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Research Article

Effect of Fungicide Application and Intra-Row Spacing on Garlic Rust (*Puccinia allii*) Management and Yield of Garlic in South Ari District, Southern Ethiopia

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Abstract

A field experiment was conducted during the 2021/22 cropping season in South Ari District, South Omo Zone, Southern Ethiopia, to evaluate the effects of intra-row spacing and fungicide application on garlic rust (Puccinia allii) development, yield components, and bulb yield of garlic. The study also aimed to identify an effective and economically feasible management option for garlic producers in the area. Local garlic planting materials obtained from farmers were used for the experiment. Treatments consisted of three intra-row spacings (7 cm, 10 cm, and 13 cm) combined with four fungicides: Nativo (trifloxystrobin + tebuconazole), Natura (epoxiconazole + thiophanate-methyl), Tilt (propiconazole), and Ridomil (metalaxyl), along with an untreated control. The experiment was arranged in a randomized complete block design (RCBD) with three replications. The results indicated that both intra-row spacing and fungicide application significantly influenced garlic rust development and yield performance. The combination of 13 cm intra-row spacing with Ridomil fungicide application was the most effective treatment in reducing disease pressure. This treatment recorded the lowest disease incidence (13.33%), percent severity index (24.33%), and AUDPC value of 1692 %-days at 125 days after planting. It also produced the highest bulb diameter (16.0 mm), bulb weight per plant (76.0 gm), marketable bulb yield, and total bulb yield (7.69 t ha^{-1}), while resulting in the lowest unmarketable bulb yield. In contrast, narrow spacing without fungicide application resulted in higher disease severity and reduced yield. Therefore, the combination of 13 cm intra-row spacing and Ridomil fungicide application significantly ($P < 0.01$) reduced disease severity and disease progression compared with the untreated control and can be recommended for effective management of garlic rust and improved garlic productivity under the agro-ecological conditions of South Ari District.

Key words: Garlic rust disease, Intra-row spacing, Fungicide application, Ridomil, Garlic yield.

Introduction

Garlic (Allium sativum L.) is one of the oldest cultivated vegetable crops in the world and belongs to the family Amaryllidaceae and genus Allium [1]. It is an important bulb crop grown extensively for its nutritional, medicinal, and economic values. Garlic is widely cultivated in tropical, subtropical, and temperate regions due to its adaptability to diverse environmental conditions and high market demand [2]. Among bulb vegetables, garlic ranks second after onion in terms of production and consumption worldwide [3]. Historical records indicate that garlic originated in Central Asia, particularly in arid and semi-arid regions, and has been cultivated for thousands of years for food and medicinal purposes [4]. The crop later spread to Europe, Africa, and other parts of the world through trade and human migration due to its wide adaptability and multiple uses.

Garlic is highly valued as a spice and flavoring agent because of its characteristic pungent aroma and taste [5]. The pungency of garlic is mainly attributed to sulfur-containing compounds, especially allicin, which is formed when garlic cloves are crushed or cut. This reaction occurs through the action of the enzyme alliinase on alliin compounds present in the cloves [6]. In addition to its culinary importance, garlic possesses numerous medicinal properties. Scientific studies have confirmed that garlic contains bioactive compounds with antibacterial, antifungal, antiviral, antioxidant, and anti-inflammatory activities [7]. Consumption of garlic has also been associated with reduced blood cholesterol, improved cardiovascular health, blood pressure regulation, and enhancement of the immune system [8]. In Ethiopia, garlic is commonly used in traditional dishes such as “wot” and is also utilized in traditional medicine for treating various human ailments [9].

Globally, garlic production has increased significantly over recent decades due to rising demand for domestic consumption, food processing industries, and pharmaceutical uses [10]. China is the leading producer of garlic, contributing more than two-thirds of global production, followed by countries such as India, Bangladesh, Egypt, and Russia [11]. In Africa, Ethiopia is one of the major garlic-producing countries, where the crop plays an important role in household income generation, food security, and market supply [12]. The expansion of urban markets and increased awareness of the health benefits of garlic have further stimulated production in different parts of the country [13].

Despite the increasing production area, the productivity of garlic in Ethiopia remains far below the world average [14]. Several factors contribute to this low productivity, including the use of low-yielding local varieties, poor crop management practices, inadequate fertilizer application, limited irrigation facilities, and severe pest and disease infestations [15]. Among these constraints, diseases caused by fungal pathogens are among the major production challenges limiting garlic yield and quality [16].

Garlic rust caused by Puccinia allii is one of the most destructive fungal diseases affecting garlic production worldwide [17]. The disease is characterized by orange to brown pustules on leaves, which reduce photosynthetic efficiency, accelerate leaf senescence, and ultimately decrease bulb yield and quality [18]. Under favorable environmental conditions such as high humidity and moderate temperatures, garlic rust spreads rapidly and may cause severe epidemics [19]. Previous studies reported that yield losses due to garlic rust range from 25% to 60%, while complete crop failure may occur under severe infection conditions [20]. In Ethiopia, garlic rust has become a major production constraint in major garlic-growing areas, causing substantial yield reduction and economic losses to farmers [21].

Effective management of garlic rust requires the integration of appropriate agronomic practices and fungicide application strategies. Plant spacing influences crop microclimate, air circulation, and disease development, while fungicides help suppress pathogen infection and disease spread [22]. However, information on the combined effects of intra-row spacing and fungicide application on garlic rust management under the agro-ecological conditions of South Ari District is limited.

Therefore, this study was conducted to evaluate the effects of intra-row spacing and fungicide application on garlic rust development, yield components, and bulb yield of garlic, and to identify economically viable management options for garlic production in the study area.

Materials And Methods

Description of the Experimental Site

The field experiment was conducted during the main cropping season from June to October 2021 in South Ari District, South Omo Zone, Southern Ethiopia. The study area is located in a highland agro-ecological zone that is well known for vegetable production, particularly garlic cultivation. The altitude of the district ranges from approximately 540 to 3,350 meters above sea level. The area receives a mean annual rainfall ranging from 1,190 to 1,450 mm, while the average annual temperature varies between 19°C and 21°C. The dominant soil type of the experimental site is clay loam soil, which is considered suitable for garlic production due to its good moisture-holding capacity and fertility status. Climatic and soil-related information of the study area was obtained from the South Ari District Agricultural Office.

Experimental Materials and Treatments

The experiment was conducted under rain-fed conditions using a factorial arrangement of intra-row spacing and fungicide treatments. Three intra-row spacings (7 cm, 10 cm, and 13 cm between plants) were combined with four fungicides: Nativo (trifloxystrobin 100 g L^{-1} + tebuconazole 200 g L^{-1}), Natura (epoxiconazole + thiophanate-methyl), Tilt (propiconazole), and Ridomil (metalaxyl). In addition, an untreated control (without fungicide application) was included at each spacing level. Accordingly, a total of fifteen treatment combinations were evaluated. Local garlic planting material obtained from farmers in the study area was used as the experimental material. The inter-row spacing was uniformly maintained at 30 cm across all treatments.

Experimental Design and Field Management

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Each experimental plot measured 1.5 m × 2 m and consisted of five rows. The inter-row spacing was maintained at 30 cm, while the intra-row spacing varied according to the treatments (7 cm, 10 cm, and 13 cm). The spacing between adjacent plots and replications was maintained at 1 m and 1.5 m, respectively, to reduce border effects and minimize treatment interference.

All recommended agronomic and crop management practices were applied uniformly to all experimental plots throughout the growing season. Fertilizer was applied in the form of NPS (38:19:7) and urea (46% N) at the rates of 242 kg ha^{-1} and 150 kg ha^{-1}, respectively. The entire amount of NPS fertilizer was applied at planting, whereas urea was applied in two equal splits: half at planting and the remaining half three weeks after planting. Other field management practices, including weeding, cultivation, and disease monitoring, were carried out as required to ensure proper crop growth and development.

Data Collection

Data on disease parameters, growth characteristics, yield components, and yield were collected from the central rows of each experimental plot to minimize border effects. Disease assessment was conducted at seven-day intervals starting from the first appearance of garlic rust symptoms until physiological maturity of the crop. Disease incidence was recorded as the percentage of infected plants per plot, while disease severity was assessed using a standard disease rating scale and converted into percent severity index (PSI). The area under disease progress curve (AUDPC) was calculated from successive severity assessments to determine disease development over time.

Agronomic data were also collected during the experiment. Plant height (cm) was measured from the ground level to the tip of the pseudo-stem at maturity from ten randomly selected plants in each plot, and the average value was recorded. Bulb weight (gm) was determined from ten randomly selected bulbs collected from each plot after curing using a sensitive balance. Bulb diameter (mm) was measured using a digital caliper from five randomly selected bulbs after curing, and the average value was recorded.

Total bulb yield (t ha^{-1}): was obtained by harvesting bulbs from the net plot area after curing and converting the yield into tons per hectare.

Marketable bulb yield (kg ha^{-1}):- included bulbs that were free from disease, insect pest damage, and mechanical injury, and were uniform in color and acceptable in size. The weight of marketable bulbs from each plot was measured and converted into kilograms per hectare.

Unmarketable bulb yield (kg ha^{-1}) :-consisted of bulbs that were undersized, diseased, decayed, mechanically damaged, or deformed. These bulbs were separated through visual inspection, and their weight was recorded independently.

Yield loss was estimated based on the reduction in yield compared with the protected treatment using the following formula:

Yield loss was estimated based on the following formula .

YL = [(YP- YT)/YP] x 100

Where, YL = percent of yield loss,

YP = yield from the sprayed treatment;

YT = yield obtained from un-sprayed control plot.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using appropriate statistical software for a factorial experiment under RCBD. Mean separation was performed using the least significant difference (LSD) test at a 5% level of significance.

Results And Discission

Garlic Rust Onset and Intensity

Garlic rust symptoms were first observed at 87 days after planting (DAP), and disease assessment was initiated at 90 DAP. The disease appeared uniformly across all experimental plots, indicating that the initial inoculum was well distributed under field conditions. Analysis of variance revealed that intra-row spacing and fungicide application had highly significant ($P \leq 0.01$) effects on garlic rust severity and disease progression throughout the assessment period. Variations in disease intensity among treatments indicated that plant spacing and fungicide application played important roles in influencing disease development under field conditions.

Differences in plant density and canopy structure among spacing treatments likely created variations in microclimatic conditions such as relative humidity, air movement, and leaf wetness duration, which favored or suppressed disease development. Closer plant spacing increased canopy congestion, reduced air circulation, and maintained higher humidity within the crop stand, thereby enhancing the development and spread of garlic rust. In contrast, wider spacing improved ventilation and reduced moisture accumulation on leaf surfaces, which contributed to lower disease severity. Similar findings were reported by [21], who stated that narrow spacing increases rust severity because of favorable environmental conditions for pathogen multiplication and transmission between plants.

The interaction effects of spacing and fungicide treatments on garlic rust severity were highly significant ($P < 0.01$) at all assessment dates except the initial observation at 90 DAP (Table 1). Considerable variation in disease severity was observed among the treatments throughout the growing season. At 90 DAP, the highest percentage severity index (PSI) of 67.00% was recorded from the untreated control plots, while the lowest PSI (25.33%) was obtained from plots planted at 13 cm intra-row spacing and treated with Nativo fungicide. Disease severity progressively increased over time in all treatments; however, the rate of increase was considerably lower in plots treated with fungicides and wider spacing. At the final assessment date (125 DAP), the untreated control plots recorded the highest PSI value (82.00%), indicating severe disease development in the absence of fungicide protection. In contrast, plots planted at 13 cm spacing and treated with Ridomil fungicide recorded the lowest PSI value (24.33%), followed by plots treated with 10 cm spacing combined with Ridomil application (28.33%). Similarly, plots treated with Nativo fungicide under wider spacing also showed lower disease severity compared with narrow spacing treatments and untreated plots. These results demonstrate that integrating wider intra-row spacing with effective fungicide application can substantially reduce garlic rust intensity under field conditions.

Overall, the findings of the study indicated that wider plant spacing combined with fungicide application effectively suppressed garlic rust development and minimized disease severity. Ridomil and Nativo fungicides were found to be the most effective treatments for managing garlic rust under the agro-ecological conditions of South Ari District. The present findings are in agreement with the report of [22], who observed significantly reduced disease severity in Ridomil-treated garlic plots compared with untreated control plots.

Treatment		**Percentage severities index (PSI)**					
Spacing	**Fungicide**	**90 DAP**	**97 DAP**	**104 DAP**	**111 DAP**	**118 DAP**	**125 DAP**
7	Nativo	39.00^{cd*}	42.33^{cd}	46.33^{bc}	50.33^{bc}	53.33^{bc}	56.66^{bc}
7	Natura	42.33^{bc}	48.00^{bc}	50.00^{b}	54.66^{b}	57.00^{b}	62.00^{b}
7	Tilt	43.00^{bc}	41.66^{cd}	44.66^{bcd}	47.33^{cd}	53.33^{bc}	54.00^{cd}
7	Ridomil	47.00^{b}	49.33^{b}	51.33^{b}	55.00^{b}	58.66^{b}	61.33^{b}
10	Nativo	33.00^{d}	34.33^{ef}	39.00^{cd}	41.66^{de}	44.33^{d}	48.00^{de}
10	Natura	34.33^{d}	35.33^{de}	38.00^{d}	41.00^{e}	44.00^{d}	46.00^{e}
10	Tilt	36.00^{d}	38.33^{de}	38.66^{cd}	43.66^{de}	45.66^{d}	49.33^{de}
10	Ridomil	35.33^{d}	36.33^{de}	41.00^{cd}	45.33^{cde}	47.66^{cd}	28.33^{g}
13	Nativo	25.33^{e}	28.33^{f}	30.33^{e}	33.66^{f}	36.33^{de}	38.66^{f}
13	Natura	35.00^{d}	36.00^{de}	44.66^{bcd}	45.66^{cde}	46.33^{cd}	47.33^{de}
13	Tilt	33.00^{d}	35.33^{de}	38.00^{d}	41.66^{de}	44.00^{d}	46.00^{e}
13	Ridomil	32.33^{d}	36.33^{de}	37.00^{de}	41.00^{e}	42.33^{de}	24.33^{g}
Control	Unsprayed	67.00^{a}	69.00^{a}	73.33^{a}	76.00^{a}	79.00^{a}	82.00^{a}
	Mean	38.66	40.82	44.02	47.46	50.15	49.53
	LSD (5%)	5.99	6.14	6.97	5.49	6.54	6.94
	CV (%)	9.19	8.93	9.4	6.87	7.74	8.32

* Means followed by the same letter(s) with in columns are not significantly different at 5% level of significance; CV (%): Coefficient of variation; LSD: list significant differences at 5% level of significance; PSI: percentage severity index; DAP: Day after planting.

Table 1. Garlic rust severity index (PSI) at different days after planting under fungicide application.

Effect of Intra-row Spacing and Fungicide Application on Garlic Rust Severity Over Time

The progression of garlic rust severity over time under different intra-row spacings and fungicide applications is presented in Figure 1. The result clearly shows that disease severity increased gradually with crop age across all treatments from 90 to 125 days after planting (DAP), indicating continuous disease development under field conditions.

Among the treatments, the 7 cm intra-row spacing consistently recorded the highest percentage severity index (PSI) across all assessment dates, particularly in the untreated control plots. This suggests that closer plant spacing creates a favorable microclimate characterized by high humidity and reduced air circulation, which enhances disease development and spread.

In contrast, the 13 cm intra-row spacing combined with fungicide application, particularly Ridomil, consistently showed the lowest disease severity throughout the assessment period. This reduction in disease intensity may be attributed to improved air movement within the canopy and reduced leaf wetness duration, as well as the protective effect of systemic fungicides.

The 10 cm spacing showed intermediate disease levels between the two extremes, indicating a moderate effect of plant density on disease development. Across all spacings, Ridomil-treated plots showed better disease suppression compared to Nativo, Tilt, and Natura, confirming its superior effectiveness against garlic rust.

Overall, Figure 1 demonstrates that both intra-row spacing and fungicide application significantly influence the temporal development of garlic rust, with wider spacing and Ridomil application providing the most effective disease management strategy under field conditions

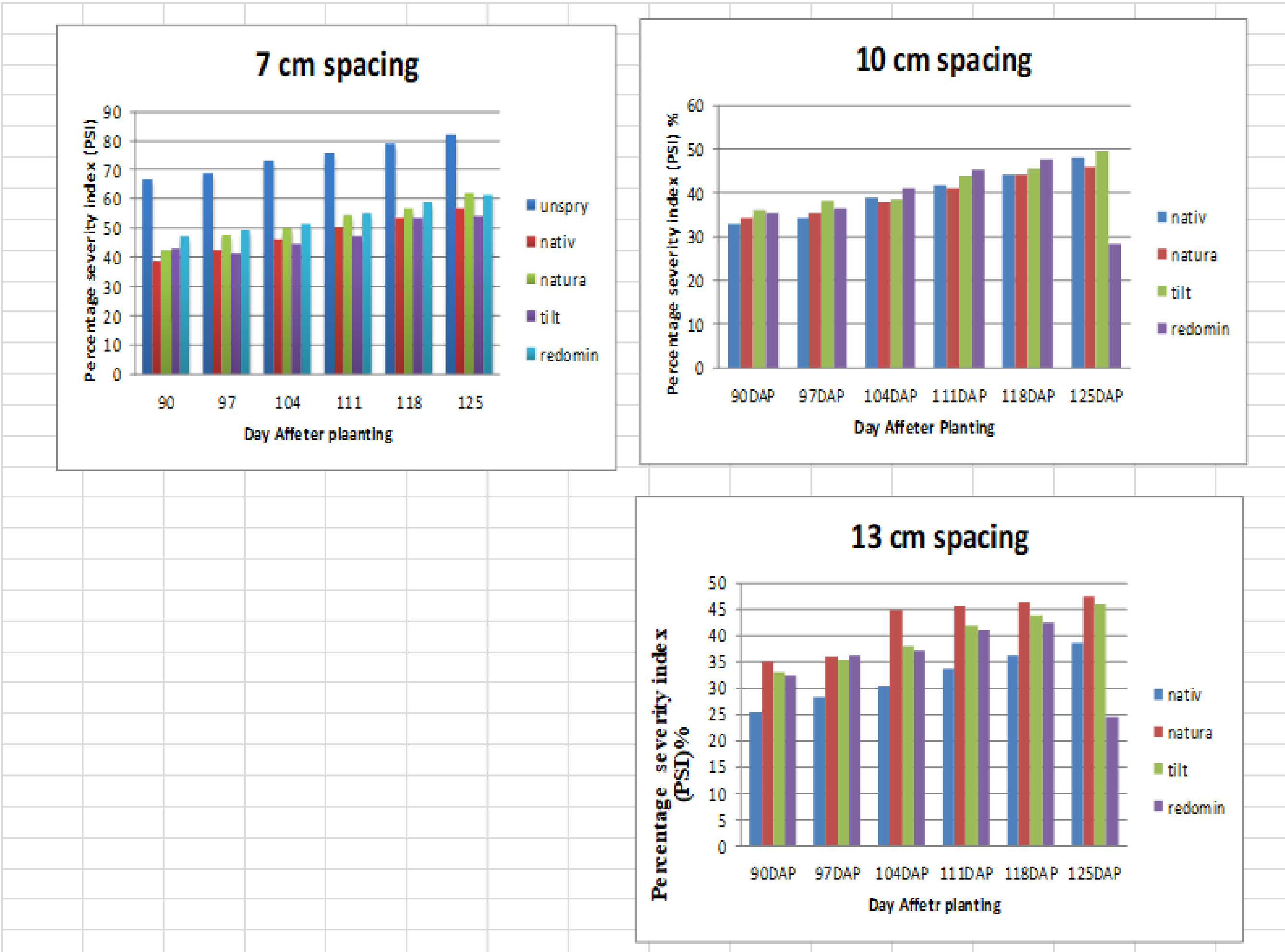

Figure 1. Garlic rust severity index (PSI) at different days after planting under fungicide application.

Area Under Disease Progress Curve (AUDPC)

The area under disease progress curve (AUDPC) is a widely used epidemiological parameter that integrates multiple disease severity observations over time into a single quantitative value. It provides a reliable estimate of disease development and is commonly used to assess levels of quantitative disease resistance by summarizing both the intensity and progression of disease over the growing period.

In the present study, the analysis of variance revealed highly significant differences ($P < 0.01$) among treatments for AUDPC values (Table 2), indicating that plant spacing and fungicide application had a strong influence on the temporal development of garlic rust. The lowest AUDPC values were recorded in garlic plants spaced at 13 cm and sprayed with Nativo and Ridomil fungicides (739.67 and 891.33, respectively) applied at 7-day intervals. These treatments significantly ($P < 0.05$) educed disease development compared with closer spacing treatments, other fungicide applications, and the unsprayed control plots.

The reduction in AUDPC under wider spacing (13 cm) may be attributed to improved canopy architecture, which enhances air circulation, reduces leaf wetness duration, and creates less favorable microclimatic conditions for rust development. Similarly, the effectiveness of systemic and protectant fungicides such as Nativo and Ridomil likely contributed to suppression of spore germination and reduced infection efficiency, thereby slowing disease progression over time.

Although all fungicide-treated plots showed lower AUDPC values compared with the untreated control (1692.00), the differences between Nativo and Ridomil were not statistically significant, suggesting comparable efficacy of these fungicides in managing garlic rust under the experimental conditions. Similar findings have been reported in previous studies, where integrated management practices combining optimal plant spacing and fungicide application effectively reduced AUDPC and improved disease control

Spacing	Fungicide	AUDPC	Incidence (%)
7	Nativo	1102.83^{bcd*}	60.00^{b}
7	Natura	1202.83^{bc}	50.00^{bc}
7	Tilt	1073.50^{cd}	60.00^{b}
7	Ridomil	1226.17^{b}	46.66^{bcd}
10	Nativo	918.00^{e}	36.66^{cde}
10	Natura	907.83^{e}	43.33^{cde}
10	Tilt	957.17^{de}	46.66^{bcd}
10	Ridomil	974.50^{de}	30.00^{e}
13	Nativo	739.67^{f}	16.66^{f}
13	Natura	977.67^{de}	33.33^{de}
13	Tilt	909.50^{e}	43.33^{cde}
13	Ridomil	891.33^{e}	13.33^{f}
Control	Unsprayed	1692.00^{a}	90.00^{a}
Mean		1044.077	43.846
LSD (5%)		133.4	13.27
CV (5)		7.58	17.95

* Means followed by the same letter(s) with in columns are not significantly different at 5% level of significance; CV (%): Coefficient of variation; LSD: list significant differences at 5% level of significance; AUDPC: Area under disease progress curve

Table 2. Effect of spacing and fungicide application on garlic rust incidence and AUDPC (2021/22).

Agronomic Data

Plant height (cm)

As revealed by analysis of variance (ANOVA), the main effect of plant spacing was highly significant ($P < 0.01$) for garlic plant height. However, fungicide application and its interaction with plant spacing were not significant. The result showed that plant height decreased with increasing plant spacing (Table 3). The increase in plant height at closer spacing (higher plant population density) might be attributed to competition for light, particularly in broadcasted or closely spaced plots. Under high plant density, plants tend to elongate in response to shading, resulting in taller plants. In contrast, wider spacing reduces competition for light, nutrients, and other growth resources, allowing plants to grow under less stress, which may result in comparatively shorter but more robust plants. These findings are consistent with previous reports on garlic where plant spacing significantly influenced plant height due to variation in inter-plant competition for growth resources [16, 17].

Treatments	Plant height (cm)
Plant spacing (cm)	
7	39.87^{b}
10	38.74^{b}
13	36.61^{c}
Control	43.20^{a}
LSD (5%)	1.18
Fungicide	
Nativo	39.57
Natura	37.92
Tilt	38.56
Ridomil	39.05
Unsprayed	38.77
LSD (5%)	NS
CV (%)	3.6

Where, LSD (5%) = Least significant difference at 5% level of significance; CV= Coefficient of variation; NS= non-significant; Means followed by the same letter(s) with in columns are not significantly different at 5% level of significance

Table 3. Effects of spacing and fungicide application on onion plant height (cm).

Bulb diameter (mm)

Analysis of variance revealed that garlic bulb diameter was highly significantly ($P < 0.01$) influenced by the main effects of the treatments. In addition, the interaction between fungicide application and plant spacing was significant ($P < 0.05$). The highest bulb diameter (16.00 mm) was recorded from Ridomil-treated plots at 13 cm spacing, which was statistically at par with Nativo application at the same spacing. In contrast, the minimum bulb diameter (9.14 mm) was obtained from the unsprayed control plots (Table 4).

The increase in bulb diameter under wider spacing combined with Ridomil application may be attributed to reduced disease pressure and improved availability of growth resources such as nutrients, moisture, and sunlight. Wider spacing reduces inter-plant competition, while effective fungicide application suppresses garlic rust severity, thereby enhancing assimilate accumulation and bulb development.

Conversely, the lower bulb diameter observed in unsprayed and closely spaced plots may be due to intense competition for growth resources and higher disease severity, which collectively reduced photosynthetic efficiency and assimilate partitioning to the bulbs. Therefore, the superior performance observed at 13 cm spacing combined with Ridomil application highlights the importance of integrated disease and spacing management for improved bulb development.

These findings are in agreement with previous reports, where wider spacing and fungicide application significantly increased bulb diameter [23]. Similarly, [14] reported a 16.33% reduction in bulb diameter in unsprayed plots compared to treated plots.

might resulted in high disease severity and, therefore, prominent to higher bulb diameter observed from 13 intra row spacing ridomil fungicide. The results in agreement with the finding of [29], who reported that wider plant spacing and fungicide application had significantly increased the bulb diameter. Similarly, [14] reported the highest relative reduction (16.33%) in bulb diameter in the unsprayed plots.

Bulb weight (g)

The results of analysis of variance revealed that both the main effects and the interaction between plant spacing and fungicide application had a highly significant ($P < 0.01$) effect on bulb weight of garlic. The maximum bulb weight per plant (176.3 g) was recorded from plots spaced at 13 cm and treated with Ridomil fungicide, whereas the minimum value (76.0 g) was obtained from broadcasted and unsprayed control plots (Table 4). On average, bulb weight per plant increased by 58.89% over broadcasted and untreated plots due to the combined effect of wider spacing and Ridomil application.

The increased bulb weight under 13 cm spacing combined with Ridomil fungicide application indicates that improved crop management enhanced vegetative growth, particularly leaf production, which likely increased photosynthetic activity and assimilate accumulation. This ultimately contributed to greater bulb development and weight. The superiority of these treatments may be attributed to reduced garlic rust severity, as wider spacing improves air circulation while fungicide application effectively suppresses disease development.Previously, similar findings were reported, where protected and widely spaced garlic plots significantly reduced rust epidemics and improved yield-contributing traits such as bulb weight [23]. On the other hand, the lowest bulb weight recorded in broadcasted and unsprayed plots may be due to intense competition for nutrients, moisture, and space, as well as higher disease pressure resulting from close plant proximity and efficient spore transmission. The present findings are consistent with Worku et al. (2018), who reported that severe garlic rust infection significantly reduces bulb yield and related traits [22]. In addition, similar studies reported that reducing plant spacing from 20 cm to 10 cm decreased garlic yield from 9176.7 to 5263.3 kg/ha [18]. Furthermore, earlier research indicated that severe disease outbreaks can reduce bulb weight by 25–60% depending on infection level and environmental conditions [24]

Trt	Spacing	Fungicide	BW (g)	BD (mm)	Yield (t ha-1)	RYL (%)
1	7	Nativo	96.00^{e}	10.87^{cd}	4.177^{fg}	49.99
2	7	Natura	110.00cd^{e}	10.24^{cd}	4.603^{ef}	39.97
3	7	Tilt	104.00d^{e}	9.93^{cd}	4.833d^{ef}	37.12
4	7	Ridomil	120.00b^{cd}	10.61^{cd}	5.330^{de}	33.19
5	10	Nativo	121.66^{bc}	12.14^{bc}	5.667^{cd}	26.28
6	10	Natura	111.00^{cde}	10.73^{cd}	5.277^{de}	31.30
7	10	Tilt	129.33^{b}	11.32b^{cd}	5.080^{de}	33.87
8	10	Ridomil	126.66^{bc}	13.30^{b}	6.267^{bc}	18.42
9	13	Nativo	133.66^{b}	15.88^{a}	6.927^{ab}	18.56
10	13	Natura	125.33^{bc}	11.92^{bc}	5.427^{cde}	29.40
11	13	Tilt	127.33^{bc}	11.53^{bcd}	5.377^{de}	30.08
12	13	Ridomil	176.33^{a}	16.00^{a}	7.687^{a}	0
13	Control	Un-sprayed	76.00^{f}	9.14d	3.363^{g}	55.01
		Mean	119.7^{9}	11.81	5.386	

	LSD	P<5%	15.66	2.112	0.876	
		CV%	7.8	10.6	9.7	

Note: Means followed by the same later are not significantly different CV%; coefficient of variation, LSD: list significant difference at 5%, PH; Plant height, BW; Bulb weight, BD: bulb diameter, (RYL): relative yield loss.

Table 4. Effects of intra-row spacing and fungicide application on growth and yield traits of garlic (2021/22).

Relative yield loss assessment (%)

Yield losses were computed relative to the average yield of plots with maximum protection against the disease, i.e., plots with 13 cm plant spacing and Ridomil fungicide application. Relatively, lower bulb yield losses were also obtained from plots sprayed with other fungicides such as Nativo, Natura, and Tilt combined with 13 cm spacing, as well as Ridomil application at 10 cm spacing (Table 4). However, total bulb yield losses were reduced by fungicide application and wider spacing compared with broadcasted and unsprayed control plots.

The highest relative bulb yield loss (55.1%) was recorded from broadcasted and unsprayed plots. This level of yield loss is lower than the 83% yield loss reported for garlic rust (Puccinia allii) in Nepal [24].and also lower than the 58.75% yield loss reported at Sinana, Ethiopia [25], but higher than the 50% yield loss reported in the USA [26]. These differences may be attributed to variation in environmental conditions, disease pressure, cultivar susceptibility, and effectiveness of management practices across locations.

Marketable and Unmarketable garlic bulb yield (Kg ha-1)

The result of analysis of variance indicated that main factors of plant spacing and different fungicide application and their interaction highly significantly (P<0.01) influenced the marketable yield of garlic plant. The highest mean marketable yield (225.33 kg ha-1) was produced with the combination of 13 cm intra-roe spacing and ridomil fungicide, while, the lowest value (66.67 kg ha-1) was recorded for the control (broadcasted) and unsprayed plots, which was at statistically par with 7 cm intra-row spacing and native fungicide application (Table 5).

The substantial marketable garlic bulb yield increase with 13 cm plant spacing and application of ridomil fungicide could be accounted for effective control of the spread and severity of the garlic rust disease and best field performance of the plant during the field experiment with respect to plant height, bulb weights and diameters. This is in line with the finding of [34] who stated that the proper spacing and application of systemic fungicides could suppress further uredospore proliferation, uredia expansion and enhance the marketable bulb yield in Ethiopia. On the other hand, marketable bulb yield of garlic was highly penalized in control (broadcasted) and unprotected (unsprayed) plots. This might be attributed to weighty infection and the contagious nature of the pathogen in unprotected check and closely spaced plots. Similarly, bulbs infected with garlic rust remain small and are of low storage quality [26].

The highest unmarketable bulb yield (80.33 kg ha^{-1}) was recorded from the control treatment (broadcast planting with no spacing) combined with unsprayed plots, whereas the lowest unmarketable bulb yield (30.33 kg ha^{-1}) was obtained from the combination of 13 cm intra-row spacing and Ridomil fungicide application (Table 5).

The higher unmarketable yield observed in the control (broadcasted) and unsprayed treatments compared to the 13 cm spaced and Ridomil-treated plots may be attributed to the rapid spread and higher severity of garlic rust disease under dense planting and absence of chemical protection. This heavy infection level likely contributed to increased production of small, deformed, and low-quality bulbs, thereby increasing unmarketable yield. Conversely, improved spacing combined with effective fungicide application reduced disease pressure and enhanced bulb development, leading to lower unmarketable yield.

Similarly, previous studies have reported that garlic rust significantly reduces bulb quality traits such as bulb weight, bulb size, number of cloves per bulb, and overall marketable yield, while increasing unmarketable yield [4]. In addition, closely spaced plants tend to produce smaller bulbs with poor storage quality when infected by rust disease[26] . Furthermore, rust pustules on infected plants reduce product quality and ultimately decrease market value of garlic[6].

Trt	Spacing	Fungicide	Marketable Yield (kg ha-1)	Unmarketable Yield (kg ha-1)
1	7	Nativo	90.33^{ef}	61.00^{b}
2	7	Natura	106.00^{de}	61.33^{b}
3	7	Tilt	97.67^{de}	55.33^{b}
4	7	Ridomil	112.33^{cde}	44.66^{c}
5	10	Nativo	103.67^{de}	40.66^{cd}
6	10	Natura	108.00^{de}	42.00c

7	10	Tilt	140.67bc	40.66cd
8	10	Ridomil	147.67b	43.33c
9	13	Nativo	145.67b	32.00de
10	13	Natura	116.33bcde	43.66c
11	13	Tilt	129.00bcd	39.33cd
12	13	Ridomil	225.33a	30.33e
13	Control	Unsprayed	66.67f	80.33a
		Mean	122.25	47.28
	LSD	P<5%	29.07	8.33
		CV%	14.10	10.5

Note: Means followed by the same later are not significantly different CV%; coefficient of variation, LSD: list significant difference at 5%

Table 5. Effects of spacing and fungicide application on marketable and unmarketable garlic bulb yield (kg ha^{-1}).

Conclusion

Garlic rust disease caused by Puccinia allii was found to be one of the major constraints affecting garlic production in the study area. The results of the experiment clearly showed that both intra-row spacing and fungicide application had significant effects on disease development, bulb yield, and yield-related traits of garlic. The untreated and broadcasted plots recorded the highest disease severity, incidence, and AUDPC values, indicating the serious impact of garlic rust when no proper management practices are applied.

Among the tested treatments, the combination of 13 cm intra-row spacing with Ridomil fungicide application gave the best performance in reducing garlic rust disease and improving yield. This treatment significantly lowered disease incidence, percent severity index (PSI), and AUDPC values compared with the untreated plots. In addition, it produced the highest bulb diameter, bulb weight per plant, total bulb yield, and marketable bulb yield, while reducing unmarketable yield. The findings suggest that wider spacing improves air circulation within the crop canopy, thereby reducing favorable conditions for disease development, while Ridomil fungicide effectively suppresses the rust pathogen.

Generally, the study confirmed that integrating proper plant spacing with effective fungicide application is an important strategy for managing garlic rust disease and increasing garlic productivity. Therefore, the use of 13 cm intra-row spacing together with Ridomil fungicide application can be considered as an effective management practice for garlic producers in Dell Kebele and areas with similar agro-ecological conditions.

Recommendation

Based on the findings of the study, the combination of 13 cm intra-row spacing and Ridomil fungicide application is recommended for effective management of garlic rust disease and improvement of garlic yield in the study area. Farmers should be encouraged to avoid overcrowded planting practices because narrow spacing increases humidity within the crop canopy and favors the development and spread of garlic rust disease. Agricultural extension workers and local agricultural offices should create awareness among farmers about the importance of proper spacing and timely fungicide application in garlic production. Training programs and demonstrations should also be organized to improve farmers' knowledge and skills regarding integrated garlic disease management practices. In addition, researchers are encouraged to conduct further studies using different garlic varieties, fungicide rates, and spraying frequencies under various agro-ecological conditions and across multiple growing seasons. Such studies would help to generate more reliable and comprehensive recommendations for sustainable garlic rust management and improved garlic production in Ethiopia.

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