Agriculture & Food Security

RESEARCH

Open Access

# Yield loss of ginger (*Zingiber officinale*) due to bacterial wilt (*Ralstonia solanacearum*) in different wilt management systems in Ethiopia

Merga Jibat Guji[1], Habtamu Terefe Yetayew[2*] and Eshetu Derso Kidanu[3]

## Abstract

**Background:** Ginger bacterial wilt is the most destructive disease that causes qualitative and quantitative rhizome yield losses in Ethiopia. Field studies were conducted to assess yield loss caused by bacterial wilt of ginger in different wilt management systems at Teppi and Jimma, Ethiopia, during 2017. Management systems were host resistance (Boziab and Local) and cultural practices (lemon grass, potassium fertilizer and soil solarization), which were applied as sole and in different levels of integrations. The experiments were factorial arranged in a randomized complete block design with three replications. Disease, growth, yield and yield-related data were collected from central rows of each experimental plot. Data were subjected to analysis of variance using linear general model (GLM) procedure of SAS version 9.3. Mean separation was made using least significant difference test. Correlation among parameters and linear regression of rhizome yield versus final wilt incidence were computed using Minitab 14 statistical package.

**Results:** Analysis of variance indicated that variety, cultural practices and variety × cultural practice interaction effects significantly reduced wilt incidence and increased rhizome yield and its components. Variety Boziab recorded relatively more yield and yield components than the Local variety. Rhizome yield gains of about 51.4% in Local and 51.9% in Boziab at Teppi and 39.4% in Local and 49.1% in Boziab at Jimma were obtained due to integrated application of lemon grass with soil solarization and soil fertilization. The mean relative yield loss calculated for control plots due to bacterial wilt ranged from 51.4 to 51.9% at Teppi and 39.4 to 49.1% at Jimma. The lowest relative yield loss was computed from plots treated with either lemon grass with soil fertilization and solarization or lemon grass with soil fertilization. Final wilt incidence was inversely and highly significantly ($P \leq 0.001$) correlated ($r = -0.90$** and $-0.88$**) with rhizome yield of Boziab and Local, respectively, at Teppi. The slope of the regression line also estimated that for each unit increase in percent of final mean wilt incidence, there was a rhizome yield reduction of 0.18 t $ha^{-1}$ for Boziab and 0.19 t $ha^{-1}$ for Local variety at Teppi. Similar trends were observed at Jimma. Moreover, the most integrated treatment provided higher net benefit with optimum marginal rate of return than others.

**Conclusion:** The overall results indicated that integration of host resistance with cultural practices reduces yield loss, improves ginger productivity and significantly reduces bacterial wilt epidemics, and thus, it is recommended in the study areas and other related agroecologies.

**Keywords:** Bacterial wilt, Ginger, Lemon grass, Solarization, Soil amendment, Yield loss

*Correspondence: habmam21@gmail.com
[2] School of Plant Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia
Full list of author information is available at the end of the article

## Background

Ginger (*Zingiber officinale* Rosc.), belonging to the family Zingiberaceae, is one of the earliest known oriental spices and is being cultivated widely both as a fresh vegetable and dried spice. Ginger has been used as spice and medicine [1, 2]. The crop is known to have been introduced to Ethiopia as early as in the thirteenth century [3]. It is cultivated in south, southwestern and northwestern parts of the country as cash crop for its aromatic rhizomes and is among the important spices used in every Ethiopian dish [4]. Almost 10 years back, 22.6 million $USD had been earned from ginger export in Ethiopia [5]. The potential ginger production belt of the country is dominated by southern areas. For instance, in the previous years, 85% of the total arable land allotted for ginger production and 35% of the farmers involved in ginger production are from southern Ethiopia [6].

The production of ginger, however, is largely affected by diseases caused by bacteria, fungi, viruses, mycoplasma and nematodes [1, 7]. Bacterial wilt of ginger (*Ralstonia solanacearum* Yabuuchi) inflicts serious economic losses, and it is widely distributed in tropical and subtropical regions of the world [8]. Bacterial wilt is very important in major ginger growing areas of southwestern Ethiopia, where ginger is widely and mainly produced for commercial purposes [9, 10]. Disease incidence in the field usually ranges from 10 to 40%, but the disease is also known to destroy the crop completely [11]. Bacterial wilt incidence of 80–100% is also reported in ginger in Ethiopia [12].

*Ralstonia solanacearum* is soil- and plant-inhabiting and highly heterogeneous bacterial pathogen of many important crops worldwide [13]. A wilting and yellowing of the lower leaves which extend upward until all the leaves appear golden yellow in appearance are the first recognizable symptom of bacterial wilt in ginger. Thereafter, it also moves up through the vascular system and finally blocks water transportation, which causes wilting [14]. *R. solanacearum* is transmitted by infected rhizome seed, contaminated soil, public irrigation water and equipment [15]. Management of bacterial wilt is very difficult because of its wide host range, long survival in the soil, several modes of spread, survival potential as latent infection, ability to grow endophytically, relationship with weeds and its genetically diverse strains [16].

However, different management methods including cultural, biological, chemical and physical are described in the literatures. Bio-fumigation is a potential candidate option for integrated bacterial wilt management system through the release of toxic and volatile chemical gases during decomposition and simultaneously improving soil health via incorporating valuable organic matter [17]. Previous studies also revealed the importance of fertilizer application to reduce incidences of bacterial wilt in several pathosystems [18, 19]. For example, applications of potassium fertilizer enhance host resistance through carbohydrate accumulation and translocation of important chemicals and make them available in the xylem, which in turn strengthens stem tissue and resistance toward pathogen attack [20]. Moreover, soil solarization through plastic mulches is intended to raise soil temperature to a level lethal to survival of soil pathogens [21]. It is found important in reducing incidence of wilt diseases in various crops [22, 23]. Host resistances are also suggested; but resistant ginger genotypes do not exist in the country.

Nevertheless, there is no single control effective measure against the pathogen [24, 25]. As a result, ginger bacterial wilt is still highly distributed and severe in the country, and ginger growing farmers considered the disease as a major production constraint. Thus, it is recommended to have some level of bacterial wilt control through combined application of diverse methods such as host resistance, cultural practices, biological and chemical control in integrated disease management schemes. However, there is very little research done so far on the effects of integrated ginger bacterial wilt management through soil solarization, fertilizer soil amendment and bio-fumigation in Ethiopia. Therefore, the objective of the current study was to determine the magnitude of ginger rhizome yield losses due to bacterial wilt in different wilt management systems in Ethiopia.

## Materials and methods

### Experimental sites

The experiments were conducted at Teppi National Spice Research Centre (TNSRC) and Jimma Agricultural Research Center (JARC), Ethiopia, in the 2017 main cropping season. TNSRC is found between 35°08′ longitude and 7°08′ latitude and at an altitude of 1200 m above sea level. The average maximum and minimum temperatures are 30 and 15 °C, respectively. It receives an average annual rainfall of 1630 mm [26]. Jimma Agricultural Research Center is located between 7°40′37′N and 36°49′47′E and at an altitude of 1753 m above sea level. The average maximum and minimum temperatures are 26.2 and 11.9 °C, respectively. It receives an average annual rainfall of 1532 mm [27]. The daily minimum temperatures range from 9.2 to 12.9 °C at Teppi and 9.4 to 11.2 °C at Jimma, while the daily mean maximum temperatures range from 26.4 to 32.2 °C at Teppi and 26.4 to 28.4 °C at Jimma (May to December) in 2017.

### Experimental materials and treatments

Rhizomes of ginger varieties treated with hot water at 50 °C for 10 min were used for all treatments including the control. Boziab (37/79) variety of ginger which was released from TNSRC and the local variety (Jimma local) was evaluated for their response to bacterial wilt alone and in integration with potassium fertilizer soil amendment, soil solarization and bio-fumigation by lemongrass (*Cymbopogon citratus*). Both varieties are adapted to low-to midland areas and propagated by rhizome with variable productivity potential, but without disease resistance reaction report. Boziab is known to take 210 to 270 days to mature and was released in 2007.

Seed soaking with hot water was used to disinfect seeds from the target bacterium for all treatments including control, which was intended to free/reduce seed borne inocula. In addition, soil bio-fumigation with lemon grass plus soil solarization, and inorganic soil amendment with potassium fertilizer were applied as cultural management practice to reduce pathogen inocula and prevent disease epidemics and in turn to increase ginger productivity. The soil of the experimental unit was amended with potassium fertilizer at a rate of 100 kg ha$^{-1}$ [28]. Lemon grass was obtained from TNSRC, and shoots of young lemon grass were chopped and incorporated into each plot at the rate of 10 t ha$^{-1}$ [29] 4 weeks before planting. The soil was thoroughly mixed with chopped lemon grass, ensuring that all the residues were well incorporated into the soil. The soil was then re-moistened with water to increase the rate of decomposition.

For soil solarization, the plot to be solarized was thoroughly cultivated and leveled so as to prevent tearing of sheet. Thereafter, all plots were irrigated to moisten and covered with a clear and transparent polyethylene sheet of 15 mm thickness for 6 weeks. All free edges were buried, and then, the soil around them compacted so as to prevent escape of heated air or moisture from solarized plots. Hot water-treated rhizome of each test variety without any cultural practice was left as control (Table 1). The experiment relied entirely on natural epidemics of bacterial wilt, because both experimental areas are hot spot to the disease and considered as sick plots for screening studies, and the previous history of the field also confirmed it. The identity of the pathogen was confirmed by modified procedures of Kelman [30].

**Table 1 Treatments, descriptions and their respective combinations for the experiment at Teppi and Jimma, Ethiopia, during the 2017 main cropping season**

| S/n | Description of treatment and respective combinations[1] |
|---|---|
| 1 | HWT + Boziab (control) |
| 2 | HWT + Boziab with lemon grass |
| 3 | HWT + Boziab with potassium fertilizer |
| 4 | HWT + Boziab with soil solarization |
| 5 | HWT + Boziab with lemon grass and potassium fertilizer |
| 6 | HWT + Boziab with lemon grass and soil solarization |
| 7 | HWT + Boziab with potassium fertilizer and soil solarization |
| 8 | HWT + Boziab with potassium fertilizer, lemon grass and soil solarization |
| 9 | HWT + Jimma local (control) |
| 10 | HWT + Jimma local with lemon grass |
| 11 | HWT + Jimma local with potassium fertilizer |
| 12 | HWT + Jimma local with soil solarization |
| 13 | HWT + Jimma local with lemon grass and potassium fertilizer |
| 14 | HWT + Jimma local with lemon grass and soil solarization |
| 15 | HWT + Jimma local with potassium fertilizer and soil solarization |
| 16 | HWT + Jimma local with potassium fertilizer, soil solarization and lemon grass |

[1] HWT = hot water treatment of ginger rhizome to free/reduce load of seedborne inocula

## Experimental design and management

A total of 16 treatments including controls were laid out in a randomized complete block design in a factorial arrangement with three replications. Planting was made on a gross plot size of 2.88 m$^2$ (1.2 m width and 2.4 m length) with four rows of ginger and two harvestable central rows. A recommended spacing of 0.15 m between plants and 0.3 m between rows was used. Spacing between plots and blocks was 0.5 and 1 m, respectively. The two central rows were considered for data collection in both locations. Planting was done on May 05, 2017, at Teppi and May 12, 2017, at Jimma. All other cultural practices for growing ginger under field conditions were done uniformly following recommended practices.

## Data collection

### *Growth and yield parameters*

Data on ginger growth and yield parameters were recorded from the central two rows of each plot. Plant height (cm) was measured from 12 plants per plot starting from the base of the stem to the tip of the plant by using meter tape, and their mean was taken per plot at the time of maturity. The number of tillers per plant (NTPP) was counted as the number of tiller shoots produced by 12 sample plants, and their mean was considered as number of tillers per plant per plot at the time of maturity. The number of fingers per plant (NFPP) was determined as the number of rhizome fingers arose from mother rhizome of 12 plants, and their mean was taken to get number of finger per rhizome per plot at the time of harvesting. Total rhizome yield (kg ha$^{-1}$) was also calculated as the rhizome yield in kilogram harvested from two central rows and converted to per hectare using the following formula and later on expressed in t ha$^{-1}$ for analysis:

$$\text{Yield (kg ha}^{-1}) = \frac{\text{Yield (kg) of two central rows} \times 10{,}000\,\text{m}^2}{\text{Net area (m}^2\text{) of the two central rows/plot}}$$

Relative yield loss (%) from each plot was calculated using the formula suggested by Sharma and Sharma (2008).

$$\text{RYL}\ (\%) = \frac{(Y_1 - Y_2) \times 100}{Y_1}$$

where RYL = relative yield loss in rhizome yield (reduction in rhizome yield); $Y_1$ = maximum mean rhizome yield of the best treatment in the experiment; and $Y_2$ = mean yield of the other treatments and control plots.

#### *Wilt incidence assessment*

Ginger bacterial wilt incidence (number of plants wilted) was visually assessed at 15 days interval starting from 45 days after planting (DAP) at Teppi and 60 DAP at Jimma. The assessment was made eight and seven times at Teppi and Jimma, respectively. Ginger plants that showed either complete or partial wilting were all considered wilted and staked to avoid double counting in subsequent assessments. Wilt incidence for each treatment was then calculated as percentage of total number of plants emerged.

### Data analysis

Analysis of variance (ANOVA) was run for growth, yield and wilt incidence data to see the effect of treatments and their interactions. When ANOVA was found significant, least significant difference (LSD) was used for mean separation at 5% level of significance. ANOVA was performed using SAS GLM procedure version 9.3 [31]. Correlation coefficients of ginger growth and yield parameters with final wilt incidences were computed to establish their relationships. Linear regression analysis was computed by plotting rhizome yield data against final wilt incidence. Regression analysis and coefficient of determination ($R^2$) were done using the Minitab 14 statistical package. Variation in the regression was estimated using the coefficient of determination ($R^2$). The two locations were considered as different environments because of heterogeneity of variances as tested using Bartlett's test [32], and the F-test was significant. Thus, data were not combined for analysis.

## Results

### Disease incidence

Wilted ginger plants of experimental plots were examined, and the identity of the pathogen and the cause of wilting were once again confirmed to be *R. solanacearum* using standard procedures. Interaction effects of varieties by cultural management practices on mean wilt incidence showed a highly and significant ($P < 0.001$) difference at all dates of wilt assessments at Teppi and at late wilt recording (120, 135 and 150 DAP) periods of the epidemics at Jimma. Also, there was significant ($P \leq 0.05$) difference at 90 and 105 DAP, but there was no any significant difference at 60 and 75 DAP at Jimma. Analysis of variance also resulted in significant variations between locations, varieties and among management practices. Mean disease incidence ranged from 49.03 to 75.24% in treated plots in comparison with 79.47% in control plots of variety Local at Teppi and from 42.04 to 78.92% in managed plots in comparison with 80.44% in untreated plots of variety Local at Jimma at the final date of wilt assessment (150 DAP). Very similar trends were also observed for the variety Boziab at both experimental locations at same date of wilt assessment (Table 2).

Percentage mean wilt incidence reduction computations made for both ginger varieties per treatment revealed clear differences between management imposed plots and control plots. At 150 DAP, lemon grass with fertilizer application and soil solarization reduced mean wilt incidence by 38.30%, followed by lemon grass with fertilizer application (25.91%) compared to control plots of the variety Local. Similarly, 47.74% reduction in mean wilt incidence was obtained from plots treated with integrated application of lemon grass and fertilizer, followed by lemon grass with fertilizer application and soil solarization treated plots (42.06%) in comparison with controls in the Local variety at Jimma at the final date of wilt assessment. The lowest (5.32% at Teppi and 1.89% at Jimma) mean wilt incidence reduction was calculated from variety Local managed by sole application of soil solarization in the cropping season. With regard to Boziab, closely similar trends were obtained in mean wilt incidence reduction at both locations.

### Effect of bacterial wilt on ginger growth

Interaction effects of variety by cultural management practices were highly and significantly ($P < 0.001$) different in growth parameters both at Teppi and at Jimma, except for plant height, which recorded nonsignificant difference and number of tillers per plant, which was significant ($P \leq 0.05$) at Teppi. At Jimma, the maximum plant height (70.2 cm) was recorded from plots treated with integrated application of lemon grass and soil solarization in Local variety and Boziab (70.0 cm) but statistically on par with the most integrated treatment (combined application of lemon grass with fertilizer and soil solarization). In contrast, the lowest plant height was recorded from untreated control plots, which included 55.9 cm in Local and 53.3 cm in Boziab variety (Table 3).

A marked difference was also observed between managed and untreated control plots of both ginger varieties for NTPP at both experimental sites. Higher NTPP was counted from plots that obtained the most integrated

**Table 2 Interaction effects of cultural management practices and ginger varieties on bacterial wilt (*R. solanacearum*) initial and final mean disease incidence (%) at Teppi and Jimma, Ethiopia, during the 2017 main cropping season**

| Treatment combination[1] | Mean disease incidence (%) at Teppi[2] | | | | Mean disease incidence (%) at Jimma[2] | | | |
|---|---|---|---|---|---|---|---|---|
| | Local | | Boziab | | Local | | Boziab | |
| | $PDI_i$ | $PDI_f$ | $PDI_i$ | $PDI_f$ | $PDI_i$ | $PDI_f$ | $PDI_i$ | $PDI_f$ |
| Control | 15.79$^{a}$ | 79.47$^{a}$ | 14.49$^{a}$ | 79.76$^{a}$ | 15.46$^{a}$ | 80.44$^{a}$ | 15.21$^{a}$ | 77.15$^{c}$ |
| L | 9.65$^{cd}$ | 63.02$^{d}$ | 6.48$^{f}$ | 48.74$^{g}$ | 8.02$^{ef}$ | 52.75$^{fg}$ | 6.93$^{ef}$ | 51.07$^{gh}$ |
| F | 11.91$^{b}$ | 58.88$^{e}$ | 9.64$^{cd}$ | 64.47$^{d}$ | 13.20$^{bc}$ | 64.45$^{d}$ | 11.73$^{c}$ | 63.60$^{d}$ |
| S | 14.37$^{a}$ | 75.24$^{b}$ | 15.30$^{a}$ | 77.87$^{a}$ | 14.94$^{a}$ | 78.92$^{ab}$ | 14.40$^{ab}$ | 75.21$^{bc}$ |
| L + F | 9.89$^{c}$ | 58.88$^{e}$ | 7.88$^{ef}$ | 64.48$^{d}$ | 7.86$^{ef}$ | 42.04$^{k}$ | 7.41$^{ef}$ | 46.96$^{ij}$ |
| L + S | 9.41$^{cd}$ | 75.24$^{b}$ | 10.00$^{c}$ | 52.15$^{f}$ | 9.93$^{d}$ | 54.72$^{ef}$ | 8.33$^{e}$ | 47.90$^{ij}$ |
| F + S | 14.70$^{a}$ | 69.44$^{c}$ | 9.60$^{cd}$ | 64.46$^{d}$ | 12.72$^{c}$ | 64.08$^{d}$ | 11.84$^{c}$ | 55.71$^{e}$ |
| L + F + S | 8.25$^{de}$ | 49.03$^{g}$ | 7.40$^{ef}$ | 45.85$^{h}$ | 7.20$^{ef}$ | 46.61$^{j}$ | 6.44$^{f}$ | 49.75$^{hi}$ |
| LSD (0.05) | | 2.19 | 1.02 | | ns | 2.81 | | |
| CV (%) | | 2.20 | 7.84 | | 8.93 | 2.80 | | |

[1] L = lemon grass; F = fertilizer; S = soil solarization; L + F = lemon grass with fertilizer application; L + S = lemon grass with soil solarization; F + S = fertilizer application with soil solarization; and L + F + S = lemon grass with fertilizer application and soil solarization

[2] $PDI_i$ = percent mean disease incidence at 45 and 60 days after planting (DAP) at Teppi and Jimma, respectively, and $PDI_f$ = percent mean disease incidence at 150 DAP. [ns] nonsignificant. Means followed by same letter(s) within adjacent columns of same parameter under each variety are not significantly different at 5% level of significance

treatment in variety Local (11.6) and in Boziab (12.5) than NTPP gained from the rest treatments. The next highest NTPP (10.7) was registered from plots treated with lemon grass in Local and combined application of lemon grass and soil solarization in Boziab (11.9), which was compared numerically, while the lowest NTPP was recorded from untreated control, which was 8.9 in variety Local and 8.10 in Boziab variety (Table 3). Similar trends were recorded for both varieties evaluated at Jimma experimental site.

#### Effect of bacterial wilt on number of fingers per rhizome

Analysis of variance for interaction of variety by cultural management practices showed highly significant ($P < 0.001$) variation in number of fingers per rhizome at both experimental locations and mean values are presented in Table 4. In this regard, plots that received Boziab with lemon grass, soil solarization and fertilizer application had the highest (7.7) number of fingers per rhizome at Teppi. Similarly, the same treatment obtained the maximum (6.9) number of fingers per rhizome in the

**Table 3 Interaction effects of ginger varieties by cultural management practices on plant height and number of tillers per plant at Teppi and Jimma, Ethiopia, during the 2017 main cropping season**

| Treatment combination[1] | Growth parameters at Teppi | | | | Growth parameters at Jimma | | | |
|---|---|---|---|---|---|---|---|---|
| | Plant height (cm) | | Tiller number | | Plant height (cm) | | Tiller number | |
| | Local | Boziab | Local | Boziab | Local | Boziab | Local | Boziab |
| Control | 54.83$^{i}$ | 55.03$^{hi}$ | 8.9$^{f}$ | 8.10$^{f}$ | 55.9$^{fg}$ | 53.3$^{g}$ | 7.1$^{fgh}$ | 6.8$^{h}$ |
| L | 58.97$^{ef}$ | 60.4$^{de}$ | 10.7$^{cd}$ | 9.5$^{ef}$ | 67.3$^{bc}$ | 60.7$^{d}$ | 9.3$^{bcd}$ | 9.2$^{cd}$ |
| F | 58.66$^{efg}$ | 59.53$^{e}$ | 10.5$^{cd}$ | 10.0$^{de}$ | 59.7$^{de}$ | 61.0$^{d}$ | 7.5$^{efg}$ | 7.4$^{efgh}$ |
| S | 55.46$^{hi}$ | 57.03$^{fgh}$ | 9.2$^{ef}$ | 10.0$^{de}$ | 56.7$^{f}$ | 56.9$^{f}$ | 7.8$^{e}$ | 6.9$^{gh}$ |
| L + F | 63.93$^{bc}$ | 64.9$^{b}$ | 10.5$^{cd}$ | 11.2$^{bc}$ | 68.2$^{abc}$ | 57.4$^{ef}$ | 9.9$^{b}$ | 9.2$^{cd}$ |
| L + S | 62.36$^{cd}$ | 63.86$^{bc}$ | 10.6$^{cd}$ | 11.9$^{ab}$ | 70.2$^{a}$ | 70.0$^{a}$ | 7.5$^{ef}$ | 9.8$^{bc}$ |
| F + S | 56.66$^{ghi}$ | 58.53$^{efg}$ | 10.5$^{cd}$ | 9.8$^{de}$ | 57.9$^{ef}$ | 66.7$^{c}$ | 9.0$^{d}$ | 7.1$^{fgh}$ |
| L + F + S | 64.06$^{bc}$ | 67.97$^{a}$ | 11.6$^{b}$ | 12.5$^{a}$ | 69.2$^{abc}$ | 69.8$^{ab}$ | 9.7$^{bc}$ | 10.9$^{a}$ |
| LSD (0.05) | ns | | 0.85 | | 2.5 | | 0.66 | |
| CV (%) | 2.14 | | 4.9 | | 2.61 | | 4.6 | |

[1] L = lemon grass; F = fertilizer; S = soil solarization; L + F = lemon grass with fertilizer application; L + S = lemon grass application with soil solarization; F + S = fertilizer application with soil solarization; L + F + S = lemon grass application with fertilizer and soil solarization. [ns] nonsignificant. Means followed by same letter(s) within adjacent columns of same parameter under each variety are not significantly different at 5% level of significance

Local variety as compared to other treatments and control plots at Teppi. The same story was maintained for number of fingers per rhizome at Jimma. Control plots recorded only 3.2 and 3.3 number of fingers per rhizome, which were half less than the mean value, in Local and Boziab variety, respectively, at Jimma. However, both ginger varieties recorded relatively lower number of fingers per rhizome in which Boziab recorded average number of fingers per rhizome of 6.0 at Teppi and 5.8 at Jimma.

**Effect of bacterial wilt on ginger rhizome yield**

Analysis of variance also revealed highly significant ($P<0.001$) variation for variety by cultural management practices in rhizome yield both at Teppi and at Jimma (Table 4). The highest (16.0 t $ha^{-1}$ in Boziab and 14.6 t $ha^{-1}$ in Local) rhizome yield was obtained from integrated application of lemon grass with soil solarization and soil fertilization, followed by plots treated with combined application of lemon grass and soil fertilization where 13.5 and 13.1 t $ha^{-1}$ rhizome yield were obtained in Boziab and Local variety, respectively, at Teppi. Similarly, the lowest rhizome yield was harvested from untreated plots, which was about 7.1–7.7 t $ha^{-1}$ at Teppi. Closely similar results were obtained for rhizome yield from both varieties at Jimma experimental location. Accordingly, untreated plots had lower rhizome yields (on average 7.4 t $ha^{-1}$ at Teppi and 8.4 t $ha^{-1}$ at Jimma) than rhizome yields obtained from other treated plots. In same analogy, the most integrated treatment provided higher net benefit with optimum marginal rate of return than others for each variety at both locations (data not shown).

The mean yield loss calculated against untreated plots due to bacterial wilt ranged from 51.4 to 51.9% at Teppi and 39.4 to 49.1% at Jimma (Table 5). Relative yield loss was reduced by all combinations of varieties with cultural practices. The most integrated treatment recorded none to only 10.9% relative yield loss in comparison with other treatments excluding the control. Following it, integrated application of lemon grass and soil fertilization caused the lowest (10.3% in Local and 15.6% in Boziab) mean relative yield loss at Teppi. More or less a similar trend in rhizome yield loss for both varieties was computed at Jimma.

**Association of disease and growth and yield parameters**

Computing correlation between final mean disease incidences and growth and yield parameters was important since change of wilt incidence influenced the response of growth and yield parameters during the experiment. Mean bacterial wilt incidence (at 150 DAP) had negative and highly significantly ($P\leq0.01$) correlation ($r=-0.90^{**}$ and $-0.88^{**}$) to rhizome yield in variety Boziab and Local at Teppi, respectively. Similarly, mean wilt incidence (at 135 DAP) was negatively and highly significantly ($P\leq0.01$) correlated with rhizome yield of Local ($r=-0.91^{**}$) and Boziab ($r=-0.92^{**}$) variety at Teppi (Table 6). Final mean disease incidence (at 135 DAP) and yield ($r=-0.91^{**}$ and $-0.85^{**}$) in Boziab and Local variety, respectively, at Jimma had negatively and highly significant ($P\leq0.01$) correlation.

Moreover, final mean disease incidence (at 150 DAP) and number of fingers per rhizome were observed to negatively and highly significantly ($P\leq0.01$) correlated

**Table 4 Interaction effects of ginger varieties by cultural management practices on number of fingers per rhizome and yield at Teppi and Jimma, Ethiopia, during the 2017 main cropping season**

| Treatment combination[1] | Ginger yield parameters at Teppi | | | | Ginger yield parameters at Jimma | | | |
|---|---|---|---|---|---|---|---|---|
| | Finger per rhizome | | Yield (t $ha^{-1}$) | | Finger per rhizome | | Yield (t $ha^{-1}$) | |
| | Local | Boziab | Local | Boziab | Local | Boziab | Local | Boziab |
| Control | $5.1^{fgh}$ | $5.0^{fgh}$ | $7.1^{g}$ | $7.7^{f}$ | $3.2^{f}$ | $3.3^{f}$ | $8.3^{e}$ | $8.4^{e}$ |
| L | $6.1^{cde}$ | $6.6^{bc}$ | $11.2^{d}$ | $11.7^{d}$ | $5.9^{d}$ | $7.4^{b}$ | $11.3^{cd}$ | $14.0^{b}$ |
| F | $5.9^{de}$ | $4.4^{h}$ | $11.3^{d}$ | $11.4^{d}$ | $5.4^{de}$ | $5.0^{e}$ | $9.0^{e}$ | $11.4^{cd}$ |
| S | $4.6^{h}$ | $5.5^{ef}$ | $8.3^{e}$ | $8.6^{e}$ | $3.6^{f}$ | $3.4^{f}$ | $9.1^{e}$ | $9.1^{e}$ |
| L + F | $5.9^{de}$ | $6.7^{bc}$ | $13.1^{c}$ | $13.5^{c}$ | $5.4^{de}$ | $6.6^{c}$ | $13.7^{b}$ | $14.5^{b}$ |
| L + S | $5.5^{efg}$ | $6.5^{bcd}$ | $11.5^{d}$ | $13.2^{c}$ | $5.2^{e}$ | $6.5^{c}$ | $11.1^{d}$ | $14.1^{b}$ |
| F + S | $4.8^{gh}$ | $5.6^{ef}$ | $8.5^{e}$ | $11.5^{d}$ | $5.4^{de}$ | $4.9^{e}$ | $11.8^{cd}$ | $11.0^{d}$ |
| L + F + S | $6.9^{b}$ | $7.7^{a}$ | $14.6^{b}$ | $16.0^{a}$ | $5.8^{d}$ | $9.2^{a}$ | $12.2^{c}$ | $16.5^{a}$ |
| LSD (0.05) | 0.74 | | 0.59 | | 0.59 | | 0.96 | |
| CV (%) | 7.7 | | 3.2 | | 6.6 | | 5.0 | |

[1] L = lemon grass; F = fertilizer; S = soil solarization; L + F = lemon grass with fertilizer application; L + S = lemon grass application with soil solarization; F + S = fertilizer application with soil solarization; and L + F + S = lemon grass application with fertilizer and soil solarization. Means followed by same letter(s) within adjacent columns of same parameter under each variety are not significantly different at 5% level of significance

**Table 5 Effects of lemon grass, soil solarization and fertilizer application on rhizome yield (t ha$^{-1}$) and rhizome yield losses at Teppi and Jimma, Ethiopia, during the 2017 main cropping season**

| Variety | Treatment combination[1] | Relative yield loss (%) at Teppi | | | Relative yield loss (%) at Jimma | | |
|---|---|---|---|---|---|---|---|
| | | Yield (t ha$^{-1}$) | Relative yield (%) | Relative yield loss (%) | Yield (t ha$^{-1}$) | Relative yield (%) | Relative yield loss (%) |
| Local | Control | 7.1 | 48.6 | −51.4 | 8.3 | 60.6 | −39.4 |
| | L | 11.2 | 76.7 | −23.3 | 11.3 | 82.5 | −17.5 |
| | S | 8.3 | 56.8 | −43.2 | 9.1 | 66.4 | −33.6 |
| | F | 11.3 | 77.4 | −22.6 | 9.0 | 65.7 | −34.3 |
| | L+S | 11.5 | 78.8 | −21.2 | 11.1 | 81.0 | −19.0 |
| | L+F | 13.1 | 89.7 | −10.3 | 13.7 | 100 | 0.00 |
| | F+S | 8.5 | 58.2 | −41.8 | 11.8 | 86.1 | −13.9 |
| | L+F+S | 14.6 | 100 | 0.00 | 12.2 | 89.1 | −10.9 |
| Boziab | Control | 7.7 | 48.1 | −51.9 | 8.4 | 50.9 | −49.1 |
| | L | 11.7 | 73.1 | −26.9 | 14.0 | 84.8 | −15.2 |
| | S | 8.6 | 58.3 | −46.3 | 9.1 | 55.2 | −44.8 |
| | F | 11.4 | 71.3 | −28.8 | 11.4 | 69.1 | −30.9 |
| | L+S | 13.2 | 82.5 | −17.5 | 14.1 | 85.5 | −14.5 |
| | L+F | 13.5 | 84.4 | −15.6 | 14.5 | 87.9 | −12.1 |
| | F+S | 11.5 | 71.9 | −28.1 | 11.0 | 66.7 | −33.3 |
| | L+F+S | 16.0 | 100 | 0.00 | 16.5 | 100 | 0.00 |

[1] L = lemon grass; F = fertilizer; S = soil solarization; L + F = lemon grass with fertilizer application; L + S = lemon grass application with soil solarization; F + S = fertilizer application with soil solarization; L + F + S = lemon grass application with fertilizer and soil solarization

($r = -0.84^{**}$ for variety Boziab) and ($r = 0.82^{**}$ for Local variety) in the cropping season at Jimma (Table 7). More or less similar phenomena were noted for the correlation between mean wilt incidence and growth parameters of both ginger varieties at both locations.

The linear regression of final mean wilt incidence better described the relationship between rhizome yield and wilt incidence than other disease parameters (Fig. 1). The relationship described by the model accounted for 70.5–85.0% of the variance. The estimated slope of the regression line obtained for variety Boziab was −0.18 at Teppi and −0.22 at Jimma, whereas it was −0.19 and −0.12 for Local variety at Teppi and Jimma, respectively. The estimates showed that for each unit increase in percent of final mean wilt incidence, there was a rhizome yield reduction of 0.18 t ha$^{-1}$ for Boziab and 0.19 t ha$^{-1}$ for Local variety at Teppi and 0.22 and 0.12 t ha$^{-1}$ for Boziab and Local ginger varieties at Jimma, respectively.

## Discussion

To date, there is no single and effective control measure against bacterial wilt causing pathogen [25, 33]. However, in this study, lower wilt incidence and higher reductions in mean wilt incidence were possible through the application of cultural management practices alone and in integration than control plots across locations. This might be attributed to availability of nutrients, release of essential oils and enhanced population of soil beneficial microorganisms. Available nutrients could increase crop vigor and essential oils might incorporate lethal chemicals that could reduce wilt epidemics. Previous studies with regard to bio-fumigation by *Brassica* spp., palmarosa and lemongrass followed by mulching released volatile essential oils into pathogen-infested fields and reduced bacterial wilt incidence [34]. Such plants have high glucosinolate, and upon mulching, it hydrolyzes to antimicrobial isothiocyanates, nitriles or thiocyanates, thereby reducing *R. solanacearum* populations in the soil and wilt incidence on the crops [7, 35].

A related study also revealed that soil amendment with *Sesbania sesbana* and *Leucaena diversifolia* either singly or in combination with inorganic fertilizer reduced wilt incidence or increased potato tuber yield [18]. Similarly, Blok et al. [35] found an effective control of soil-borne pathogens by applying fresh organic amendments followed by plastic mulching. Moreover, Ayana et al. [19] noted that application of silicon fertilizer significantly reduced bacterial population and wilt incidence which could be attributed to induced resistance [36] and increased tomato fruit yield. A study by Lemaga et al. [28] also indicated that application of potassium fertilizer reduced bacterial wilt by 29% over the control in potato.

Comparative growth advantage recorded due to application of soil amendment could be due to increased soil

**Table 6 Coefficients of correlation (*r*) between growth, yield and disease incidence in ginger varieties at Teppi, Ethiopia, during the 2017 main cropping season**

| Variety | Parameter[a] | Yield (t ha$^{-1}$) | Finger per rhizome | Plant height | Tiller per plant | FDI (135 DAP) | FDI (150 DAP) |
|---|---|---|---|---|---|---|---|
| Boziab | Yield (t ha$^{-1}$) | 1 | | | | | |
| | Finger per rhizome | 0.71** | 1 | | | | |
| | Plant height | 0.94** | 0.75** | 1 | | | |
| | Tiller per plant | 0.78** | 0.65** | 0.89** | 1 | | |
| | FDI (135 DAP) | −0.90** | −0.73** | −0.84** | −0.61** | 1 | |
| | FDI (150 DAP) | −0.91** | −0.75** | −0.86** | −0.64** | 0.98** | 1 |
| Local | Yield (t ha$^{-1}$) | 1 | | | | | |
| | Finger per rhizome | 0.76** | 1 | | | | |
| | Plant height | 0.88** | 0.62** | 1 | | | |
| | Tiller per plant | 0.81** | 0.66** | 0.70** | 1 | | |
| | FDI (135 DAP) | −0.88** | −0.62** | −0.89** | −0.74** | 1 | |
| | FDI (150 DAP) | −0.92** | −0.64** | −0.93** | −0.76** | 0.98** | 1 |

[a] FDI = final disease incidence

** Describes level of statistical significance at $P \leq 0.01$

**Table 7 Coefficients of correlation (*r*) between growth, yield and disease incidence in ginger varieties at Jimma, Ethiopia, during the 2017 main cropping season**

| Variety | Parameter[a] | Yield (t ha$^{-1}$) | Finger per rhizome | Plant height | Tiller per plant | FDI (135 DAP) | FDI (150 DAP) |
|---|---|---|---|---|---|---|---|
| Boziab | Yield (t ha$^{-1}$) | 1 | | | | | |
| | Finger per rhizome | 0.96** | 1 | | | | |
| | Plant height | 0.61** | 0.63** | 1 | | | |
| | Tiller per plant | 0.92** | 0.93** | 0.61** | 1 | | |
| | FDI (135 DAP) | −0.91** | −0.84** | −0.68** | −0.80** | 1 | |
| | FDI (150 DAP) | −0.92** | −0.84** | −0.64** | −0.79** | 0.99** | 1 |
| Local | Yield (t ha$^{-1}$) | 1 | | | | | |
| | Finger per rhizome | 0.64** | 1 | | | | |
| | Plant height | 0.64** | 0.67** | 1 | | | |
| | Tiller per plant | 0.80** | 0.64** | 0.44* | 1 | | |
| | FDI (135 DAP) | −0.85** | −0.82** | −0.81** | −0.78** | 1 | |
| | FDI (150 DAP) | −0.83** | −0.80** | −0.87** | −0.73** | 0.98** | 1 |

[a] FDI = final disease incidence

** Describes level of statistical significance at $P \leq 0.01$ and * level of statistical significance at $P \leq 0.05$

health and improved physical and chemical status of the soil, which in turn reduced infection by soil pathogens. In this connection, Bailey and Lazarovits [37] indicated that organic amendments to soil have direct effect on plant health and crop productivity through improving the physical, chemical and biological properties of the soil, which can have positive effects on plant growth. On the other hand, degradation of organic matter in soil directly affects the viability and survival of a soil pathogen by restricting available nutrients and releasing natural chemical substances with varying inhibitory properties and stimulates the activities of microorganisms that are antagonistic to the pathogens [38] and increases soil microbial activities, thereby leaving to intense competition [37].

Cultural practices are the most popular approaches to manage bacterial wilt by reducing incidence and severity of wilt and consequently sustaining productivity of crops. The mechanisms of disease suppression and increase in rhizome yield and its components were supposed to be an increase in soil nutrients, changes in physical and chemical properties of the experimental soil due to fertilizer and lemon grass incorporation. In this regard, lemon grass might release essential oils to the soil and reduce bacterial population. Moreover, soil solarization could enhance the capabilities of beneficial microbes against

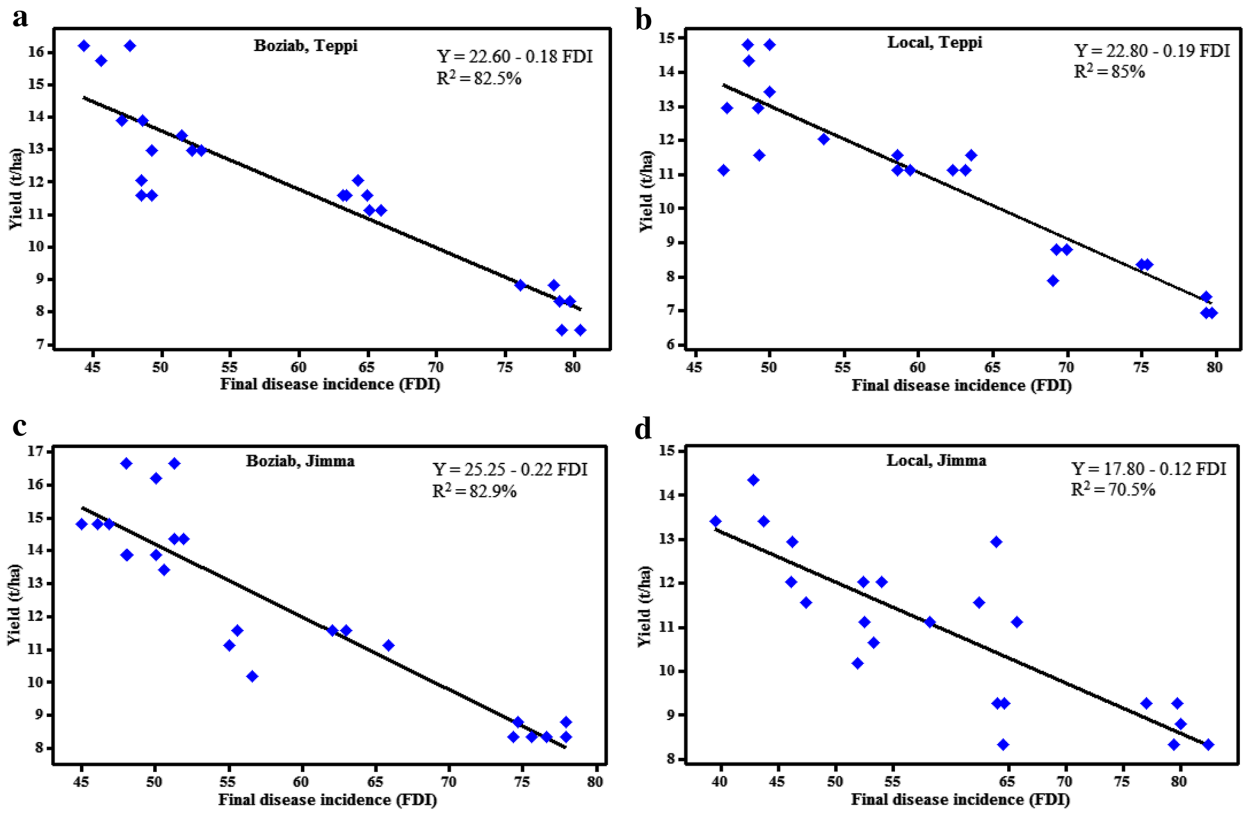


**Fig. 1** Linear regression relating ginger rhizome yield (t $ha^{-1}$) with bacterial wilt (*R. solanacearum*) final mean disease incidence (FDI) at 150 days after planting at Teppi (**a**, **b**) and at Jimma (**c**, **d**), Ethiopia

the target pathogen. Subsequently, such treatment combination might have reduced wilt incidence, in one hand, and increased rhizome yield and its components, on the other hand.

In line with this finding, Yadessa et al. [39] found that soil amendments with cocoa peat, farmyard manure, compost and green manure significantly reduced bacterial wilt incidence by 81% and enhanced tomato yield over unamended soil. Some other studies also noted that lemon grass oil provided complete protection from tomato wilt by reducing pathogen population and increased yield under controlled conditions, and disease suppression reached 45–60% under field conditions [40]. However, efficacy of lemon grass excelled when integrated with other soil amendment tactics under field conditions [41]. Furthermore, related findings demonstrated that soil solarization combined with fumigant [42] and with biological control agents [22] reduced incidence of tomato bacterial wilt and increased fruit yield.

Due to integrated application of lemon grass with soil solarization and fertilization, yield gains of 51.6 and 31.6% were obtained for Local and 51.9 and 48.6% for Boziab variety at Teppi and Jimma, respectively. Theoretically, integrated disease management is intended to eliminate or reduce effectiveness of initial inocula, increase resistance of hosts, delay onset of disease and slow secondary cycles of infections [43]. This might imply that lemon grass bio-fumigation with soil solarization and fertilizer application highly reduced *R. solanacearum* population and subsequent damage on ginger by various mechanisms. Previous research results have also shown that application of *Brassica* spp. as green manure is effective in reducing soilborne pathogens through the release of toxic and volatile chemicals up on decomposition [44]. Application of plastic mulch, following green manure incorporation, would enhance the decomposition process, minimize escape of volatile gases into the atmosphere and raise soil temperature to kill soilborne pathogen propagules and as a result reduce the yield losses of the plant due to disease [45].

Findings of this study also confirmed the presence of highly and negatively significant correlation and association between wilt incidence and growth and yield parameters. This could assert the negative effects of bacterial wilt on growth, rhizome yield and its component of ginger during the cropping season. This complies with the findings of [46] who found that late blight disease parameters are strongly and negatively correlated with final tuber yields. Research reports of Fekede [47] also confirmed that disease parameter is associated with yield components but had negative impacts on the components under consideration. There are inverse relations between chocolate spot disease and grain yield and its components in faba bean in sole and mixed cropping systems [48].

## Conclusions

The present field data provided empirical evidences that the interaction of varieties and cultural practices influenced the amount of yield loss attributed to ginger bacterial wilt. Integration of host resistance with cultural management practices increased rhizome yield and yield components, improved ginger growth and maximized net benefit compared to alone application of cultural practices and untreated control. Results demonstrated that, among treatments used, combined application of host resistance with lemon grass, soil solarization and soil fertilization enhanced rhizome yield and growth parameters and highly reduced associated damages due to bacterial wilt incidence and earned high monetary benefits over untreated controls. These present findings can benefit farmers through increased productivity and can increase produces and income via reduced inputs and nonchemical means in the face of bacterial wilt epidemics. However, further research should be undertaken on host resistance in integration with other cultural management practices and an urgent need is also required to establishing disease-free ginger seed rhizome production.

#### Abbreviations

DAP: days after planting; HWT: hot water treatment; JARC: Jimma Agricultural Research Center; NFPP: number of fingers per plant; NTPP: number of tillers per plant; PDI: percent mean disease incidence; RYL: relative yield loss; TNSC: Teppi National Spices Research Center.

#### Authors' contributions

MJG initiated and executed the field experiment, managed and followed the field, collected data and wrote the draft manuscript. HTY was the main advisor who guided the field study, underwent the analysis, edited and reorganized the draft manuscript. EDK was the advisor who co-guided the field work and edited the manuscript. All authors read and approved the final manuscript.

#### Author details

[1] Teppi National Spices Research Centre, P.O. Box 134, Teppi, Ethiopia. [2] School of Plant Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia. [3] Ethiopian Institute of Agricultural Research, P.O. Box 2003, Addis Ababa, Ethiopia.

#### Acknowledgements

The study was financed by Ethiopian Institute of Agricultural Research (EIAR). The contributions of individuals, who involved directly and indirectly in field follow up and data collection, are well acknowledged. We are also very grateful to farmers and daily laborers who toiled during the field experiments.

#### Competing interests

The authors declare that they have no competing interests.

#### Availability of data and materials

All data generated from the study and reported in the manuscript are included in the article. Further data sets are available from the corresponding author upon request.

#### Consent for publication

Not applicable.

#### Ethics approval and consent to participate

It is not applicable to this study.

#### Funding

The study was financed by Ethiopian Institute of Agricultural Research, and we are very grateful to it.

## Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 5 November 2018 Accepted: 19 December 2018
Published online: 10 January 2019

#### References

1. Sharma BR, Dutta S, Roy S, Debnath A, Roy MD. The effect of soil physico-chemical properties on rhizome rot and wilt disease complex incidence of ginger under hill agro climatic region of West Bengal. J Plant Pathol. 2010;26:198–202.
2. Minima A, Sentayehu A, Girma HM, Abush T. Variability of ginger (*Zingiber officinale* Rosc) accessions for morphological and some quality traits in Ethiopia. Int J Agr Res. 2011;6:444–57.
3. Jansen PCM. Spices, condiments and medicinal plants in Ethiopia: their taxonomy and agricultural significance. Centre for Agriculture publishing and documentation, Wageningen, The Netherlands. J Gen Microbiol. 1981;98:39–66.
4. Girma H, Digafie T. Annual report on the current status of spice s research, Jimma, Agricultural Research Centre, Teppi Agricultural Research Sub-Centre; 2004.
5. Wubshet Z. Economic importance and management of ginger bacterial wilt caused by *Ralstonia solanacearum*. Int J Res Stud Agric Sci. 2018;4(2):1–11.
6. Endrias G, Asfaw K. Production, processing and marketing of ginger in Southern Ethiopia. J Hortic For. 2011;3:207–13.
7. Paret ML, Cabos R, Kratky BA, Alvarez AM. Effect of plant essential oils on *Ralstonia solanacearum* race 4 and bacterial wilt of edible ginger. Plant Dis. 2010;94:521–7.
8. Kumar A, Sarma YR. Characterization of *Ralstonia solanacearum* causing bacterial wilt of ginger in India. Indian Phytopathol. 2005;57:12–7.
9. Habetewold K, Bekelle K, Kasahun S, Tariku H. Prevalence of bacterial wilt of ginger (*Zingiber Officinale*) caused by *Ralstonia Solansearum* (Smith) in Ethiopia. Int J Res Stud Agric Sci. 2015;6:14–22.
10. Kurabachew H, Ayana G. Bacterial wilt caused by *Ralstonia solanacearum* in Ethiopia: status and management approach. Int J Phytopathol. 2016;5(3):107–19.
11. Zhang G, Fan G, Zhu H, Zheng J, Wang J, Ding A, et al. Study on the pathogen of the ginger wilt disease in Shandong. J Shandong Agric Univ. 2001;32(4):418–22.
12. Tariku H, Kassahun S, Gezahegne G. First report of ginger (*Zingiber officinale*) bacterial wilt disease in Ethiopia. Res J Agric For Sci. 2016;4(4):5–9.
13. Nair KP. The agronomy and economy of turmeric and ginger: The valuable medicinal spice crops. London: Elsevier; 2013.
14. Tahat MM, Sijam K. Roasting solanacearum: the bacterial wilt causal agent. Asian J Plant Sci. 2010;9(7):385.
15. Kelman A, Hartman GL, Hayward AC. Introduction. In: Hayward AC, Hartman GL, editors. Bacterial wilt: the disease and its causative agent, *Pseudomonas solanacearum*. Wallingford: CAB International; 1994. p. 1–7.

16. Sarkar S, Chaudhuri S. Bacterial wilt and its management. Curr Sci. 2016;110(8):1439–45.
17. Cardoso SC, Soares ACF, Brito ADS, Laranjeira FF, Ledo CAS, Dos Santos AP. Control of tomato bacterial wilt through the incorporation of aerial part of pigeon pea and crotalaria to soil. Summa Phytopathol. 2006;32:27–33.
18. Lemaga B, Siriri D, Ebanyat P. Effect of soil amendments on bacterial wilt incidence and yield of potatoes in Southwestern Uganda. Afr Crop Sci J. 2001;9(1):267–78.
19. Ayana G, Fininsa C, Ahmed S, Wydra K. Effects of soil amendment on bacterial wilt caused by *Ralstonia solanacerum* and tomato yields in Ethiopia. J Plant Prot Res. 2011;51(1):72–6.
20. Jones JB Jr, Wolf B, Mills HA. Plant analysis handbook. Athens: MicroMacro Publishing Inc; 1991.
21. DeVay JE, Stapleton JJ, Elmore CL. Diseases when using pathogen tested (certified) planting material. Food and Agricultural Organization of the United Nations. FAO Report 109. Rome, Italy; 1990.
22. Kumar P, Sood AK. Management of bacterial wilt of tomato with VAM and bacterial antagonists. Indian Phytopathol. 2001;55:513–5.
23. Vinh MT, Tung TT, Quang HX. Primary bacterial wilt study on tomato in vegetable areas of Ho Chi Minch city, Vietnam. Bacterial Wilt Disease and the *Ralstonia solanacearum* Species Complex. St. Paul: American Phytopathological Society Press; 2005.
24. Bekele K, Berga L. Effects of preceding crop, variety and post emergence cultivation (hilling) on the incidence of bacterial wilt. In: Proceedings of the seventh triennial symposium of the international society for tropical root crops-Africa Branch; 11–17 October 1998. International Conference Center, Benin; 2001.
25. Lemessa F, Zeller W. Isolation and characterization of *Ralstonia solanacearum* strains from Solanaceae crops in Ethiopia. J Basic Microbiol. 2007;47:40–9.
26. Shamil A, Abebe G, Wakjira G. Study on performance evaluation of tomato (*Lycopersicon esculentum* Mill.) varieties under off-season condition at Teppi, Southwestern part of Ethiopia. Green J Agric Sci. 2017;7(5):120–5.
27. Lemi B, Sentayew A, Ashenafi A, Gerba D. Genotype × environment interaction and yield stability of Arabica coffee (*Coffea arabica* L.) genotypes. In: International conference on agriculture and horticulture; 02–04 October 2017. Agrotechnology 2018;6 Suppl 4. https://doi.org/10.4172/2168-9881-c1-028.
28. Lemaga B, Kakuhenzine R, Bekele K, Ewell PT, Priou S. Integrated control of potato bacterial wilt in eastern Africa: the experience of African highlands initiative. In: Allen P, Prior, Hayward AC, editors. Bacterial Wilt Disease and the *Ralstonia solanacearum* Species Complex. St. Paul, Minnesota: American Phytopathological Society Press; 2005. p. 145–58.
29. Matthiessen JN, Warton B, Shackleton MA. The importance of plant maceration and water addition in achieving high Brassica derived isothiocyanate levels in soil. Agro-industries. 2004;3:277–80.
30. Kelman A. The relationship of pathogenicity in *Pseudomonas solanacearum* to colony appearance on tetrazolium medium. Phytopathology. 1954;44:693–5.
31. SAS Institute. SAS/STAT user's guide, version 9.3. Cary: SAS Institute Inc; 2014.
32. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: Wiley; 1984.
33. Nelson S. Bacterial wilt of edible ginger in Hawai'i. Effect of plant essential oils on *Ralstonia solanacearum* race 4 and bacterial wilt of edible ginger. Plant Dis. 2013;94:521–7.
34. Arthy JR, Akiew EB, Kirkegaard JA, Trevorrow PR, Allen C, Prior P, et al. Using *Brassica* spp. as biofumigants to reduce the population of *Ralstonia solanacearum*. Bacterial wilt disease and the *Ralstonia solanacearum* species complex. 2005;159–65.
35. Blok WJ, Lamers JG, Termoshuizen AJ, Bollen GJ. Control of soil-borne plant pathogens by incorporating fresh organic amendments followed by taping. Phytopathology. 2000;90:253–9.
36. Diogo RVC, Wydra K. Silicon induced basal resistance in tomato against *Ralstonia solanacearum* is related to modification of pectic cell wall polysaccharide structure. Physiol Mol Plant Pathol. 2007;70:120–9.
37. Bailey KL, Lazarovits G. Suppressing soil-borne diseases with residue management and organic amendments. Soil Tillage Res. 2003;72(2):169–80.
38. Akhtar M, Malik A. Roles of organic soil amendments and soil organisms in the biological control of plant-parasitic nematodes: a review. Bioresour Technol. 2000;4(1):35–47.
39. Yadessa GB, van Bruggen AHC, Ocho FL. Effects of different soil amendments on bacterial wilt caused by *Ralstonia solanacearum* and on the yield of tomato. J Plant Pathol. 2010;92(2):439–50.
40. Ji P, Momol MT, Olson SM, Pradhanang PM, Jones JB. Evaluation of thymol as biofumigant for control of bacterial wilt of tomato under field conditions. Plant Dis. 2005;89:497–500.
41. Hong JC, Momol MT, Pingsheng J, Stephen SM, Colee J, Jones JB. Management of bacterial wilt in tomatoes with thymol and acibenzolar-S-methyl. Crop Prot. 2011;30:1340–5.
42. Yamada T, Kawasaki T, Nagata S, Fujiwara A, Usami S, Fujie M. New bacteriophages that infect the phytopathogen *Ralstonia solanacearum*. Microbiology. 2007;153:2630–9.
43. Agrios GN. Plant pathology. 5th ed. New York: Academic Press; 2005.
44. Brown J, Morra MJ. Glucosinolate containing seed meal as a soil amendment to control plant pests: 2000–2002 (No. NREL/SR-510-35254). National Renewable Energy Lab., Golden, CO, USA; 2005.
45. Katan J, DeVay JE. Soil solarization: historical perspectives, principles, and uses. In: Katan J, DeVay JE, editors. Soil solarization. Boca Raton: CRC Press; 1991. p. 23–37.
46. Bekele K, Gebremedhin W. Effect of planting dates on late blight severity and tuber yields on different potato varieties. Pest Manag J Ethiop. 2000;4:53–63.
47. Fekede G. Management of late blight (*Phytophthora infestans*) of potato (*Solanum tuberosum*) through potato cultivars and fungicides in Hararghe Highlands, Ethiopia Master's Thesis, Haramaya University, Ethiopia; 2011.
48. Sahile S, Fininsa C, Sakhuja PK, Ahmed S. Yield loss of faba bean (*Vicia faba*) due to chocolate spot (*Botrytis fabae*) in sole and mixed cropping systems in Ethiopia. Arch Phytopathol Plant Prot. 2010;43(12):1144–59.