SOIL & CROP SCIENCES | RESEARCH ARTICLE

Integrated management of ginger bacterial wilt (Ralstonia solanacearum) in Southwest Ethiopia

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Abstract: Bacterial wilt incited by Ralstonia solanacearum is the most important disease threatening ginger production in southwestern Ethiopia. A field experiment was conducted to determine the effect of integrated management methods on bacterial wilt disease and yield of ginger. Thus, a total of seven treatment combinations comprising hot-water, bio-fumigation, soil-solarization, Mancozeb, and bleaching powder were tested in a randomized complete block design with three replications. Data on disease incidence, yield, and yield components of ginger were collected from a random sample of plants. Then, analysis of variance (ANOVA) was performed using R-studio 9.9 statistical software, and the means were compared by the least significant test. The results from ANOVA revealed that the incidence of bacterial wilt, rhizome yield, and its components were highly significantly ($P < 0.001$) affected by management methods. An integrated application of rhizome seed treatment ($0.1 \text{ L}^{-1}$) and soil drenching (0.3%) using Mancozeb, lemongrass for soil bio-fumigation at a rate of 10 t ha$^{-1}$, along with solarization significantly reduced the incidence of bacterial wilt, the disease progress over time and produced the highest rhizome yield per hectare. Seed soaking and soil drenching in Mancozeb along with bio-fumigation was effective in reducing the disease, but a comparative yield advantage was gained through the application of bleaching powder as a seed treatment at 10% solution and soil amendment at a rate of 25 kg ha$^{-1}$, along with bio-fumigation. Thus, a combined application of Mancozeb, bio-fumigation using lemongrass, and solarization with polyethylene plastic sheet can be applied to control ginger bacterial wilt disease. Alternatively, bleaching powder, bio-fumigation with lemongrass and solarization can also be used as an integrated management system against the disease.

Subjects: Agriculture and Environmental Sciences; Botany; Entomology

Keywords: seed soaking; soil-treatment; bio-fumigation; chemical; soil-solarization; disease incidence; yield

1. Introduction

Ginger (Zingiber officinale Rosc.) is one of the most important commercial spice crops widely grown in Ethiopia. It is primarily cultivated by small-scale farmers in the south and southwest, as well as in a few confined areas in the northern parts of the country. The aromatic rhizomes are commonly used in Ethiopian dish and as a medicinal remedy. Ginger production on a small and medium scale has contributed to alleviation of poverty among small-scale household farmers (Hegde & Hegde, 2014). Furthermore, it aided economic growth by generating significant volume of foreign currency from the export market during the years 2007–2013 (Shimelis, 2021).
Despite its socioeconomic benefits, ginger production is heavily influenced by biotic and abiotic factors. Among the biotic factors, bacterial wilt caused by *Ralstonia solanacearum* (R.S.) is the most serious disease threatening ginger production in major ginger-growing areas in Ethiopia (Wubshet, 2018). The first bacterial wilt disease outbreak was reported on ginger in Bench-Maji Zone, early in 2010. Since then, it has rapidly spread to the major ginger production areas of the country (Kifelew et al., 2015). Disease prevalence was ranged from 91.6% to 98.9%, causing yield losses of up to 100%, in areas where small and marginal farmers relied on this crop for a living (Kassa et al., 2016). A review by Kurabachew & Ayana (2016) highlighted similar reports from different parts of the globe indicating 50–100% yield loss of potato in Kenya, 95% loss of tobacco in the United States, 70% yield loss of potato in India, 88% loss of tomato in Uganda, and 100% loss of pepper in Ethiopia.

Bacterial wilt is primarily a seed and soil-borne disease, as it is frequently spread by latently infected planting materials to new disease-free areas or by planting on infected soil. Latently infected rhizomes play a significant role in disease spread and yield loss (Meenu & Jebasingh, 2019). The pathogen enters the host body through wounds caused by cultural practices, parasitic insects, or root-knot nematodes, as well as openings where lateral roots emerge (Kumar et al., 2018; Salanoubat et al., 2002). The bacterium then gains access to the vascular system, where it rapidly multiplies and causes infection by filling the xylem with bacterial cells and obstruct water transport, leading the plant to wilt and die quickly (Álvarez et al., 2010).

Due to soil-borne nature of the pathogen, long survivability in the deeper soil layers, and ease of transmission, management of bacterial wilt has been so difficult. For decades, various management strategies have been studied in many parts of the world however, no single effective universal method has been reported (Zeist et al., 2019). As a result, the search for alternative bacterial wilt management options remains critical. Currently, disease management programs integrating cultural, physical, disease resistance, biological, and chemical methods have attracted particular attention (Yuliar et al., 2015).

The use of disease-free planting materials, as well as planting in healthy soil, are principal ways of avoiding the disease occurrence. Infected rhizomes can be treated in hot water or with chemicals to eliminate the initial inoculum carried by the seeds. Exposing ginger rhizomes to hot water treatment at 50 °C for 10 minutes effectively disinfected the pathogen on the seed surface (Nelson, 2013). Despite the lack of evidence on the use of Mancozeb against soil-borne bacterial pathogens, in a greenhouse study soil-drenching with Mancozeb was found to be effective in reducing the severity of bacterial wilt by 96.96% (Wang et al., 2015). Rhizome soaking in bleaching powder solution, combined with soil bio-fumigation with cabbage, was reported in controlling bacterial wilt and increasing ginger yield (Bandyopadhyay & Khalko, 2016). Singh et al. (2012), also stated that the incidence of bacterial wilt was minimum in tomato pots treated with bleaching powder and calcium chloride. Application of bleaching powder suppresses the growth of R.S. by altering the acidic soil property resulting in reduction of wilting disease in plants (Sharma & Kumar, 2009).

Bio-fumigation is the use of volatile chemicals released from plant residues to suppress soil-borne plant pathogens. Crops in the *Brassicaceae* family are frequently used to control many soil-borne pathogens. When the tissue of such plants is damaged and quickly incorporated into the soil, a powerful volatile biocidal agent (isothiocyanate) is released, sterilizing the soil environment. The beneficial effect of soil bio-fumigation along with other disease management methods has already been demonstrated in controlling bacterial wilt disease on different crops (Oz et al., 2017; Sharma & Kumar, 2009; Zeist et al., 2019).

Soil-solarization is one of the physical methods suggested for an integrated management system of soil-borne pathogens such as R.S. It allows solar radiation to be trapped beneath the plastic sheet and raises the temperature of the upper layer of soil surface sufficiently to suppress
pathogens of interest. The effectiveness of this method is reliant on temperature but its efficacy can be increased through an integrated measures combining the plants having allelopathic effect such as *Allium* and *Brassica* species (Panth et al., 2020). Similarly, Guji et al. (2019) reported that, an integrated application of lemongrass, fertilizer, and soil-solarization reduced bacterial wilt and improved ginger yield. Soil-solarization plus bio-fumigation with chicken manure also reported to increase the plant health index, and the yield of tomato (Zeist et al., 2019).

Currently, unavailability of healthy planting materials, resistant cultivars, and effective bactericidal compounds regarded as major problems of bacterial wilt management in southwestern Ethiopia. Only a few preliminary studies on the integrated management of ginger bacterial wilt have been conducted thus far, and the results are inconclusive. Therefore, the objective of this study was to identify a suitable method of managing ginger bacterial wilt disease using hot-water, bio-fumigation, chemicals, and soil-solarization.

2. Material and methods

2.1. Description of the study area

The study was conducted in Bench-Sheko Zone, southwest Ethiopia in 2019 main cropping season. The experimental farm field was previously infested in R.S. and ginger was severely smashed with bacterial wilt disease. The study area is found 590 km way from Addis Ababa the capital city of Ethiopia at an altitude which ranges between 900 to 1200 m.a.s.l situated between Latitude of 6°51’30” North and Longitudes of 35°20’3” to East. The area is characterized by tropical rainforest and humid climate conditions with maximum (30°C) and minimum (16°C) mean annual temperature. It receives high amount of rainfall between April and September with annual mean rainfall of 1960 mm (Guji et al., 2019). Fruits, field crops, oil crops, coffee, and spices are majorly produced by the household and private owned farms in the district.

2.2. Treatments, experimental design and procedures

A local ginger cultivar was used in the experiment. The treatment combinations used in the experiment includes $T_1$ = (control), $T_2$ = (hot-water + bio-fumigation), $T_3$ = (hot-water + bio-fumigation + soil-solarization), $T_4$ = (seed soaking and soil-drenching with Mancozeb + bio-fumigation), $T_5$ = (seed soaking and soil drenching with Mancozeb + bio-fumigation + soil-solarization), $T_6$ = (seed and soil treatment with bleaching powder + bio-fumigation), $T_7$ = (seed and soil treatment with bleaching powder + bio-fumigation + soil-solarization). Hot-water @ 50°C for 10 minutes, seed dipping in commercial bleach @ 10% solution for 10 minutes and seed dipping in MANCOZEB 75% W.P @ 0.1 g litter$^{-1}$ for 30 minutes were used as required for rhizome treatments. For bio-fumigation of the experimental plots, freshly cut young lemongrass shoots at a rate of 10 t ha$^{-1}$, were incorporated into the soil six weeks prior to planting (Panth et al., 2020). Soil-solarization was also done with a 25 μm thick polyethylene plastic sheet for six weeks. Bleaching powder at a rate of 25 kg ha$^{-1}$, was applied and thoroughly mixed into the soil. Subsequently, plots were solarized with polyethylene plastic cover and kept undisturbed. After two weeks, the plastic was removed and the soil was ploughed and left for two weeks to escape the remnants of bleaching powder in the air (Bandyopadhyay & Khalko, 2016). Soil drenching with MANCOZEB 75% W.P @ 0.3% was done 15 days before planting (Yuliar et al., 2015; Zeist et al., 2019). The second soil drenching was started after the first wilt incidence was observed and continued for six times at 15-day intervals. In controlled treatment, rhizome seeds were dipped in distilled water. A total of seven treatments were laid out in randomized complete block design (RCBD) with three replications.

2.3. Data collection

2.3.1. Disease assessment

The occurrence of bacterial wilt disease was visually investigated based on the sign and symptoms revealed on the plant tissues as described by Nelson (2013). Number of infected plants per plot was counted starting from 45 days after planting (DAP) and continued until the final disease
assessment date in 15-day intervals. Number of infected plants from a total number of plants per plot was then, converted into percentage disease incidence (PDI). The area under disease progress curve (AUDPC) in percent-days, was computed from PDI data recorded at each disease assessment date (time) under each treatment of the experiment according to the formula by Campbell & Madden (1990).

\[ \text{AUDPC} = \sum_{i=1}^{n-1} 0.5(x_{i+1} + x_i)(t_{i+1} + t_i) \]

where \( n \) is total number of assessments; \( t_i \) is the time of the \( i^{th} \) assessment in days from the first assessment date, \( x_i \) is percentage disease incidence at \( i^{th} \) assessment date.

2.3.2. Ginger growth and yield parameters

Data on plant height (PH), number of tillers plant\(^{-1} \) (NTPP), rhizome length (RL) and width (RW), and number fingers rhizome\(^{-1} \) (NFPR) were collected from the two central rows of 10 randomly selected plants at each plot. PH was measured in cm and the number of tillers emerged from individual plant were counted by the time of physiological maturity and their means were calculated per each experimental plot. Number of rhizome fingers emerged from the mother rhizome of sampled plants were counted and their means were used to determine mean number of fingers rhizome\(^{-1} \) (NFPR) at the time of harvesting. Rhizome length and width (cm) were measured from individual sampled plant of each treatment at the time of harvest. Finally, the rhizome yield obtained from the two central rows of each plot was calculated as kilogram per plot (kg plot\(^{-1} \)) and converted into kilogram per hectare (kg ha\(^{-1} \)) with the following formula

\[ \text{Yield (Kg ha}^{-1} \text{)} = \frac{\text{yield of two rows (kg)}}{\text{net area (m}^2\text{) two rows of each plot}} \times 10,000 \text{m}^2 \]

The relative yield loss of ginger due to bacterial wilt was calculated from each plot as percentage yield reduction of controlled plots compared with the most protected plot using the formula by Ayub et al. (2010).

\[ \text{RYL(\%)} = \frac{\text{MYP} - \text{YT}}{\text{MYP}} \times 100 \]

where RYL (%) is relative yield loss in percentage, MYP is maximum yield of protected plot, and YT is yield of other treatments.

2.4. Data analysis

Analysis of variance (ANOVA) was performed to determine the effect of integrated management methods on bacterial wilt epidemic, growth, and yield parameters. A data analysis was conducted in R (http://www.R-project.org). Means were compared using Fisher pare-wise comparison test and the least significant differences (LSD) between means were inspected at 5% probability level. The PDI data were transformed using the Arcsine transformation to normalize the distribution of responsive variance then the transformed PDI values were regressed over time (DAP) using the model, Logistic, \( \ln(\frac{Y_1-Y}{Y}) \), (Gopi et al., 2016) to determine the disease progress rate (r) through time. The slope from regression analysis estimated the disease progress rate. The magnitudes of the coefficient of determination (R\(^2\)) and residuals (S.E) were used to test the goodness-of-fit of the model. Regression was computed using Minitab (Release 18.0 for windows®, 2007).

3. Results

3.1. Disease symptoms and sign

During the early stages of wilt development, slight yellowing disease symptoms appeared on the plants, followed by wilting of the lower leaves. Within a short period of time, the wilt progresses upward, affecting the younger leaves, followed by a complete yellowing and browning of the entire pseudo-stem. Under conditions favorable for disease development, the entire shoot becomes
flaccid and wilts with little or no visible yellowing. Subsequently, the plant dries very rapidly and the foliage becomes yellow-brown in less than 3 days. As wilting of pseudo-steam advances, young succulent shoots normally become soft and completely rotted, and the diseased shoots break off easily from the underground rhizome at the soil line. From the cut surface of diseased rhizome, typical sign of bacterial ooze was observed as slimy, creamy exudate when the cut rhizomes were suspended in a glass of water and the disease was confirmed as bacterial wilt caused by R.S.

3.2. Disease incidence
The incidence of bacterial wilt was first observed 45 days after planting (DAP) and continued to infect new plants on the consecutive disease assessment dates. The results from the analysis of variance (ANOVA) indicated that disease incidence was highly significantly ($P < 0.001$) affected by management practices in all disease assessment dates (DAD). Application of T$_5$ (seed soaking and soil drenching in Mancozeb + bio-fumigation + soil-solarization) resulted in a minimum (1.11 and 35.0%) of wilt incidences at the initial (45 DAP) and final (165 DAP) disease assessment dates, respectively (Table 1). On the contrary, the maximum (28.33 and 95.56%) of wilt incidences were recorded on untreated plots at the initial and final disease assessment dates. Furthermore, application of T$_6$ (seed soaking and soil treatment with bleaching powder + bio-fumigation) and T$_7$ (seed soaking and soil drenching with Mancozeb + bio-fumigation) were the second best treatments of the experiment, with a minimum of (9.44 and 47.22%) bacterial wilt incidence at the initial and final disease assessment dates, respectively.

3.3. Area under disease progress curve
The result from the analysis of variance (ANOVA) indicated that the AUDPC was highly significantly ($P < 0.001$) different among treatments. The highest AUDPC, 1429.17% -days was recorded in controlled plots while the lowest (512.5%-days) was from plots of T$_5$ (seed soaking and soil drenching with Mancozeb + bio-fumigation + soil-solarization), followed by 704.17%-days in T$_4$ (seed soaking and soil drenching with Mancozeb + bio-fumigation), which resulted in a 64.14 and 50.73% reduction of AUDPC over the controlled plots, respectively (Table 2). Apparently, 40.52 and 34.99% of reduction in the AUDPC were recorded through the application of T$_6$ and T$_7$, respectively.

| Treatments | PDI$_i$ | PDI$_i$ reduction | PDI$_f$ | PDI$_f$ reduction |
|------------|---------|-------------------|---------|-------------------|
| T$_1$      | 28.33$^a$ | 00.0              | 95.56$^a$ | 00.0              |
| T$_2$      | 18.33$^b$ | 35.29             | 84.44$^b$ | 11.63             |
| T$_3$      | 15.00$^c$ | 47.05             | 79.44$^c$ | 16.86             |
| T$_4$      | 10.56$^c$ | 62.72             | 47.22$^c$ | 50.58             |
| T$_5$      | 1.11$^d$  | 96.08             | 35.00$^d$ | 63.37             |
| T$_6$      | 9.44$^d$  | 66.67             | 58.33$^d$ | 38.95             |
| T$_7$      | 11.67$^c$ | 58.80             | 62.22$^c$ | 34.88             |
| LSD (0.05) | 7.44     | -                 | 9.27     | -                 |
| CV (%)     | 31.01    | -                 | 7.89     | -                 |

T$_1$ = (control), T$_2$ = (hot water+bio-fumigation), T$_3$ = (hot water+bio-fumigation+soil-solarization), T$_4$ = (seed soaking and soil-drenching with Mancozeb+bio-fumigation), T$_5$ = (seed soaking and soil drenching with Mancozeb+bio-fumigation+soil-solarization), T$_6$ = (seed and soil treatment with bleaching powder+bio-fumigation), T$_7$ = (seed and soil treatment with bleaching powder+bio-fumigation+soil-solarization). PDI = Percentage disease incidence at initial disease assessment date, PDI$_i$ = Percentage disease incidence at final disease assessment date. Means followed by same letters are not statistically different at 0.05% significance level.
Table 2. Effect of integrated management methods on disease progress rate \((r)\) and area under disease progress curve (AUDPC) of bacterial wilt of ginger in 2019 under field condition

| Treatments | Disease progress rate | AUDPC (% day\(^{-1}\)) | AUDPC reduction |
|------------|-----------------------|-------------------------|-----------------|
|            | Intercept \((r)\)     | SE of intercept | SE of \(r\) | \(R^2\) | \(\%\) |
| \(T_1\)   | -2.72                 | 0.03634          | 0.148           | 0.00132 | 99.08 | 1429.17^a | 0.0 |
| \(T_2\)   | -2.694                | 0.02843          | 0.216           | 0.00193 | 96.87 | 1245.83^b | 12.83 |
| \(T_3\)   | -2.798                | 0.02823          | 0.326           | 0.00292 | 93.06 | 1191.67^b | 16.62 |
| \(T_4\)   | -2.617                | 0.0164           | 0.140           | 0.00125 | 96.10 | 704.17^c  | 50.73 |
| \(T_5\)   | -4.882                | 0.0297           | 0.549           | 0.00491 | 83.96 | 512.50^d  | 64.14 |
| \(T_6\)   | -2.881                | 0.02184          | 0.310           | 0.00277 | 89.91 | 850.00^c  | 40.52 |
| \(T_7\)   | -2.657                | 0.02207          | 0.381           | 0.0034  | 85.74 | 929.17^e  | 34.99 |
| LSD (0.05) | -                     | -                | -               | -      | -      | 143.61 | - |
| CV (%)     | -                     | -                | -               | -      | -      | 8.23   | - |

\(T_1\) = (control), \(T_2\) = (hot water+bio-fumigation), \(T_3\) = (hot water+bio-fumigation+soil-solarization), \(T_4\) = (seed soaking and soil-drenching with Mancozeb+bio-fumigation), \(T_5\) = (seed soaking and soil-drenching with Mancozeb+bio-fumigation+soil-solarization), \(T_6\) = (seed and soil treatment with bleaching powder+bio-fumigation), \(T_7\) = (seed and soil treatment with bleaching powder+bio-fumigation +soil-solarization). Intercept = Intercept of the regression equation, \(r\) = disease progress rate, SE of intercept = standard error of parameter estimates, \(R^2\) = Coefficient of determination of the model, AUDPC = area under disease progress curve. Means followed by same letters are not statistically different at 0.05% significance level.
3.4. Disease progress rate
The disease progress rate (r) among treatments were computed by fitting the percentage incidence data with all the disease assessment dates. The highest r (0.03634 units day⁻¹) was recorded from untreated plots while the lowest (0.0164 units day⁻¹) was from ginger plants treated with T₆ (seed and soil drenching with Mancozeb + bio-fumigation), followed by 0.02184 units day⁻¹ from T₅ (seed and soil treatment with bleaching powder + bio-fumigation; Table 2). An integrated application of T₇ also resulted in the slowest r of 0.0221 units day⁻¹ throughout the growth period in comparison to controlled plots.

3.5. Growth parameters
Plant height (PH) and tiller number plant⁻¹ (TNPP) were highly significantly (P < 0.001) affected by management practices imposed. The highest PH (71.73 cm) and TNPP (10.86) were recorded on ginger plants treated with T₃ (seed and soil treatment with bleaching powder + bio-fumigation + soil-solarization) and T₅ (seed soaking and soil drenching with Mancozeb + bio-fumigation + soil-solarization), respectively (Table 3). On the other hand, the least (53.3 cm) PH and minimum (7.03) TNPP were obtained from untreated plots, followed by (60.33 cm) PH and (8.76) TNPP from the plots of T₂ (hot water treatment of seed + bio-fumigation).

3.6. Yield and yield components
The highest rhizome yield of 15.09 t ha⁻¹ with a maximum (9.7) number of fingers rhizome⁻¹ (NFPR) as well as a maximum rhizome length (RL) of 9.9 cm and a rhizome width (RW) of 3.74 cm was harvested from the integrated application of T₅ (seed soaking and soil drenching with Mancozeb + bio-fumigation + soil-solarization); whereas, the lowest rhizome yield of 5.00 t ha⁻¹, with the least (4.5) NFPR, the lowest RL (5.97 cm) and RW (2.72 cm) was received from the controlled plots (Table 3). An integrated application of T₄ (seed soaking and soil drenching with Mancozeb + bio-fumigation) and T₆ (seed and soil treatment with bleaching powder + bio-fumigation) were the 2nd and 3rd best treatments of the experiment, resulting in 13.01 and 12.18 t ha⁻¹ rhizome yield, along with 8.36 and 7.83 rhizome fingers, respectively.

Table 3. Effect of integrated management methods on the growth, yield components and yield of ginger in 2019 under field condition

| Treatments | Growth parameters | Yield and yield components |
|------------|-------------------|----------------------------|
|            | PH (cm) | TNPP | RL (cm) | RW (cm) | NFR | Yield (t ha⁻¹) |
| T₁         | 53.53    | 7.03 | 5.97    | 2.72    | 4.50 | 5.00           |
| T₂         | 60.33    | 8.76 | 7.60    | 2.90    | 5.43 | 9.29           |
| T₃         | 69.60    | 9.23 | 7.93    | 3.27    | 6.26 | 9.75           |
| T₄         | 70.83    | 10.50 | 9.46    | 3.60    | 7.83 | 12.18            |
| T₅         | 71.66    | 10.86 | 9.90    | 3.74    | 9.70 | 15.09            |
| T₆         | 70.53    | 10.26 | 9.23    | 3.54    | 8.36 | 13.01            |
| T₇         | 71.73    | 9.93 | 9.66    | 3.67    | 7.43 | 11.56            |
| LSD (0.05) | 2.85     | 0.66 | 0.68    | 0.31    | 0.76 | 1.12             |
| CV(%)      | 2.39     | 3.95 | 4.52    | 5.20    | 6.08 | 5.84             |

T₁ = (control), T₂ = (hot water+bio-fumigation), T₃ = (hot water+bio-fumigation+soil-solarization), T₄ = (seed soaking and soil-drenching with Mancozeb+bio-fumigation), T₅ = (seed soaking and soil drenching with Mancozeb+bio-fumigation+soil-solarization), T₆ = (seed and soil treatment with bleaching powder+bio-fumigation), T₇ = (seed and soil treatment with bleaching powder+bio-fumigation+soil-solarization). PH = plant height, TNPP = tiller number per plant, RL = rhizome length, RW = rhizome width, NFR = number of finger per rhizome. Means followed by some letters are not statistically different at 0.05% significance level.
Table 4. Effect of integrated management methods on relative yield and yield loss of ginger in 2019 under field condition

| Treatment | Relative yield and yield loss (%) | Reduction of YL (%) |
|-----------|-----------------------------------|---------------------|
|           | RY (%) | RYL (%) |                        |
| T<sub>1</sub> | 33.14  | −66.86  | 0.00                 |
| T<sub>2</sub> | 61.61  | −38.39  | 42.58                |
| T<sub>3</sub> | 64.60  | −35.40  | 47.05                |
| T<sub>4</sub> | 80.76  | −19.24  | 71.22                |
| T<sub>5</sub> | 100.00 | 0.00    | 100.00               |
| T<sub>6</sub> | 86.25  | −13.75  | 79.43                |
| T<sub>7</sub> | 76.63  | −23.37  | 65.1                 |

T<sub>1</sub> = (control), T<sub>2</sub> = (hot water+bio-fumigation), T<sub>3</sub> = (hot water+bio-fumigation+soil-solarization), T<sub>4</sub> = (seed soaking and soil-drenching with Mancozeb+bio-fumigation), T<sub>5</sub> = (seed soaking and soil drenching with Mancozeb+bio-fumigation+soil-solarization), T<sub>6</sub> = (seed and soil treatment with bleaching powder+bio-fumigation), T<sub>7</sub> = (seed and soil treatment with bleaching powder+bio-fumigation+soil-solarization). RY (%) = relative yield in percent, RYL (%) = relative yield loss in percent.

3.7. Relative yield and yield loss

Prominent differences were observed among treatments in terms of relative yield and yield loss (Table 4). The highest (66.86%) relative yield loss was recorded on untreated plots, while the lowest (13.75%) was from T<sub>6</sub> (seed and soil treatment with bleaching powder + bio-fumigation), which resulted in a 79.43% reduction in yield loss in comparison with the controlled plots. The next minimum of 19.24% relative yield loss was recorded from the integrated application of T<sub>4</sub> (seed soaking and soil drenching with Mancozeb + bio-fumigation), followed by 23.37% of yield loss from T<sub>7</sub> (seed and soil treatment with bleaching powder + bio-fumigation + soil-solarization) which gives a considerable reduction of the yield loss by 71.22 and 65.1%, respectively.

4. Discussion

The results of the present study confirmed that all the treatments were able to provide some level of disease control over the untreated plots. However, disease was significantly reduced by treatments that comprised Mancozeb and bleaching powder. Application of T<sub>5</sub> reduced the mean final percentage of disease incidence (PDI) by 63.37% and the AUDPC by 64.14% in comparison to the maximum 95.56% of PDI and 1429.1 unit-day<sup>−1</sup> of AUDPC in the controlled plots. This might be attributed to the combined benefits of rhizome soaking in Mancozeb, soil bio-fumigation using lemongrass, and soil-solarization in disinfecting the pathogen carried by the seed and the sphere of soil around the seed.

Using disease-free planting material and planting in healthy soils are the main strategies for preventing R.S. because it is a seed and soil-borne pathogen (Kumar et al., 2018). Mancozeb has been used for seed and soil treatments to control ginger rhizome rot complex diseases (Ayub et al., 2010). Despite the lack of evidence for its efficacy in controlling R.S., a corresponding report by Bandyopadhyay & Khalko (2016), indicated that integrated application of Mancozeb for rhizome seed treatment along with soil bio-fumigation using cabbage reduced the incidence of bacterial wilt by 73.22%. Similar results were obtained in a greenhouse research where Mancozeb was applied to the soil before planting help reduce the severity of the tobacco bacterial wilt disease by 94.96% (Wang et al., 2015).

Our findings also revealed that combined application of bleaching powder as a seed and soil treatment, bio-fumigation, along with (T<sub>4</sub>) or without (T<sub>7</sub>) solarization, considerably reduced the incidence of bacterial wilt. Rhizome dipping in bleaching powder solution was reported to effectively sterilize and eliminate R.S. on the surface of ginger rhizomes (Nelson, 2013). In addition, soil amendment in bleaching powder raises the pH level of acidic soil, where the growth and multiplication of R.S. promoted. As a result, it inhibits bacterial development, thereby reducing the
disease incidence. Consistent with Singh et al. (2012) who reported a reduction of bacterial wilt incidence by 51.2% when bleaching powder was used in conjunction with other disease management methods.

Bio-fumigation is a biological technique widely used to control soil-borne pathogens and pests using volatile chemicals released from plant residues (Gopi et al., 2016). Crops in the family of Brassicaceae are commonly used to control many soil-borne pathogens, including R.S. (King et al., 2018). Damaging and incorporating tissues of such plants into the soil releases a powerful volatile biocidal agent (isothiocyanate) into the soil environment. Consequently, these volatile substances with varying antimicrobial activity may either directly affect the viability and survival of the pathogen or be involved in inducing systemic resistance of the host plant (Yuliar et al., 2015). A related study showed that the combined application of bio-fumigation, inorganic fertilizer, and solarization reduced the incidence of bacterial wilt by 42.06% (Guji et al., 2019). Essential oils extracted from palmarosa, lemongrass, and eucalyptus also showed antibacterial effects on R. S. and reduced the incidence of bacterial wilt on ginger (Paret et al., 2010). However, Panth et al. (2020) highlighted the limitations of sole use of bio-fumigation against soil-borne pathogens. This was consistent with our findings in treatments that comprising hot-water and bio-fumigation, which resulted in the highest disease incidence and AUDPC next to the controlled treatment.

It was also evident that regardless of T5 and T6, the disease was comparatively reduced in solarized plots than in non-solarized plots, but the mean final PDI and AUDPC of these plots were not statistically different. This might be due to the sub-lethal effect of the temperature created by solarization on the pathogen inhibited in the deeper layers of soil, which hardly reduced the disease. Although the efficacy of this method is temperature dependent, it can be boosted through an integrated measure incorporating plants with allelopathic effects such as Allium and Brassica species (Mihajlovic et al., 2017; Panth et al., 2020). Furthermore, solarization may have an indirect effect on the pathogen and the reduction of the disease by hindering the leakage of toxic volatile substances released from damaged lemongrass tissues during the bio-fumigation process. In line with the current findings, the combined application of soilarization, soil amendment with nitrogen and CaO reduced the incidence of bacterial wilt by 20% (Vinh et al., 2005). Similarly, soil-solarization plus bio-fumigation with chicken manure was reported to increase the plant health index and the yield of tomatoes over control (Zeist et al., 2019).

The growth and yield parameters of ginger were notably promoted by the management methods which were effective in the reduction of bacterial wilt. Plant height, number of tillers, rhizome length and width were comparatively increased under the integrated management in comparison with the control treatment. Rhizomes harvested from the integrated application of Mancozeb and bleaching powder were bigger in size (in length and width) and produced a maximum number of fingers than those rhizomes obtained from the rest of the treatments. This holds true for rhizome yield in which the maximum was harvested from T5 followed by T6 and T4 but the rhizome yield ha⁻¹ harvested from the latter two treatments was not statistically different.

A related experimental finding by Ghosh & Mandal (2009) showed that the combined use of Mancozeb with other disease management methods significantly reduced bacterial wilt and resulted in the highest potato yield. Likewise, Mancozeb was suggested as a potential protectant for field management of tobacco bacterial wilt (Wang et al., 2015). Furthermore, due to its bactericidal effect on the R.S. population in the soil, the integrated application of bleaching powder may have benefited the healthy growth and yield increase of ginger by reducing the disease. Consistent with Sharma & Kumar (2009) who reported a significant amount of disease reduction and yield increase by integrating karanj cake along with bleaching powder for the management of tomato bacterial wilt disease. In addition to the bio-fumigation benefit of lemongrass, its decomposition in the soil could return a significant amount of organic matter to the soil profile and improve soil properties, both of which can benefit plant development and productivity (Bailey & Lazarovits, 2003). Furthermore, applying solarization after soil bio-fumigation with lemongrass
could speed up the decomposition process and improve soil properties, which could benefit ginger growth and yield. The benefits of integrating bio-fumigation and soil-solarization to reduce bacterial wilt and improve crop yield have already been demonstrated by Gopi et al. (2016) and Moulas et al. (2013).

5. Conclusion
Bacterial wilt is the most distracting disease threatening ginger production in southwest Ethiopia. Farmers currently have no control options for this disease. As a result, they discourage producing ginger and other related solanaceous crops. The present experimental findings demonstrate that an integrated use of Mancozeb for seed soaking and soil-drenching, soil bio-fumigation using lemongrass, along with soil-solarization using polyethylene plastic sheet, significantly reduced bacterial wilt disease parameters and improved the growth and yield of ginger. Thus, it can be used as an integrated management system for ginger bacterial wilt disease. Furthermore, a combined application of bleaching powder as rhizome seed and soil treatment, soil bio-fumigation using lemongrass, along with or without polyethylene plastic sheet for soil-solarization, also resulted in disease reduction and an improved yield of ginger. Therefore, it can be used as an alternative means of control of ginger bacterial wilt disease. Nonetheless, further experimental research integrating cultural, physical, host-resistance, biological, and chemical methods should be conducted to develop an effective and sustainable management of ginger bacterial wilt disease.

Acknowledgements
The authors would like to thank Mizan-Tepi University for financing the study and Horizon Coffee Plantations for providing the experimental farm field. We would also like to extend our thanks to the contributions of individuals who involved in the filed preparation, and data collection.

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Disclosure statement
No potential conflict of interest was reported by the author(s).

Funding
The authors received no direct funding for this research.

Data accessibility
The data supporting the results or analysis presented in this study can be obtained from the corresponding author on request.

Citation information
Cite this article as: Integrated management of ginger bacterial wilt (Ralstonia solanacearum) in Southwest Ethiopia, Eyob Aysanew & Desalegn Alemayehu, Cogent Food & Agriculture (2022), 8: 2125033.

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