Management of Rust (*Puccinia allii* R.) through Host Resistance and Alternate Application of Fungicides on Garlic (*Allium sativum* L.) in North Wollo, Ethiopia

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Abstract: Rust (*Puccinia allii* R.) is the major problem constraining garlic production in most areas of northern Ethiopia. Thus, this study was conducted during 2018 with the objectives to (1) evaluate the effects of integrated disease management through host resistance and alternate fungicide applications on rust epidemic and bulb yield; and (2) determine the economics of fungicide application in the management of garlic rust. Field experiments were conducted in Gidan and Lalibella districts of North Wollo, Ethiopia, using three garlic varieties, namely Chelenko-1, Tseday, and a local cultivar. Nativo and Tilt fungicides were sprayed with alternate and alone applications during the 2018 cropping season. Treatments were arranged factorially in a randomized complete block design with three replications. Analyses of variance revealed that interaction effects of Nativo, Tilt, and their alternate applications with Chelenko-1 and Tseday varieties showed the lowest disease severity, area under the disease progress curve, and disease progress rate as compared to the unsprayed plots of all varieties. In Lalibella, the variety Chelenko-1 showed significantly higher (9 t ha^{-1}) yield and, exhibited 28 and 21% yield advantages over Tseday variety and the local cultivar, respectively. However, there was no significant difference among the fungicides tested on bulb yield in both districts, but lower relative yield losses were recorded in response to application of Nativo and Tilt alone. The economic analysis also confirmed that sole application of Nativo on Local and Tilt on both Tseday and Chelenko-1 showed higher net profit and marginal rates of return than other treatment combinations. Thus, the fungicides Tilt and Nativo alone were relatively effective against garlic rust and economically profitable in Lalibela and related agro-ecologies for the variety Chelenko-1. However, there was no significant variation in garlic bulb yield of all varieties in Gidan, and the same fungicides with local garlic variety can be used for rust management and sustainable garlic production.

Keywords: AUDP; Bulb yield; DPR; Fungicides, Nativo; Severity, Tilt

1. Introduction

Garlic (*Allium sativum* L.) is the second most important *Allium* species next to onion (*Allium cepa* L.). It grows worldwide in all temperate to subtropical and mountainous tropical areas (Rabinowitch, 2002). Annual production and area coverage of garlic reached 26,573,001t and 1,468,811 ha, respectively, in the world (FAOSTAT, 2016). Ethiopia, which provides an annual bulb production of 138,664 t, is the 2nd most garlic producer next to Egypt in Africa and it ranked 13th in the world (FAOSTAT, 2016). However, Ethiopia accounts for lower production and productivity (9.18 t ha^{-1}) than the world's average production (CSA, 2018). In different parts of Ethiopia, production, productivity, and area coverage of the garlic crop are significantly different. In North Ethiopia, especially North Wollo, garlic is among the major bulb vegetable crops, which is cultivated mostly under irrigation conditions in all small-scale farming practices. Annual average production area and garlic productivity in North Wollo have been estimated with corresponding 347.82 ha and 6.9 t ha^{-1}, the yield of which is by far less than the national average (9.18 t ha^{-1}) yield (CSA, 2018).

In spite of its lower productivity from time to time due to numerous biotic threats, the demand behind garlic is very high due to its medicinal value and it is recognized in the treatment of hypertension, diabetes, bacterial and fungal diseases, cancer, rheumatism, ulcer and whooping cough (Ahmed *et al*., 2007). It is among the condiments and flavoring vegetable crops, which have numerous nutritional values. The production of dried and processed garlic products are also used for food preparation and as dietary health-food supplements (Diriba, 2016; Getu *et al*., 2017). Others, like vegetative propagation of garlic, allows the production of a uniform crop that preserves quality traits, flavor and the nutritive properties of the crop (Gebremedhin and Abrha, 2015).

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Various biotic and abiotic factors are the major bottleneck constraints for diminishing production and productivity of garlic in different agro-ecologies. Among the various challenges, biotic factors are the main contagious and infectious diseases, of which garlic rust (*Puccinia allii* R.), white rot (*Sclerotium cepivorum* B.), pink rot, mosaic virus and nematodes are the most widespread and destructive pathogens of cultivated garlic crops (Daniel *et al*., 2017). Garlic rust, that can pose a high epidemic within a short period, is the major constraint in garlic production areas in North Wollo and is able to spread a long distance for infection. Accumulation of the pathogen causes severe bulb yield reduction due to the high density and even distribution on the host plants (Flory and Clay, 2013). At higher epidemic level, garlic rust resulted in significant yield penalty in garlic production (CSCC, 2007). According to Shah *et al.* (2016), garlic rust is responsible for huge losses under favorable climatic conditions and the disease incidence ranges from 95.0 to 100%, whereas the disease severity can be greater than 65%. In this regard, Tadesse (2014) confirmed that 49% of bulb yield loss was due to severe infection of garlic rust. However, management options, such as the use of resistant/tolerant garlic varieties with supplementation of appropriate and compatible fungicides are recommended applicable management strategies for a long period production system of garlic crop (Malik *et al*., 2017). Although the application of fungicides alone against garlic rust is a common practice, the use of integrated management to subdue the disease through combination of various garlic varieties along with compatible systemic fungicides is a more effective means than sole fungicide application. Therefore, integrated management of garlic rust is the most efficient, environmentally sound and socially acceptable management strategy for sustainable garlic crop production and productivity.

So far, management of the disease under irrigation and main rainy season production systems in all small-scale farmers have not been done in Lalibella and Gidan Districts of North Wollo, northern Ethiopia. Hence, finding an effective integrated management tactic for this particular disease is a prerequisite. Therefore, the study was carried out with the objectives to (i) evaluate the effects of host resistance, alone and alternate application of the different fungicides on garlic rust epidemic and bulb yield; and (2) determine the economics of fungicide application in the management of garlic rust.

2. Materials and Methods

2.1. Overview of the Study Areas

A field experiment was conducted under irrigation schemes in Lalibella Zuria and Gidan districts of North Wollo, Amhara National Regional State of Ethiopia, during the 2018 cropping season. The sites where the experiments were conducted and their respective geographic locations are depicted in Figure 1. Lalibella and Gidan are located on an altitudinal ranges of 2000-2400 and 2500-2700 meters above sea level (m.a.s.l.), respectively. Data obtained from the National Meteorological Agency, Kombolcha Branch, indicated that the areas in Gidan and Lalibella Zuria received an average annual rainfall of 800 and 814.9 mm, respectively, with corresponding mean minimum and maximum temperature of 8 and 11 °C and 24 and 27 °C. The districts are mainly variable in their various agro-ecological features: mountainous landscape, groundwater potential, soil type, altitudinal ranges, cropping systems and typical humid/sub-humid weather conditions (National Meteorological Agency, Kombolcha Branch, 2018).

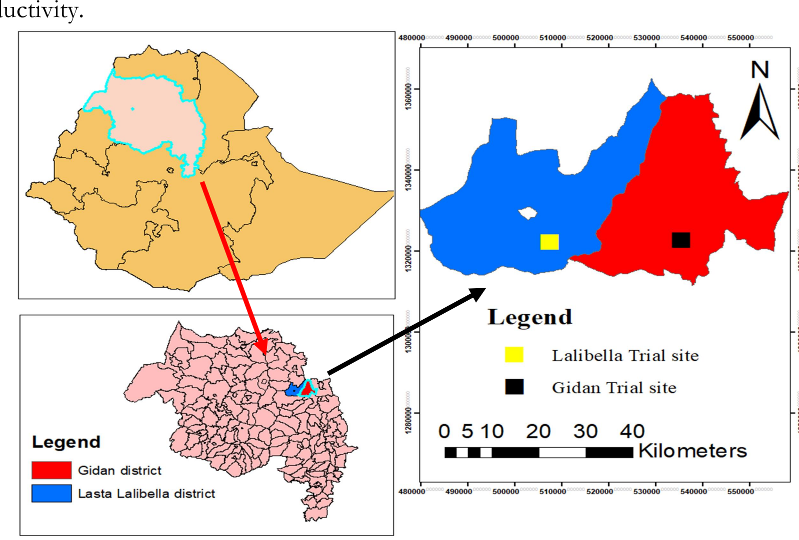

Figure 1. Map of the study areas showing field experimental sites in North Wollo, Ethiopia, during the 2018 cropping season.

2.2. Planting Materials and Fungicides

The experiment was carried out in hot spot areas of farmers' fields under irrigation conditions during the 2018 cropping season. Three garlic varieties, namely Chelenko-1 (obtained from Haramaya University) and Tseday (from Debre Zeit Agricultural Research Center) and one local control, all of which had different responses to garlic rust, were used as varietal components of the experiment. Brief descriptions are presented on the agronomic characteristics of the garlic varieties in Table 1. Additionally, two commercially available and registered foliar fungicides were used for the experiment at the dose of manufacturers' recommendations. These fungicides were Tilt (Propiconazole), Nativo 75 WG (Water Dispersible Granule of 250 g kg^{-1} Trifloxystrobin + 500 g kg^{-1} Tebuconazole) and alteration of Tilt and Nativo 75 WG, which were used alternatively or one after the other and alone. The detail descriptions of fungicides used are presented in Table 2.

2.3. Treatments, Experimental Design and Management Procedures

The experiments consisted of 15 treatment combinations (Table 3). A plot size of 2.5 m x 1.8 m area, and 0.3 m inter-rows and 0.1 m intra-plants spacing were used during the experiment. Plots and blocks were separated by 1.0 m and 1.5 m, respectively. There were five rows of garlic per plot and the plants were spaced at 0.25 m in each row. The central three rows were used as effective rows for data collection. The treatments were arranged in factorial experiment in a randomized complete block design (RCBD) with three replications. Planting was made at Gidan and Lalibella on 03 and 10 September 2018, respectively.

Applications of fungicides were done at 5:30 p.m. starting from the onset of the first typical symptom of the disease. Four times spray frequencies of fungicides were employed at seven-day interval as used by Worku (2017). Plastic sheets were used to shield from drift problems of fungicides among the plots and between the blocks. Garlic cloves were treated with Apron star prior to planting to prevent untargeted seedborne disease(s) as this fungicide is good for seed treatment and also effective for white rot disease management as suggested by Dilbo *et al.* (2015). Recommended fertilizers, including NPS and urea, were applied and urea was used in split applications where half of it was applied at planting and the remaining half was applied at 35 days after planting. Irrigation interval was set following farmers' practices and furrow irrigation method was employed. Other agronomic practices, like weeding, earthing up, removal of off-types and regular monitoring were done uniformly to each experimental plot as recommended for the crop in the areas

Table 1. Characteristic features of tested garlic varieties in Lalibella Zuria and Gidan districts of North Wollo, Ethiopia, during the 2018 cropping season.

Variety	Year of release	Altitudinal range (m.a.s.l.)	Days to maturity (day)	Soil type	Disease reaction	Yield (t ha^{-1})	Maintaining center/institute
Chelenko-1	2014	2000-2400	132	Black	Moderately susceptible	9.3	Haramaya University
Tseday	1999	1800-2500	133	Black	Moderately susceptible	8.13	Debre Zeit Agricultural Research Center
Local Material	--	--	--	--	Susceptible	--	--

Table 2. Descriptions of fungicides tested for their efficacies on garlic rust intensity in Lalibella Zuria and Gidan districts of North Wollo, Ethiopia, during the 2018 cropping season.

S/N	Trade name	Active ingredient	Nature (Mode of action)	Product formulation	Product rate (L ha^{-1})	Amount of diluting water (L ha^{-1})
1	Propiconazole (Tilt)	Triazole	Systemic, protective and curative	Emusifiable concentration (EC)/wettable powder (WP)	0.5 L	1000 L
2	Nativo 75 WG	Tebuconazole 50%+ Trifloxystrobin 25%	Systemic Broad-spectrum, protective and curative	Water dispersible granule (WG)	1.0 L	1000 L

Table 3. Treatments and respective treatment combinations of fungicides with varieties used in the experiments under irrigation condition in Gidan and Lalibella Zuria districts of North Wollo, Ethiopia, during 2018 cropping season.

S/N	Varieties	Fungicides	Treatment combinations
1	Chelenko-1	Tilt	Chelenko-1 + Tilt
2	Tseday	Nativo 75 WG	Chelenko-1 + Nativo
3	Local	Tilt + Nativo	Chelenko-1 + Tilt + Nativo
4	--	Nativo + Tilt	Chelenko-1 + Nativo + Tilt
5	--	Control	Chelenko-1 control
6			Tseday + Tilt
7			Tseday + Nativo
8			Tseday + Tilt + Nativo
9			Tseday + Nativo + Tilt
10			Tseday control
11			Local + Tilt
12			Local + Nativo
13			Local + Tilt + Nativo
14			Local + Nativo + Tilt
15			Local control

2.4. Disease Assessment

Garlic rust incidence and severity were assessed in a weekly basis. Disease incidence was determined by counting the number of plants that showed visible disease symptoms/signs of the total plants of three central rows per plot.

$$\text{Incidence (\%)} = \frac{\text{Number of infected plants}}{\text{Total number of plants visited}} \text{ X } 100$$

Disease severity was estimated as the percentage of infected leaf areas from the total leaf areas of sampled plants in the central three rows of garlic plants. It was assessed on 15 randomly pre-tagged plants at the central three rows of each plot. The disease severity was assessed six times using 0-5 scoring scale as suggested by Koike *et al.* (2001); where, 0 = non-infected, 1 = 1 to 10% infected leaves, 2 = 11 to 25% infected leaves, 3 = 26 to 50% infected leaves, 4 = 51 to 75% infected leaves, and 5 =76 to 100% infected leaves from the total areas coverage of each plant. The percentage severity index (PSI) was determined from the disease severity data following the procedure suggested by Wheeler (1969).

$$\text{PSI} = \frac{\text{Sum of numerical ratings}}{\text{Total number of plants scored x maximum score on scale}} \text{ X } 100$$

Area under disease progress curve (AUDPC): It was calculated from disease severity data following the formula suggested by Campbell and Madden (1990):

$$\text{AUDPC} = \sum_{i=1}^{n-1} \left(\frac{\text{Xi} + \text{Xi} + 1}{2}\right)(\text{ti} + 1 - \text{ti})$$

Where, X_i is the disease severity at the i^{th} assessment, ti is the time of the i^{th} assessment in days from the first assessment date and n is the total number of disease assessments. Thus, AUDPC summarizes the disease progress data in each treatment and it could be expressed in %-days.

2.5. Yield and Growth Parameters Assessment

Leaf number, leaf length, days to physiological maturity, plant height (cm), stand count at harvest, bulb diameter (mm), number of cloves/bulb, marketable and unmarketable yields (kg) were recorded from harvested plots in the field. Description of each parameter entry is presented as follows.

Leaf number: Number of alternative or sideway leaves from the base of the plant to the tip from the three central rows of 15 randomly taken plants per plot were considered and average leaf numbers of 15 sample plants in each plot were used for analysis.

Plant height (cm): Plant height was measured at physiological maturity stage from the harvestable rows of 15 randomly taken plants. Mean of 15 measured plants in each plot was used for statistical data analysis.

Stand count at harvest: Number of plants from the three central/harvestable rows per plot was counted at harvest for data analysis.

Days to physiological maturity (DM): Physiological maturity was determined by visual observation of plants in each plot. Hence, when the aerial plant parts were ready for harvest, that date was considered as the last date of recording for physiological maturity.

Bulb weight (g): Bulb weight was measured from the harvestable rows of 15 randomly taken plants. Individual bulb weight was measured through sensitive balance and average bulb weights of 15 bulbs per plot were used for final data analysis.

Bulb diameter (mm): Bulb diameter was measured from the three central/harvestable rows of 15 sample plants in each plot. After harvesting, each individual bulb diameter was measured via caliper and average bulb diameters from 15 plants were used in each plot for data analysis.

Cloves per bulb: Number of individual cloves was obtained from the harvested three central rows of each plot in individual bulbs of 15 sampled plants. Clove numbers were hatched manually and average clove numbers of 15 individual bulbs were used for analysis.

Total bulb yield (kg): Total bulb yield was measured from the middle three rows of each plot. From the three central rows, bulbs were harvested and later converted into tons per hectare (t ha^{-1}).

Marketable bulb yield (kg): The marketable bulb yield was obtained by deduction of the unmarketable yield from the total bulb yield per plot.

Unmarketable bulb yield (kg): Unmarketable bulbs were separated from the middle harvestable rows and weighed and these included disease-infected bulbs, like white rot, especially in Gidan district but since it occurred lately, it was not a serious problem. However, size and underweight were not the issue of unmarketable bulb yield in both locations.

2.6. Relative Yield Loss

Bulb yield loss is the reduction of crop yield due to garlic rust and it was measured as percentage of yield reduction from unsprayed (unprotected) plots compared with maximum chemical protected plot using the following formula:

$$\text{RYL}(\%) = \frac{Y1 - Y2}{Y1} X100$$

Where, RYL = relative yield loss (%), Y_1 = mean of the respective parameter on maximum protected plot, and Y_2 = mean of the respective parameter in other treatments and/or unprotected plot.

2.7. Data Analyses

Disease incidence, severity, AUDPC, growth parameters, yield and yield-related components were subjected to analysis of variance (ANOVA) using SAS version 9.0 (SAS, 2004) following the standard procedures of Gomez and Gomez (1984). Least significant difference (LSD) values were used to separate differences among the treatment means at 5% probability level. Relationships of disease severity, AUDPC, disease progress rate with yield and yield-related parameters were examined through Pearson correlation analysis.

Logistic [(y/1-y)] (Van der Plank, 1963) and Gompertz [–ln(-ln(y)] (Berger, 1981) epidemiological models were used for the goodness of fit in estimating of disease progression from each treatment. The goodness of fit of the models was determined based on the magnitude of the coefficient of determination (R^2) and residuals of standard error (SE) (Campbell and Madden, 1990). The Logistic model had higher values of the coefficient of determination (R^2) and the lower value of standard error than the Gompertz model. Thus, the data were better fitted to Logistic model and the transformed PSI data were regressed over time to determine the regression equation and the slope of the equation, which defines the rate parameter. The regression analysis was done using Minitab software (new version 17 for Window). The two locations were environmentally different because of heterogeneity of variance as tested by Bartlett's test and results of the F-test for most of the parameters were found highly significantly (Gomez and Gomez, 1984). Thus, the data collected from the two locations were not combined for the analyses.

2.8. Partial Budget Analysis

The price of garlic bulb yield per kilogram and total sale from one hectare and price of fungicides were considered for the cost and benefit analysis. The price of garlic bulb (Birr kg^{-1}) was obtained from the local market and a total sale from one hectare was computed. The use of additional input cost to earn marginal benefit in the experiment was analyzed using partial and marginal rate of return (MRR) as computed by considering the variable cost available for the respective treatments. The marginal rate of return measures the effect of additional capital invested on net returns using new managements compared with the previous practices (CIMMYT, 1988).

Adjusted yield (Adj.Y): The adjusted yield was the average yield adjusted downward by 10% to reflect the difference between experimental yield and farmers' yield. It was determined as Adj.Y. = Av.Y – (Av.Y*0.1); where, Av.Y = average bulb yield and Adj.Y = adjusted bulb yield.

MRR = ΔNI/ΔIC, where, MRR = marginal rate of returns, ΔNI = change in net income compared with control and ΔIC = change in input cost compared with control.

3. Results

3.1. Onset of Garlic Rust and its Incidence

Garlic rust first appeared at Gidan and Lalibella Zuria on 08 and 25 November 2018, i.e. 65 and 75 days after planting (DAP), respectively. Incidence of the disease, that was 100%, was equally distributed in all plants in each plot, and subsequent assessments were performed for six times at seven-day interval and the disease progress was relatively rapid in unsprayed plots.

3.1.1. Effect of garlic varieties, fungicides and their combinations on garlic rust development

Results obtained from the different garlic varieties/fungicide application alone and in alternation had significant impacts on garlic rust development. Even though the resistance level of each garlic variety was lower, garlic rust was highly influenced by the application of Tilt and Nativo fungicides alone, in combination and in alternation. Interaction effects of garlic variety x fungicide indicated that PSI at final assessment date, AUDPC and disease progress rate revealed a significant ($p \leq 0.05$) difference at both locations.

3.1.2. Disease severity

Analysis of variance revealed that there was an interaction effect of variety x fungicide for mean severity of garlic rust at final date of assessment and they showed significant ($p \leq 0.05$) difference in both Gidan and Lalibella districts. The maximum (95.3%) mean severity was obtained on the untreated plots of the local cultivar, and followed by untreated plots of Chelenko-1 and Tseday varieties, which exhibited similar results with mean severity of 90.1% at 114 DAP at Lalibella. But, lower and insignificant mean severity was observed on the other treatments on the last assessment date in the same location at Lalibella. Regarding Gidan, the highest (83.3%) mean garlic rust severity was recorded on the unsprayed plot of the local cultivar, followed by Chelenko-1 (75%) and Tseday (54.8%) at the last assessment date (104 DAP). With the same date of assessment, the lowest mean severity was recorded due to treatment with Nativo on plots of Chelenko-1 (5.8%) and Nativo + Tilt treated plots of Tseday (5.4%) varieties (Table 4).

3.1.4. Area under disease progress curve (AUDPC)

The interaction effects of garlic variety x fungicide application on AUDPC revealed significant ($p \leq 0.05$) difference among the evaluated treatments. The highest (2656.7 %-days) AUDPC value was recorded from untreated plots of all treatments at Lalibella (Table 4). Untreated plots of Tseday and Chelenko-1 varieties a non-significant difference; but, the treated Tseday variety with Tilt differed significantly ($p \leq 0.05$) from Nativo and Nativo + Tilt treated Chelenko-1 variety. The treated local cultivar with Nativo, Tilt and their alternate applications showed a significant ($p \leq 0.05$) difference from the treated Chelenko-1 and Tseday varieties and this had high AUDPC value. However, the fungicides Nativo, Tilt and their alternate applications on the local cultivar revealed non-significant ($p > 0.05$) difference among themselves. A similar phenomenon was depicted in Gidan on tested garlic varieties as well as the fungicides applied (Table 4).

Table 4. Interaction effect of variety x fungicide on garlic rust on final PSI and AUDPC at Lalibella Zuria and Gidan districts of North Wollo, Ethiopia, during the 2018 cropping season.

Variety	Fungicide	Lalibella [a]		Gidan [a]	
		PSI (f)	AUDPC	PSI(f)	AUDPC
Chelenko-1	Unsprayed	90.1[a]	2203.3[b]	75.71[a]	1718.8[a]
	Nativo	18.57[c]	698.3[e]	5.80[c]	543.4[bc]
	Nativo +Tilt	16.69[c]	727.7[e]	8.95[c]	648.4[bc]
	Tilt	18.56[c]	772.7[e]	12.14[c]	681.9[bc]
	Tilt + Nativo	16.66[c]	833.7[e]	20.0[c]	768.8[b]
Tseday	Unsprayed	90.09[a]	2295[b]	54.86[b]	1392.7[a]
	Nativo	18.09[c]	636[e]	6.43[c]	584.3[bc]
	Nativo +Tilt	19.33[c]	835[e]	5.43[c]	504.7[c]
	Tilt	19.05[c]	1038.8[d]	17.62[c]	779.0[b]
	Tilt + Nativo	18.19[c]	743.3[e]	7.33[c]	608.9[bc]
Local	Unsprayed	95.3[a]	2656.7[a]	83.33[a]	1754.8[a]
	Nativo	32.38[b]	1718.8[c]	7.14[c]	547.7[bc]
	Nativo +Tilt	33.81[b]	1835[c]	12.98[c]	802.7[b]
	Tilt	36.66[b]	1855[c]	17.14[c]	800.4[b]
	Tilt + Nativo	32.86[b]	1916[c]	8.52[c]	573.8[bc]
Means		37.00	1384	22.89	802.31
CV (%)		13.4	10.74	53.55	34.92
LSD (0.05)		8.10	246.14	20.44	467.14

Note: [a] *PSI (f) = final percentage severity index at 114 DAP and 104 DAP in Lalibella and Gidan, respectively, AUDPC = Area under disease progress curve. CV = Coefficient of variation, LSD = Least significant difference at 0.05 level of probability.*

3.1.5. Disease progress rate (DPR)

Regarding disease progress rate, garlic rust progressed highly when garlic varieties were left untreated as compared to the treated plots at Lalibella. The variety Chelenko-1 with no-fungicide application revealed a high (0.227 unit day^{-1}) disease progress rate as compared the other two varieties in Lalibella (Table 5). In addition, a very high (0.3321 unit day^{-1}) disease progress rate was recorded on unsprayed plot of the local cultivar even higher than the rate computed from the untreated plots of the varieties Chelenko-1 and Tseday at Lalibella. However, the integration of varieties with fungicide applications exhibited a significant effect on the disease progress rate (Table 5). In spite of lower disease pressure in Gidan than in Lalibella, the lowest disease progress rate was recorded on the treated Chelenko-1, Tseday and Local cultivar. Even negative recording was observed on the fungicides Nativo, Tilt, Nativo + Tilt, and Tilt + Nativo treated garlic varieties because most recordings at the fifth (97 DAP) and sixth (104 DAP) assessment dates as compared with early assessments were very low due to digressive phase of the disease epidemics (Table 5).

3.1.6. Disease progress curve (DPC)

At Lalibella experimental site, the disease progress in untreated control was alarmingly increased from first date of assessment (79 DAP) to fifth assessment (107 DAP), while it was declined and continued constantly from fifth to last date of assessment (114 DAP) (Figure 2). Similar situations were observed in Gidan experimental site, where the disease progress rate increased up to 90 DAP and then increased again during 97-104 DAP. However, the pattern of disease progress in sprayed treatments was initially accelerated (during 79-86 DAP) and then the disease constantly increased up to the fourth assessment date (100 DAP) in Lalibella district. In the final two assessments, disease progress became slow since first white flecked and small yellowish symptom of rust on the lower leaves became lost and the leaves recovered to normal due to weekly-based fungicide spray

Table 5. Disease progress rate (r) and parameter estimates of garlic rust under the different garlic varieties and fungicides applications in Lalibella and Gidan districts of North Wollo, Ethiopia, during the 2018 cropping season.

Variety	Fungicide	Lalibella				Gidan			
		Disease progress rate (unit day^{-1}) [a]	SE of rate [b]	SE of intercept [c]	R^2 (%)[d]	Disease progress rate (unit day^{-1}) [a]	SE of rate [b]	SE of intercept [c]	R^2 (%)[d]
Chelenko-1	Unsprayed	0.227	0.259	-10.540	98.7	0.078	0.294	-3.96	89.8
	Nativo	-0.016	0.410	0.160	42.1	-0.015	0.336	0.997	72.8
	Nativo + Tilt	-0.026	0.517	0.930	47.5	-0.001	0.212	1.38	93.4
	Tilt	-0.023	0.583	0.540	32.2	-0.005	0.210	0.258	77.6
	Tilt + Nativo	-0.025	0.598	1.190	43.3	0.013	0.281	-0.677	17.8
Tseday	Unsprayed	0.211	0.290	-10.370	98.4	0.068	0.198	-4.436	96.3
	Nativo	-0.020	0.503	0.740	41.1	-0.007	0.252	3.316	96.2
	Nativo + Tilt	0.025	0.394	0.372	53.1	-0.006	0.346	3.081	92.6
	Tilt	-0.010	0.687	0.470	17.5	0.011	0.252	-0.473	34.4
	Tilt + Nativo	0.025	0.774	2.220	50.9	-0.005	0.314	1.391	83.9
Local	Unsprayed	0.332	0.897	-13.970	93.0	0.091	0.206	-5.511	97.3
	Nativo	0.006	0.724	-1.110	6.9	-0.005	0.224	2.415	95.6
	Nativo + Tilt	0.009	0.579	-2.740	49.3	0.012	0.291	-0.060	50.6
	Tilt	0.013	0.617	-2.250	36.4	0.017	0.214	-0.955	9.3
	Tilt + Nativo	0.011	0.673	-2.640	41.2	0.004	0.184	0.378	87.6
Means		0.047	0.430	-2.460	50.110	0.016	0.250	-0.190	73.100
SD (±)		0.111	0.177	5.012	27.070	0.034	0.052	2.647	30.200

Note: [a] *Disease progress rate obtained from regression line of disease severity against time of disease assessment (days).* [b] *Standard error of disease progress rate.* [c] *standard error of parameter estimates.* [d] *coefficient of determination of the Logistic epidemiological model*

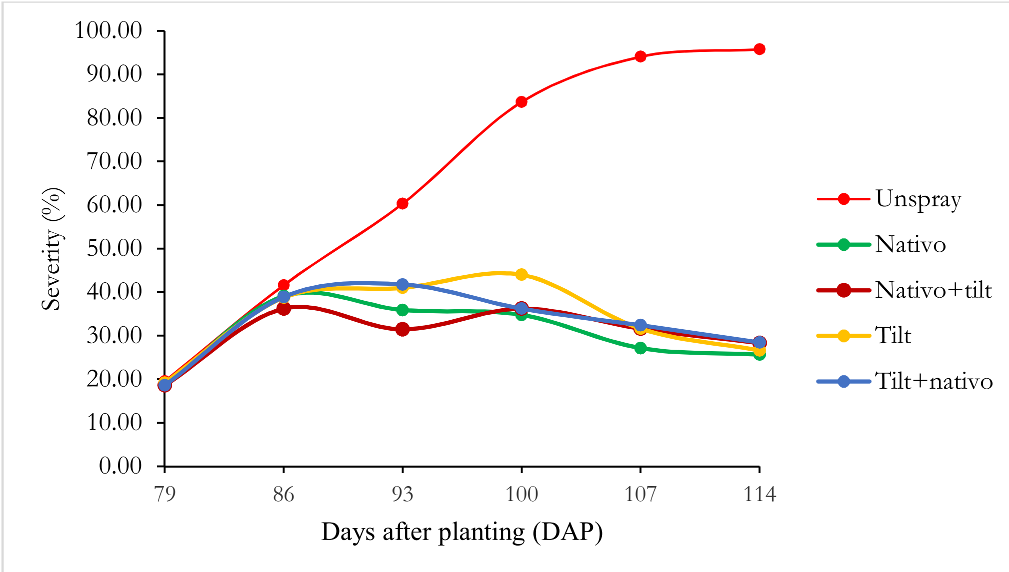

Figure 2. Garlic rust (*P. allii*) disease progress curves as influenced by alternate and alone application of the different fungicides and garlic varieties in Lalibella district, North Wollo, Ethiopia, during 2018 cropping season.

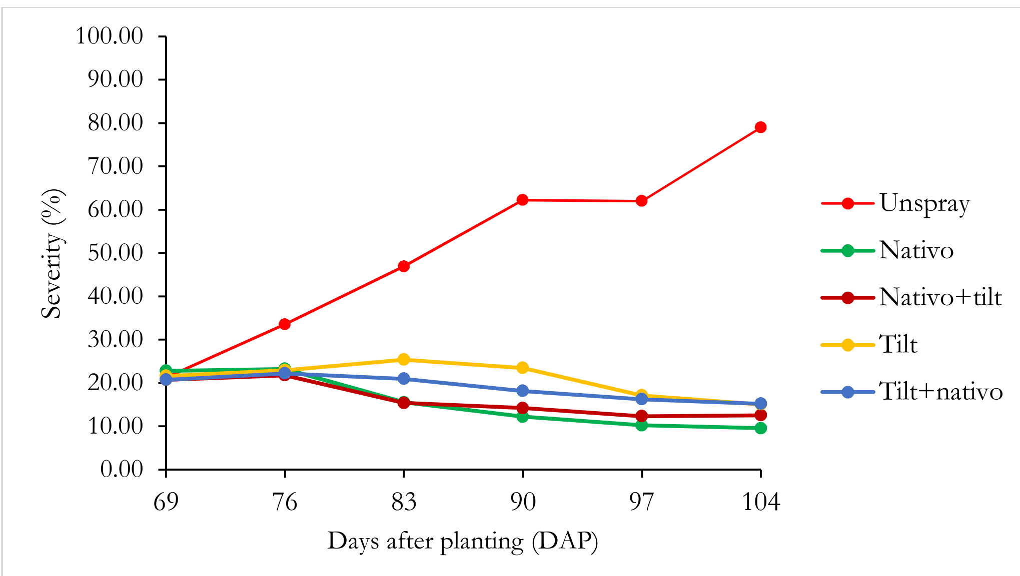

Figure 3. Garlic rust (*P.allii*) disease progress curves as influnced by alternate and alone application of fungicides and garlic varieties at Gidan district, North Wollo, Ethiopia, during 2018 cropping season.

3.2. Effect of Fungicides and Garlic Varieties on Growth, Yield and Yield-Related Components

In Lalibella, interaction effect of garlic variety x fungicide on plant height, maturity date, leaf number, number of cloves per bulb and marketable bulb yield revealed non-significant difference, while the parameters bulb diameter and bulb weight were significantly influenced by the interaction effect (Table 6). In Gidan district, variety x fungicide did not show any significant interaction effect on all measured parameters (Table 7). Thus, each individual parameter that did not reveal any interaction effect is presented separately for both locations.

3.2.1. Growth parameters

Results showed significant ($p \leq 0.05$) variation in days to physiological maturity of garlic varieties. The maximum (141.6 days) duration for maturity was recorded on the variety Chelenko-1 and it was later in maturing by 20 days than the local garlic variety. Tseday variety also exhibited delay in maturity by 15 days from the local one. But all tested unsprayed garlic varieties exhibited shorter days to maturity (127.7 days) than the sprayed treatments and this was significantly (p≤0.05) different from the treated Chelenko-1, Tseday and local cultivar. However, there was no statistical difference in days to maturity among the fungicides applied. A similar trend was observed in Gidan district in both protected and unsprayed plots of garlic varieties (Table 6).

Similarly, plant height and number of leaves per plant revealed significant (p≤0.05) differences among the tested garlic varieties in Lalibella. But, Tseday and the local cultivar were statistically on par with their plant heights. Regarding Gidan district, there was no significant (p>0.05) difference among garlic varieties on plant height and number of leaves. Additionally, insignificant difference was observed among the fungicides Nativo, Tilt and their alternate applications in both locations. However, statistically different and lower plant height and numbers of leaves were recorded on unsprayed treatments than the sprayed treatments in both Lalibella and Gidan districts.

3.2.2. Yield and yield-related parameters

In Lalibella, the least (12.1) number of cloves per bulb was recorded on local garlic variety and it was significantly (p≤0.05) different from both Chelenko-1(17.7) and Tseday (16.8) varieties. However, the two improved garlic varieties produced statistically similar number of cloves per bulb. Regarding marketable bulb yield, significant (p≤0.05) variation was recorded in bulb yield among the evaluated garlic varieties in Lalibella. The variety Chelenko-1 gave higher yield than the other two varieties, and it was 2 and 2.5 t ha^{-1} more yield than the local and Tseday garlic varieties, respectively, in Lalibella. But Tseday and local garlic varieties gave similar bulb yields and these were significantly not different from each other in Lalibella. The garlic varieties in combination with the fungicides produced comparatively higher bulb yield (8.02 t ha^{-1}) than the unsprayed plots of all garlic varieties (5.3 t ha^{-1}) despite the yields obtained in these fungicide applications were not significantly altered in Lalibella (Table 6).

Table 6. Effects of garlic varieties and fungicides on growth, yield and yield-related components of garlic at Lalibella district, North Wollo, Ethiopia, during the 2018 cropping season.

Treatment [a]	Maturity date (days)	Plant height (cm)	Leaf number per plant	Number of clove per bulb	Marketable bulb yield (t ha^{-1})
Variety					
Chelonko-1	141.6^{a}	56.7^{a}	7.4^{a}	17.7^{a}	9.0^{a}
Tseday	134.3^{b}	51.4^{b}	6.8^{b}	16.8^{a}	6.5^{b}
Local	120.2^{c}	48.4^{b}	6.2^{c}	12.1^{b}	7.1^{b}
Mean	132.0	52.2	6.8	15.5	7.5
LSD (0.05)	3.02	4.05	0.5	1.8	1.6
Fungicide					
Nativo	131.6^{ab}	51.8^{a}	7.5^{ab}	16.1^{ab}	8.8^{a}
Tilt	133.2^{a}	53.7^{a}	6.8^{b}	16.9^{a}	8.0^{a}
Nativo + Tilt	133^{a}	50.8^{a}	7.6^{a}	15.2^{ab}	7.8^{a}
Tilt + Nativo	134.6^{a}	51.6^{a}	7.4^{ab}	15.2^{ab}	7.5^{a}
Unsprayed	127.7^{b}	52.2a	4.7^{c}	14.2^{b}	5.3^{b}
Mean	132	52.2	6.8	15.5	7.5
CV (%)	3.1	10.4	11.1	15.7	28.8
LSD (0.05)	3.9	5.2	0.7	2.4	2.1

Note: [a] *LSD = Least significant difference at 0.05 probability level; and CV = Coefficient of variation.*

In Gidan, larger numbers of cloves were obtained on the treatment Nativo (17.1) and Tilt+Nativo (16.4) and significant difference was obtained compared to Tilt and the unsprayed treatments. Regarding marketable bulb yield, statistically insignificant variation was obtained in the three evaluated garlic varieties. Except Nativo-sprayed treatments that gave significantly higher bulb yield than Tilt-treated and unsprayed plots, the rest unsprayed, Tilt, Tilt+Nativo and vice versa treatments were on par with their marketable bulb yields (Table 7).

Table 7. Effect of different varieties and fungicides on growth, yield and yield related components of garlic at Gidan district, North Wollo, Ethiopia, during the 2018 cropping season.

Treatment [1]	Growth and yield parameter [2]							
	MD	PH(cm)	LNPP	BW (g)	BD(mm)	NC	MBY (t ha^{-1})	UNMBY(t ha^{-1})
Variety								
Chelonko-1	157.1^{a}	60.1^{a}	6.5^{a}	42.1^{a}	43.6^{b}	15.3^{ab}	5.2^{a}	0.04^{a}
Tseday	155.3^{b}	60.5^{a}	6.6^{a}	44.3^{a}	44.8^{ab}	16.6^{a}	5.0^{a}	0.05^{a}
Local	157.4^{a}	58.1^{a}	6.3^{a}	46.3^{a}	46.1^{a}	14.1^{b}	5.1^{a}	0.05^{a}
Mean	156.6	59.6	6.5	44.2	44.8	15.3	5.1	0.04
LSD (0.05)	0.7	2.9	0.4	4.2	1.8	1.3	1.5	0.02
Fungicide								
Nativo	157.4^{a}	60.8^{a}	7.3^{a}	50.1^{a}	46.2^{a}	17.1^{a}	7.2^{a}	0.05^{a}
Tilt	157.5^{a}	59.5^{a}	6.5^{b}	43.2^{b}	44.1^{ab}	14.6^{c}	5.4^{ab}	0.05^{a}
Nativo + Tilt	157.6^{a}	60.7^{a}	6.7^{b}	47.2^{ab}	46.1^{a}	14.8^{bc}	5.3^{ab}	0.04^{a}
Tilt + Nativo	157^{a}	61.6^{a}	6.3^{b}	43.6^{b}	45.3^{a}	16.4^{ab}	4.4^{b}	0.06^{a}
Unsprayed	153^{b}	55.2^{b}	5.6^{c}	37.2^{c}	42.5^{b}	13.9^{c}	3.6^{b}	0.06^{a}
Mean	156.6	59.6	6.5	44.3	44.8	15.4	5.2	0.05
CV (%)	0.60	6.5	8.6	12.9	5.6	11.4	38.7	63.8
LSD (0.05)	0.9	3.7	0.5	5.5	2.4	1.6	1.9	0.03

Note: [1] *LSD = Least significant difference and CV = Coefficient of variation.* [2] *MD = Maturity date, PH = Plant height (cm), LNPP = Leaf number per plant, BW = Bulb weight (g), BD = Bulb diameter (mm), NC = Number of cloves, MBY = Marketable bulb yield (t ha^{-1}); and UNMBY = Unmarketable bulb yield (t ha^{-1}).*

In Lalibella, the average bulb diameter was significantly influenced by the interaction effect of garlic variety x fungicide (Table 8). The highest (47.8 mm) mean bulb diameter was recorded on Chelenko-1 and local garlic varieties with Nativo fungicide application and this was significantly ($p \leq 0.05$) different from the unsprayed plot. Also, Nativo, Nativo+Tilt or Tilt+Nativo on the treated plot of Tseday variety was significantly lower in its bulb diameter than the maximum bulb diameter. Similarly, interaction effect of variety x fungicide application showed significant ($p \leq 0.05$) variation for the treatment of Chelenko-1 variety in combination with Nativo, Tilt, Nativo+Tilt and Tilt+Nativo fungicides applications on bulb weight in comparison of unsprayed plot of Chelenko-1 variety (Table 8). Unlike Lalibella, no significant interaction effect was observed on the mean bulb weight and bulb diameter in Gidan. But higher bulb weight was recorded on the garlic varieties sprayed with Nativo (50.1 g) and Nativo+Tilt (47.2 g) and these were significantly ($p \leq 0.05$) different from the unsprayed plots of all garlic varieties that exhibited lower (37.2 g) bulb weight (Table 8).

Table 8. Interaction effects of garlic variety x fungicide on bulb diameter and weight of garlic in Lalibella district, North Wollo, Ethiopia, during the 2018 cropping season.

Variety [1]	Fungicide	Bulb diameter (mm)	Bulb weight (g)
Chelenko-1	Unsprayed	32.6^{e}	22.5^{f}
	Nativo	47.8^{a}	56.0^{ab}
	Nativo +Tilt	44.6 $^{a-c}$	54.3^{a-d}
	Tilt	47.6^{a}	54.4 $^{a-c}$
	Tilt + Nativo	46.3^{ab}	60.2^{a}
Tseday	Unsprayed	37.1^{de}	29.6^{ef}
	Nativo	38.4^{de}	35.1^{d-f}
	Nativo + Tilt	40.8 $^{b-d}$	40.8^{b-f}
	Tilt	43.1^{a-d}	44.8^{a-e}
	Tilt + Nativo	40.8 $^{b-d}$	40.7^{b-f}
Local	Unsprayed	39.4^{cd}	36.4^{c-f}
	Nativo	47.8^{a}	56.2^{ab}
	Nativo + Tilt	45.4^{a-c}	45.6^{a-e}
	Tilt	43.2^{a-d}	44.0^{a-e}
	Tilt + Nativo	40.1 $^{b-d}$	39.1^{b-f}
Mean		42.35	43.8
LSD (0.05)		6.25	19.3
CV (%)		8.86	26.5

Note: [1] *CV = Coefficient of variation; and LSD = Least significant difference at 0.05 probability level.*

3.2.3. Association of disease parameters with growth, yield and yield-components of garlic

Association of disease progress rate and area under disease progress curve with growth, bulb yield and yield parameters were evaluated using correlation analysis. The area under disease progress curve was highly and negatively associated with all recorded growth, yield and yield-contributing parameters. Moreover, yield and area under disease progress curve were highly negatively and significantly ($p \le 0.001$) correlated ($r = -0.46^{**}$) to each other in Lalibella. On the other hand, disease progress rate was highly and negatively associated with the bulb yield ($r = -0.43^{**}$) and the most yield contributing parameters, bulb weight ($r = -0.48^{**}$) and bulb diameters ($r = -0.54^{**}$) in Lalibella (Table 9). Regarding Gidan, AUDPC and disease progress rate were highly negatively and significantly ($p \le 0.001$) associated with growth, yield and yield-components. However, unmarketable bulb yield was not significantly ($p > 0.05$) important with other yield parameters despite it was correlated negatively. The disease parameters, such as AUDPC with disease progress rate, were highly positively and significantly ($p \le 0.001$) correlated ($r = 0.91^{**}$) in Gidan (Table 10).

Table 9. Coefficient of correlation (r) between growth and yield and disease parameters in garlic in Lalibella district, North Wollo, Ethiopia, during the 2018 cropping season.

Parameter [a]	MD	PH	BD	BW	NC	MBY	AUDPC	DPR
MD	1.000							
PH	0.543**	1.000						
BD	0.1192	0.404*	1.000					
BW	0.2164	0.504**	0.903**	1.000				
NC	0.706**	0.542**	0.355*	0.504**	1.000			
TBY	0.2336	0.548**	0.797**	0.882**	0.494**	1.000		
AUDPC	-0.706**	-0.2620	-0.406*	-0.439*	-0.556*	-0.46**	1.000	
DPR	-0.382**	-0.0914	-0.54**	-0.48**	-0.302*	-0.43**	0.758**	1.000

Note: [a] *MD = Days to maturity (days), PH = Plant height (cm), BD = Bulb diameters (mm), BW = Bulb weight (g), NC = Number of cloves per bulb, MBY = bulb yield (t ha^{-1}), AUDPC = Area under disease progress curve (%-days) and DPR = Disease progress rate (unit day^{-1}). * = Significant at 0.05 and ** = Highly significant at 0.001 probability level.*

Table 10. Coefficient of correlation (r) between growth and yield and disease parameters in garlic in Gidan district, North Wollo, Ethiopia, during the 2018 cropping season.

Parameter [a]	MD	PH	BD	BW	NC	MBY	UNBY	AUDPC	DPR
MD	1.000								
PH	0.205	1.000							
BD	0.219	0.117	1.000						
BW	0.304*	0.274	0.83**	1.000					
NC	0.036	0.124	0.203	0.281*	1.000				
MBY	0.285	0.385*	0.412*	0.63**	0.312*	1.000			
UNMBY	-0.147	-0.264	-0.136	-0.138	-0.031	-0.317	1.000		
AUDPC	-0.646**	-0.54**	-0.373*	-0.470*	-0.259	-0.391	0.116	1.000	
DPR	-0.647**	-0.47**	-0.223	-0.373*	-0.318*	-0.393*	0.027	0.91**	1.000

Note: [a] *MD = Days to maturity (days), PH = Plant height (cm), BD = Bulb diameters (mm), BW = Bulb weight (g), NC = Number of cloves per bulb, MBY = Marketable bulb yield (t ha^{-1}), AUDPC = Area under disease progress curve (%-days) and DPR = Disease progress rate (unit day^{-1}). * = Significant at 0.05 and ** = Highly significant at 0.001 probability level.*

3.2.4. Relative yield loss assessment

Yield losses were computed relative to the average yield of plots with maximum protection against the disease, i.e. the plots treated with Nativo alone fungicide applications of garlic varieties in both locations. Among the sprayed treatments, Nativo alone fungicide applications gave nil/minimum bulb yield losses. Relatively, the lower bulb yield losses were also obtained from plots sprayed with Tilt alone on Tseday and Chelenko-1garlic varieties in both locations (Table 11). However, total bulb yield losses were reduced by the application of alternate and alone fungicide application compared to the unsprayed check plots. The highest (50.5%) relative bulb yield loss was obtained from unsprayed local cultivar that was higher by 5.1 and 11.9% from unsprayed Chelenko-1 and

Tseday garlic varieties, respectively, in Lalibella Zuria district. Similarly, maximum relative yield losses were calculated for the untreated Chelenko-1 (64.68%), Local (63.99%) and Tseday (63.71%) garlic varieties in Gidan district.

Table 11. Relative yield loss of garlic due to garlic rust (*P. allii*) as influenced by garlic variety and fungicide application in Lalibella and Gidan districts, North Wollo, Ethiopia, during the 2018 cropping season.

Variety	Fungicide	Lalibella [a]			Gidan [a]		
		Y (t ha^{-1})	RYL (%)	RYA (%)	Y (t ha^{-1})	RYL (%)	RYA (%)
Chelenko-1	Nativo	10.56	0.00	82.70	7.22	0.00	183.14
	Tilt + Nativo	9.78	7.38	69.20	4.33	40.03	69.80
	Tilt	9.44	10.66	63.32	6.78	6.09	165.88
	Nativo + Tilt	9.44	10.66	63.32	6.48	10.66	152.94
	Unsprayed	5.78	45.43	0.00	2.55	64.68	0.00
Tseday	Nativo	7.83	6.01	53.23	7.11	0.00	175.56
	Tilt + Nativo	7.34	11.88	43.64	4.44	37.55	72.09
	Tilt	8.33	0.00	63.01	5.44	23.49	110.85
	Nativo + Tilt	6.56	21.24	28.38	4.78	32.77	85.27
	Unsprayed	5.11	38.65	0.00	2.58	63.71	0.00
Local	Nativo	10.56	0.00	102.30	8.33	0.00	177.67
	Tilt + Nativo	5.67	46.30	8.62	4.44	46.70	48.00
	Tilt	6.44	39.01	23.37	5.11	38.66	70.33
	Nativo + Tilt	7.67	27.36	46.93	4.89	41.30	63.00
	Unsprayed	5.22	50.56	0.00	3.00	63.99	0.00

Note: [a] *Y = bulb yield (t ha^{-1}), RYL = relative yield loss in percentage and RYA = relative yield advantage in percentage.*

3.2.5. Cost and benefit analysis

The partial budget analysis was performed using net returns and marketable bulb yield was considered to compute the marginal rate of return (MRR). A significant variation was observed in net profit among the garlic varieties as well as the fungicides evaluated. The maximum marginal rate of return was obtained on the garlic varieties Chelenko-1 and Tseday in combination with Tilt fungicide alone and Local cultivar with Nativo alone. In case of alternate fungicide applications, higher marginal rate of return was noted than on unprotected plots. Especially treatment of Chelenko-1 and Local cultivar with Nativo+Tilt indicated higher marginal rate of return value than Tilt+Nativo and unsprayed plots (Table 12).

Table 12. Partial budget analysis for the garlic rust management through host resistance, and alone and alternate applications of fungicides in Lalibella and Gidan districts, North Wollo, Ethiopia, during the 2018 cropping season.

Variety	Fungicide	Adjusted yield (t ha^{-1})	Sale price (ETB kg^{-1})	Sale revenue (ETB)	Total input cost (ETB)	Net profit (ETB)	Marginal rate of return (%)
Chelenko	Nativo	8.001	40	320040	1680	318360	100.25
	Tilt + Nativo	6.3495	40	253980	1240	252740	82.90
	Tilt	7.299	40	291960	800	291160	176.525
	Nativo + Tilt	7.1505	40	286020	1240	284780	108.74
	Unsprayed	3.7485	40	149940	0	149940	0.00
Tseday	Nativo	6.723	40	268920	1680	267240	76.675
	Tilt + Nativo	5.301	40	212040	1240	210800	58.37
	Tilt	6.1965	40	227860	800	247060	135.8
	Nativo + Tilt	5.103	40	204120	1240	202880	51.98
	Unsprayed	3.4605	40	138420	0	138420	0.00
Local	Nativo	8.5005	40	340020	1680	338340	113.32
	Tilt + Nativo	4.5495	40	181980	1240	180740	26.43
	Tilt	5.1975	40	207900	800	207100	73.925
	Nativo + Tilt	5.652	40	226080	1240	224840	62.00
	Unsprayed	3.699	40	147960	0	147960	0.00

Note: *Mean unit of mean price of bulb per kilogram was $1.43 (at the current exchange rate of 1$ = 27.94 ETB) at the time of produce selling in 2018/19 cropping season.*

4. Discussion

The analysis of variance revealed that the fungicides applied on the different garlic varieties showed significant interaction effect that resulted in the lowest final severity of garlic rust in both Lalibella and Gidan districts. The fungicide-treated Chelenko-1 and Tseday varieties manifested very low final severity, which was less by 15% than the protected local cultivar. The low disease severity might be attributed to the fungicides Nativo and Tilt alone, which are the most effective systemic fungicides that interfere with and inhibit the growth and reproduction of the fungus. In this regard, the variety Chelenko-1 and Tseday might have a better response/resistance level to rust disease than the local cultivar. Bezu *et al.* (2014) stated that Chelenko-1 and Tseday garlic varieties revealed moderately susceptible to garlic rust in Ethiopia. However, the highest final severity of garlic rust was recorded from the plots of untreated local and both improved garlic varieties, which had a significant impact on bulb yield and yield-related components in both districts. The highest garlic rust severity in the untreated plots was attributed to undisturbed and continuous uredospore germination in that specific host ranges. This current finding is in agreement with the observation of Worku (2017) who reported that high (83%) garlic rust severity had been recorded in the untreated garlic crop in Ethiopia.

Interaction effect of garlic variety x fungicide significantly reduced the AUDPC values at both experimental locations. The maximum AUDPC value was recorded from the untreated local garlic variety, followed by Tseday and Chelenko-1 varieties in that order. This might have weakened and disfavored the disease progress by weekly fungicide sprays; consequently, the initial white flecked to small-yellowish disease symptoms became slightly normal and recovered at the end of disease assessment periods. Tadesse (2014) also confirmed that garlic rust epidemics were serious and higher on the untreated garlic crops than protected crops, and this revealed high AUDPC (2080%-days) value in Ethiopia. Integration of different garlic varieties and fungicide sprays lowered disease progress rates at both experimental sites. The highest disease progress rates were recorded due to heavy infection by garlic rust on all unprotected garlic varieties, while the garlic varieties treated with Nativo, Tilt and their alternate sprays resulted in minimum disease progress rates during the study. Thus, the fungicides Nativo and Tilt exhibited adverse and antagonistic effects on garlic rust physiology since they suppressed and prohibited further lesion expansions. Similarly, application of systemic fungicides consisting of Tebuconazole and Triazole active ingredients significantly reduces garlic rust and manages 100%, if the spray operation starts on the first onset or disease appearance (Gianessi and Reigner, 2005; Negash *et al.*, 2019). Other investigators also stated that epidemics and disease progress rate of garlic rust were highly inhibited due to proper and timely application of Tilt and Nativo fungicides in Ethiopia (Tadesse, 2014; Worku, 2017).

The disease progress curve was another descriptor of rust epidemics at both testing locations. A significant increase in rust epidemics resulted in unsprayed plots of all garlic varieties. However, the disease progress curves in the treated plots were almost constant and declined in the last two-assessment periods, especially in Lalibella. Thus, it was considered that constant and slow disease progress might be due to inhibition of epidemics and the digressive phase of the disease, which resulted in recovering and normal leaves in the treated-plots of all garlic varieties as compared to untreated plots in all assessment periods. These current findings also agree with the investigation of Kassaw *et al.* (2018) in eastern Amhara, Ethiopia. Negash *et al.* (2019) also reported in his findings from study undertaken in Ethiopia that garlic rust progress was enhanced in untreated-plots, while the curves in the treated-plots declined and negatively skewed.

Regarding yield components, significant variation in days to physiological maturity was obtained among garlic varieties and in different fungicide applications in both locations. It was recorded that the local garlic variety matured earlier than the varieties Chelenko-1 and Tseday in Lalibella. This might be due to the genetic nature of earliness of the variety and susceptibility to the garlic rust. That is why the most susceptible garlic variety enhanced to set bulbs early and to reach its physiological maturity to escape the disease. The current results also indicated that unsprayed plots of all garlic varieties were forced to maturity early since photosynthetic efficiency in infected leaves was reduced and this phenomenon, in turn, resulted in drying of leaves prematurely. Contrarily, the physiological maturity was extended in sprayed plots of all garlic varieties because the treated plants with fungicide remained green for a relatively longer time than the untreated plots; similarly, the undisturbed normal physiological activities might have resulted in increased garlic bulb yield. Negash *et al.* (2019) also found that fungicide-treated garlic plants were delayed in their days to physiological maturity, while untreated ones were obliged to mature early in Ethiopia.

Concerning bulb weight and diameter, an interaction effect was observed among varieties and fungicide applications in Lalibella but not in Gidan. High mean difference in bulb weight was observed between the most protected and unprotected plots of the variety Chelenko-1, implying that integration of variety with fungicide application inhibited maximum progression of garlic rust. On the other hand, garlic rust showed a significant negative impact on bulb weight reduction in unsprayed plots of all tested garlic varieties. The current investigation is in congruent with the finding of Mengesha *et al.* (2015) who reported that severe infection of garlic rust has high bulb penalty. Likewise, the protected Chelenko-1, Tseday and local garlic varieties due to spray with Nativo, Tilt and their alternate applications showed acceptable and maximum mean bulb diameter. This situation was due to the low and closely nil garlic rust severity in the fungicide-treated plots. Previously, Kassaw *et al.* (2018) also confirmed that protected garlic plots with fungicides inhibited rust epidemics and increased yield contributing parameters, such as bulb diameters and bulb weights, in Ethiopia.

The main effect of garlic varieties and fungicide applications showed a significant difference in marketable bulb yield, while their interaction effect revealed a non-significant difference. An average (9 t ha^{-1}) bulb yield of Chelenko-1 was significantly higher than the remaining garlic varieties. This could be accounted for its innate genetic potential being recently improved and have also best field performance during the field experiment with respect to plant height, number of leaves per plant, number of cloves per bulb, bulb weights and diameters, especially in Lalibella district. Reasonable garlic bulb yield was obtained on all the treated-plots since the alternate and alone fungicide applications could enhance growth parameters and suppressed disease progression at both testing locations. This is in line with the finding of Worku (2017) who stated that the application of systemic fungicides could suppress further uredospore proliferation, uredia expansion and enhance bulb yield in Ethiopia. On the other hand, marketable bulb yield of garlic was highly penalized in unprotected-plots of all garlic varieties. This might be attributed to weighty infection and the contagious nature of the pathogen in unprotected check plots.

Association of growth, yield and-related components with disease parameters revealed highly significant and negatively correlated at both experimental locations, implying that the observed level of the disease caused a considerable and adverse effects on bulb yield and yield contributing parameters on untreated plots. This current finding is in conformity with the observation of Kassaw *et al.* (2018) and Mengesha *et al.* (2015) who reported the negative relationship between garlic rust parameters with yield and yield-related components that, in turn, exhibited limited garlic bulb production.

The partial budget analysis also confirmed that application of Nativo and Tilt fungicides alone were the most cost effective and efficient towards garlic rust management option. Comparatively, maximum net benefit and marginal rate of return resulted from Tilt and Nativo fungicide applications in comparison with all other alternate and control fungicide applications in both districts. Hence, solely application of Tilt and Nativo for the management of garlic rust on the moderately resistant and susceptible varieties was the relatively more profitable and economically acceptable fungicides than other treatments.

5. Conclusions

Results revealed that maximum, i.e. 83 and 95.3%, severity indexes were observed when the garlic varieties were left unsprayed in Gidan and Lalibella, respectively. However, comparatively lower disease severity resulted from separate Tilt and Nativo alone fungicide applications in the two districts. On the other hand, the highest AUDPC and disease progress rates were calculated for unprotected plots for all garlic varieties under crosswise assessment. Consequently, greater bulb yield and yield-component reductions occurred in unprotected garlic crops due to garlic rust. However, the present investigation on three garlic varieties in integration with two kinds of fungicides provided the most important management options to fight against garlic rust. Thus, it was found that Tilt and Nativo fungicides were the most efficient and effective fungicides against garlic rust and these fungicides had the ability to suppress and inhibit rust epidemics at both experimental locations. The partial budget analysis also showed that treatment with Tilt alone accompanied by Nativo fungicide was the most economically efficient and effective management strategy against garlic rust. Lower total variable cost and higher net benefit were also obtained in all garlic varieties when sprayed with Tilt and Nativo fungicide alone.

Therefore, from the results of the present study, the application of Tilt and Nativo fungicide alone with improved Chelenko-1 garlic variety for the management of garlic rust was advisable and economically profitable in Lalibella and related agro-ecologies. However, since there was no significant variation in the bulb yield of all garlic varieties in Gidan district, the same fungicides in combination with local cultivar were found promising for garlic rust management in this specific area. Additional management strategies against garlic rust should be studied through host resistance integrated with cultural and agronomic practices, and cost-effective fungicides to provide alternatives for managing garlic rust and sustainable production and productivity.

6. Acknowledgements

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