research Center. Yitages specializes in horticultural crop research, statistical data analysis, and sustainable agricultural practices, contributing significantly to field experimentation, technology demonstration, and participatory research approaches. An accomplished academic, he has authored several publications on crop improvement and demonstrations, reflecting his commitment to enhancing agricultural productivity and resilience in Ethiopia.

Nardos Mulugeta, an Assistant Researcher II in horticulture at the Ethiopian Institute of Agricultural Research, holds a B.Sc. in Horticulture from Wolkite University (2018) and an M.Sc. in Horticulture from Ambo University (2021). Recognized for her contributions, she was designated as a Professional Horticulturalist by EIAR and has participated in national research collaborations focused on enhancing agricultural productivity and sustainability. Skilled in data analysis using tools like R and SAS, Nardos develops research proposals, analyzes experimental data, and formulates recommendations to improve agricultural practices among agro-pastoralists in Ethiopia, establishing herself as a dedicated and skilled horticulture researcher.

Research Field

Yitages Kuma Beji: Plant Breeding and genetics, Plant agronomy and physiology, Biotechnology, Horticultural crop improvements, Root crops research and improvements, Agriculture.

Nardos Mulugeta: Plant Breeding and genetics, Plant agronomy and physiology, Biotechnology, Horticultural crop improvements, Root crops research and improvements, Agriculture.