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Integrated Management of Strawberry Crown and Root Rot caused by Fusarium solani in Greenhouse Conditions

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Data Availability Statement

The data supporting the findings of this study are publicly available and are included within this published article.

ORIGINAL ARTICLE

Integrated Management of Strawberry Crown and Root Rot Caused by *Fusarium solani* in Greenhouse Conditions

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Abstract

The strawberry, or *Fragaria* x *ananassa* Duch., is a crop grown extensively around the world, including Kurdistan. However, the crop is frequently compromised by soil-borne pathogens, particularly the fungal pathogen *Fusarium solani*, which causes considerable damage and economic losses. The devastating nature of this disease has not been adequately controlled by traditional techniques of disease management. This study aimed to integrate multiple control strategies to mitigate the impact of *F. solani* on strawberry production. Strawberry samples were collected from the region, and after the pathogen was isolated, investigations revealed that *F. solani* was the main culprit causing crown and root rot of the crop. In a controlled greenhouse environment, eleven individual and combinatory control methods were tested on potted strawberry plants. Disease severity was assessed and analyzed statistically. The findings revealed a significant difference in the efficacy of the treatments, with treatments T3 (sumac extract), T4 (Pristine fungicide), and T9 (Gathering *Trichoderma harzianum* and Pristine) demonstrating superior disease prevention capabilities. Moderate control was observed with treatments T2 (*Trichoderma harzianum*) and T5 (Gathering *Pseudomonas flaorescens* and *Trichoderma harzianum*), while T6 (Gathering *Pseudomonas flaorescens* and sumac extract), T10 (Gathering sumac extract and Pristine), and T8 (Gathering *Pseudomonas flaorescens* and Pristine) exhibited minimal effectiveness. These results are fundamental for developing integrated pest management (IPM) strategies that optimize disease control in strawberry cultivation, emphasizing sustainable practices that reduce reliance on fungicides. By adopting these integrated methods, strawberry producers in Kurdistan can enhance crop resilience and sustainability.

Keywords: Integrated management, *Fusarium solani*, *Trichoderma harzianum*, *Pseudomonas flaorescens*, Plant extract

1. Introduction

Strawberry (*Fragaria* x *ananassa* Duch.) is an economically important crop worldwide that can be consumed as either fresh or processed (i.e. jams, juices, and jelly) [1]. Strawberry cultivation in Southern Region of Kurdistan has recently witnessed significant expansion due to the advancements in agricultural practices and the adoption of innovative farming techniques [2,3]. However, it has been observed that a number of soil-borne diseases, including *Macrophomina phaseolina*, *Rhizoctonia* spp., and *Fusarium* spp., cause considerable harm and losses to strawberry plants [4,5]. These fungi cause wilt, black root rot, and rot diseases [6,7]. In recent times, soil-borne pathogenic fungi like *M. phaseolina*, identified as the cause of charcoal rot [8], and *F. solani* [9] responsible for crown and root rot, have emerged in strawberry crops in Spain. *Fusarium solani* is a complex (*Fusarium solani* species complex, FSSC) comprising approximately 50 phylogenetic species [10,11]. These species within the FSSC are widespread and can be encountered as soil-dwelling saprophytes, inhabitants of the rhizosphere, or agents causing diseases in numerous plant species. *Fusarium solani* is a widely distributed fungus found

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in diverse habitats, such as soil and plant debris, where it is frequently isolated. In strawberries, *F. solani* is a significant pathogen responsible for root and crown rot, leading to wilting and severe yield reductions. This pathogen poses a major challenge for strawberry growers globally [12].

Crown and root disease control in strawberries is challenging because the causal pathogens, such as *F. solani*, can survive in the soil as resistant structures (chlamydospores), and are disseminated by various means, including wind, soil, and infected plant material [13]. Several studies have explored biological control methods to manage soil-borne diseases in strawberries. Examples include the use of *Gliocladium* and *Trichoderma* as reported by Rahman et al. [14] and various *Trichoderma* species investigated by Liu et al. [15]. *Trichoderma* species are now widely used as biological agents to protect crops from plant diseases [16]. They can inhibit plant pathogens through antibiosis, competition, cross-protection, hyperparasitism, induced resistance, and direct predation. The use of *Trichoderma harzianum, T. viride, and T. asperellum* has successfully inhibited Fusarium wilt [17]. Additionally, research by Mirzaeipour et al. [18] demonstrated that *T. harzianum* effectively reduced the severity of black root rot in strawberry plants. Abied et al. [19] concluded that *T. viride*, *T. hamatum*, and *T. harzianum* exhibited antagonistic properties against *Rhizoctonia fragariae* and *Fusarium solani*, the pathogens responsible for strawberry root rot. Another important biocontrol agent in this study is *Pseudomonas fluorescens* which recognized for their capacity to act as biological control agents in managing fungal diseases in plants [20]. These bacteria have garnered significant attention in agricultural biotechnology due to their multifaceted mechanisms for suppressing phytopathogenic fungi, enhancing plant health, and promoting sustainable agricultural practices [21]. *Pseudomonas fluorescens* has demonstrated effectiveness in managing Fusarium wilt in tomatoes and crown and root rot in strawberries. Its ability to produce antifungal metabolites and colonize roots has proven critical in disease suppression [22,23]. Furthermore, *P. fluorescens* exhibited antagonistic properties against several fungal pathogens, including *M. phaseolina*, *Helminthosporium tetramere*, *Alternaria tenuis*, as well as the soil-borne fungi *F. solani*, and *Sclerotinia rolfsii* [24]. Additionally, to the above-mentioned bioagents *T. harzianum* and *P. flurescens*, studies have demonstrated that plant extracts exhibit antimicrobial properties [25,26]. For this purpose, extracts derived from sumac (*Rhus* spp.), have gained significant attention in agriculture and food sciences due to their potent antifungal activity, because they contain bioactive compounds, including tannins, flavonoids, and phenolic acids, contribute to its ability to combat a wide range of fungal pathogens [27]. In agriculture, sumac extract has shown efficacy against soil born pathogens, post-harvest decay, and foliar diseases, offering a sustainable solution for crop protection. Furthermore, its natural origin and low toxicity make it an appealing option for organic farming systems [28]. Evidence from numerous prior studies highlighted those extracts obtained from sumac exhibited significant efficacy as growth inhibitors against several fungal pathogens on tomato plant, including *Fusarium oxysporum*, *F. solani*, *Rhizoctonia solani*, *Colletotrichum truncatum*, *Colletotrichum coccodes*, and *Alternaria alternata* [29].

The cultivation of strawberries mainly depends on using chemical fumigants for soil disinfestation. To lessen the economic losses caused by the phase-out of soil fumigants, strawberry growers can explore alternative pathogen control methods such as biological controls, crop rotation, and resistant varieties [30]. Integrated pest and disease management can benefit from several techniques to preserve the best possible crop health while guaranteeing high yields and sustainability [31]. Implementing integrated crop management (ICM) practices and investing in research and development of sustainable soil management techniques can also help minimize the impact on strawberry production and reduce the need for expensive control measures [32]. Furthermore, practicing ICM relays less on chemical substances in crop production and more on ecofriendly control agents [33]. Due to the prevalent destructive disease in the Kurdistan Region and the lack of convenient control methods, this work was achieved to manage the disease by integrating several methods as alternatives to the conventional control methods.

2. Materials and methods

2.1. Sample collection

Strawberry plants displaying signs of wilting were gathered from different nurseries in Erbil Province that provide strawberry seedlings throughout the season. On a Potato Dextrose Agar (PDA) medium, the root rot pathogens from the affected strawberry roots were separated. Hyphal tip methods were used to purify the resultant fungal cultures. Following a microscopical examination, these pure cultures were recognized using the taxonomic keys developed by Watanabe [34].

2.2. Preparation of the materials

2.2.1. Preparation of Fusarium solani inoculation

As a major fungal pathogen, the conidial suspension of *F. solani* was prepared from 5- to 7-day-old colonies growing on PDA by adding sterilized distilled water into the petri dish that contained the pathogen. Then a sterilized disposable loop scraped the colony's surface, then the suspension was filtered through three layers of muslin to remove any part of agar particles. Then the spore suspension was adjusted to 10^6 conidia/ml, calculated by adding about 50 µl of the conidial suspension by micropipette into the groove of the Hemocytometer (Improved Neubauer, Weber Scientific International, Sussex, UK). The suspension was left for 2–3 min for spores to stabilize, and then the counting started.

2.2.2. Preparation of aqueous plant extract

Seeds of Sumac (*Rhus coriaria*), were extracted and selected as an anti-fungal agent that exhibits anti-fungal activity against several plant pathogens [27]. The maceration technique was selected for the extraction process using water, based on methods described by Muthomi et al. [35] with a slight modification. Sterilized distilled water (SDW) was used at a ratio of 1:10, by adding 500 ml of SDW to 50 g of plant powder in a sterilized, screw-capped glass container. The containers were shaken on a locally made horizontal shaker for 24 h to expedite the extraction. The extracts were then filtered using a Büchner funnel connected to a vacuum pump system. An absorbent wound dressing sheet (ViTri Medical, Sweden) cut into circles was placed over Whatman #1 filter paper (Merck, Germany). Subsequently, a 5000 ppm plant extract solution was prepared by adding 50 ml of the extract to 950 ml of sterilized distilled water.

2.2.3. Preparation of the bioagents

The commercial products of the antagonistic fungus *T. harzianum* and bacterium *P. flaorescens* were obtained from ready-to-use powder (Organic Dews, India). The commercial products have been used at a rate of 1 Kg per 1000 m^2 or 1 Kg per 50 L of water.

2.2.4. Preparation of the fungicide

Pristine, a fungicide containing Pyraclostrobin and Boscalid (manufactured by BASF Corporation/USA) was used in control experiments for comparison with other treatments. The fungicide was applied as water-dispersible granules at a rate of 50 g/100 L.

2.3. Control experiment

This experiment was conducted in greenhouse conditions in pots (15 cm diameter) in February 2024. In the preparation of the pathogenic fungus *F. solani* as mentioned before, plants were was inoculated with a conidial suspension (adjusted to 10^6 conidia/mL) by adding the conidial suspension to the peatmoss at a rate of 100 ml/2 kg of peatmoss at the beginning of the experiment. One-month old seedlings were grown in pots containing 2 kg of peatmoss. The experiment contained eleven treatments listed in Table 1. The untreated control, inoculated with the pathogen only. The experiment was complete randomized design (CRD) in five

Table 1. The treatments and their descriptions used in the control experiments.

Treatment symbol	Treatment description
T1	Strawberry seedlings treated with 750 mg of *Pseudomonas flaorescens* manufactured powder to 95 g of peatmoss inoculated with *Fusarium sp.* conidial suspension.
T2	Strawberry seedlings treated with 750 mg of *Trichoderma harzianum* manufactured powder to 95 g of peatmoss inoculated with *Fusarium sp.* conidial suspension.
T3	Treating 5 strawberry seedlings with sumac (*Rhus coriaria*) plant extract at a rate of 1000 ml of the plant extract for the treatment which the volume was halved and added to the inoculated peatmoss and the other half was irrigated to the planted seedling in the pods.
T4	Treating 5 strawberry seedlings by adding 0.2 mg of fungicide to 2 g root weight of the seedling as the instruction of the manufactured product requires it only at the beginning of the experiment.
T5	Gathering *Pseudomonas flaorescens* and *Trichoderma harzianum*
T6	Gathering *Pseudomonas flaorescens* and sumac extract
T7	Gathering *Trichoderma harzianum* and sumac extract
T8	Gathering *Pseudomonas flaorescens* and Pristine
T9	Gathering *Trichoderma harzianum* and Pristine
T10	Gathering sumac extract and Pristine
T11	Integration of Trichoderma, Pseudomonas, sumac extract, and Pristine
PC	Positive or untreated control, the seedlings inoculated with the pathogen only.
NC	Untreated and uninoculated control

replicates. Data, represented development of symptoms, was measured 90 days after inoculation.

2.4. Disease assessment and data analysis

The disease was assessed visually on both root and crown and foliage depending on the symptoms that appeared. The assessment was by dedicating 0–5 disease severity scale modified from 0 to 4 evaluation scale [36] accounting for the percentage of visible symptoms, wilt and yellowing, on foliage parts or necrosis and darkness on roots, and crowns. Vascular wilt caused by *F. solani* assessed on a 0–5 disease severity scale, where: 0 = no vascular tissue discolored; 1 = <25 % vascular tissue discolored; 2 = ≥25 %, <50 % vascular tissue discolored; 3 = ≥50 %, <75 % vascular tissue discolored; 4 = ≥75 % vascular tissue discolored; 5 = all vascular tissue discolored, plant dead. Then from the disease assessment data, the disease severity index (DSI) was calculated using the following formula [37]:

$$DSI\,\% = \Sigma\,(n \times v) \times 100/x \times N$$

Where: n = number of plants in each assessed category (Infection degree); v = infection degree (0–5); x = highest scale range (in this case = 5) and N = total number of assessed plants. To compute the percentage of disease inhibition (PDI), this formula was used [38]:

$$PDI = (DIUC - DIIT) * 100/DIUC$$

Where:

PDI = percentage of disease inhibition

DIUC = disease incidence in untreated control

DIIT = disease incidence in the interesting treatment

Data was analyzed using Statgraphics XV5 to find ANOVA table and means compared using Fischer's least significant difference (LSD) test at $P = 0.05$. Data were square root transformed when necessary to minimize the variability to achieve normal distribution.

3. Results and discussion

The symptoms were assessed after three months from inoculations and applying treatments (Fig. 1). The results of measuring the disease severity index (DSI) of the aboveground plant parts have shown that both T3 and T4 had no disease severity (0 %), showing the best control of the disease (Fig. 2). They completely prevented the disease (Fig. 3) followed by T5, which had very low disease severity (4 %) and very high disease inhibition (96 %), showing a highly effective treatment, though not as perfect as T3 and T4. T6 and T9 treatments had moderate control, with around 20, and 24 % disease severity and inhibition percentages of 80 and 76 %, respectively. This indicates they were somewhat effective but did not prevent the disease or the earlier treatments. T1 (32 %) and T11 (40 %), showed medium disease severity, with T1 at 32 % and T11 at 40 %. These treatments had a higher disease level than the more effective ones (T3, T4, T5), but still managed better than some others.

However, T7 (44 %), T10 (52 %), T8 (56 %), T2 (56 %): These treatments demonstrated relatively high disease severity, ranging from 44 % to 56 %. While these are not as severe as the positive control, they were not as effective in controlling the disease. Positive Control (PC) as expected, had the highest disease severity at 80 %. This indicates that without any treatment or with minimal intervention, the disease severity would be extremely high.

The findings of the measures of disease severity on the aboveground plant parts offer important information about how well different treatments work to control the disease. Treatments T3 and T4 were the best at totally stopping the progression of the disease because they showed outstanding disease prevention with 0 % disease severity and inhibition (Fig. 2). Since these treatments provided the best control and completely stopped the disease from developing (Fig. 3), they may work through mechanisms that either increase the plant's resistance or limit the pathogen's entry. The most effective way to combat plant diseases, particularly those that affect the crops' crown and roots, is to combine multiple control techniques [39], in which T3 (sumac extract) contains substances that have biological activities [27] while T4 (Pristine, a fungicide containing two different active ingredients, Pyraclostrobin and Boscalid) has different modes of action, in which Pyraclostrobin, a quinone outside inhibitor, inhibits the electron transport chain in the mitochondrial respiratory chain at the bc1 complex, whereas Boscalid differs from the strobilurins and most other fungicides in both its mode and site of action. It inhibits the enzyme succinate ubiquinone reductase, also known as complex II, in the mitochondrial electron transport chain [40]. T5 was next in line, exhibiting low disease severity at 4 %, suggesting that although it was not as flawless as T3 and T4, it still offered potent disease suppression. Since it may not always be possible to achieve complete disease avoidance (as in T3 and T4) in a variety of field circumstances, this treatment could be quite beneficial in actual agricultural practices. Our results are

Fig. 1. The symptoms on both aboveground and roots after 3 months from inoculation with spore suspension of F. solani *in pots in greenhouse. Where: the inoculated strawberry seedlings treated with:* P. flaorescens *(T1),* T. harzianum *(T2), Sumac* (Rhus coriaria) *extract (T3), Pristine fungicide (T4),* P. flaorescens *and* T. harzianum *(T5),* P. flaorescens *and Sumac extract (T6),* T. harzianum *and Sumac extract (T7),* P. flaorescens *and Pristine (T8),* T. harzianum *and Pristine (T9), Sumac extract and Pristine (T10), Integration of* T. harzianum, P. flaorescens, *Sumac extract, and Pristine (T11), PC representing untreated control where seedlings inoculated with the pathogen only.*

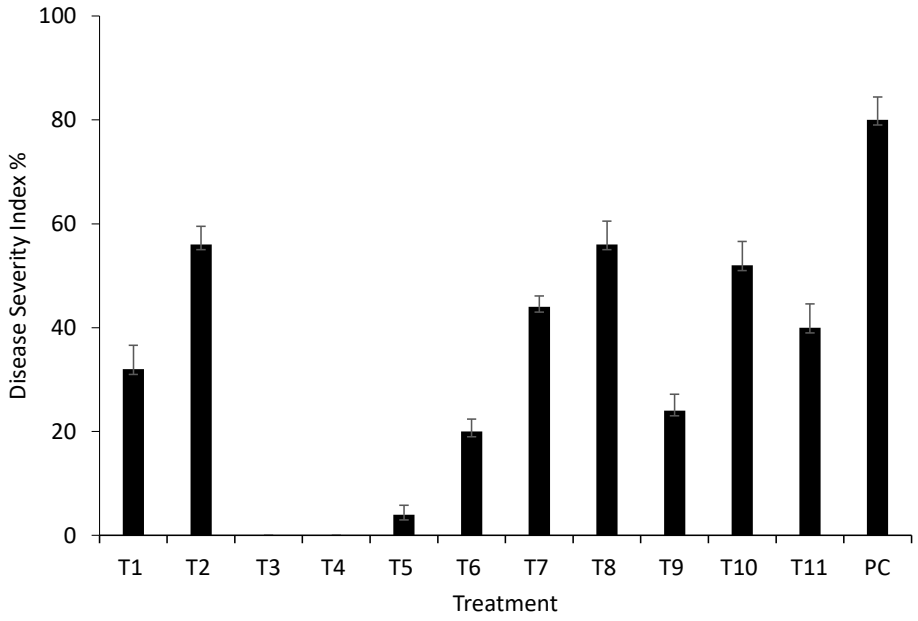

Fig. 2. The efficacy of integrated options on the severity of root rot symptoms in above-ground strawberry plants. Where: the inoculated strawberry seedlings treated with: P. flaorescens *(T1),* T. harzianum *(T2), Sumac (*Rhus coriaria*) extract (T3), Pristine fungicide (T4),* P. flaorescens *and* T. harzianum *(T5),* P. flaorescens *and Sumac extract (T6),* T. harzianum *and Sumac extract (T7),* P. flaorescens *and Pristine (T8),* T. harzianum *and Pristine (T9), Sumac extract and Pristine (T10), Integration of* T. harzianum*,* P. flaorescens*, Sumac extract, and Pristine (T11), PC representing untreated control where seedlings inoculated with the pathogen only, and NC representing negative control where seedlings immersed in water only. Error bars represent standard deviation and Fischer's least significant difference (LSD) test at P = 0.05 is 43.49.*

consistent with those of El-Marzoky et al. [41], who stated that combining multiple control methods will significantly reduce the incidence and severity of disease.

The treatments T6 and T9 offered moderate control, with disease severity levels of around 20 % and 24 %, respectively. While these treatments were somewhat effective in limiting disease spread, they

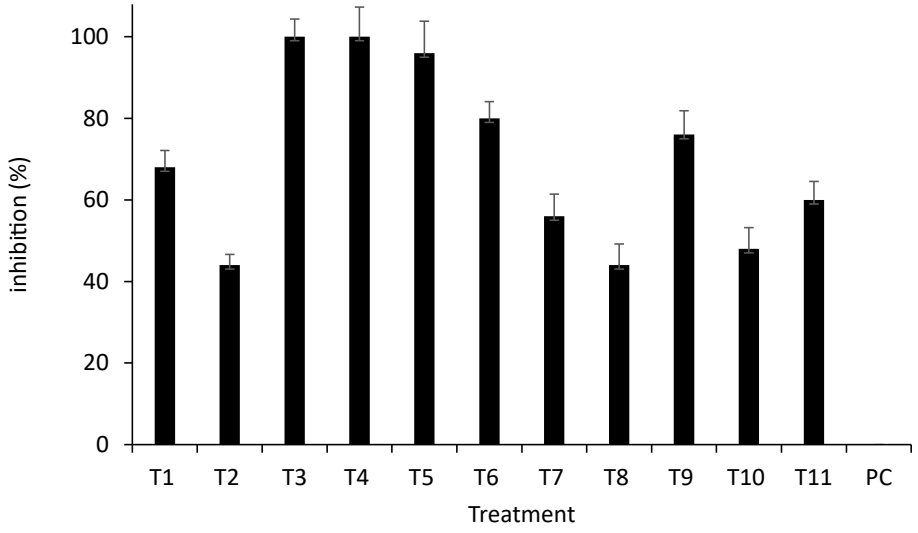

Fig. 3. The efficacy of treatments inhibiting disease severity on aboveground strawberry plants. Where: the inoculated strawberry seedlings treated with: P. flaorescens *(T1),* T. harzianum *(T2), Sumac (*Rhus coriaria*) extract (T3), Pristine fungicide (T4),* P. flaorescens *and* T. harzianum *(T5),* P. flaorescens *and Sumac extract (T6),* T. harzianum *and Sumac extract (T7),* P. flaorescens *and Pristine (T8),* T. harzianum *and Pristine (T9), Sumac extract and Pristine (T10), Integration of* T. harzianum*,* P. flaorescens*, Sumac extract, and Pristine (T11), PC representing untreated control where seedlings inoculated with the pathogen only, and NC representing negative control where seedlings immersed in water only. Error bars represent standard deviation, deviation and Fischer's least significant difference (LSD) test at P = 0.05 is 46.61.*

were not as successful as T3, T4, and T5. This moderate effectiveness may point to either less robust mechanisms of action or varying susceptibility in different environmental contexts.

Treatments T1 (32 %) and T11 (40 %) displayed medium disease severity levels. Although they were less effective than the top-performing treatments (T3, T4, and T5), they still managed to provide a reasonable degree of disease control compared to the lower-performing treatments. These findings suggest that these treatments could serve as secondary options where higher efficacy treatments are not available, but with a caveat that some disease presence will persist.

The treatments T7 (44 %), T10 (52 %), T8 (56 %), and T2 (56 %) had significantly higher disease severity, ranging from 44 % to 56 %. This indicates relatively poor control of the disease, showing that these treatments were unable to suppress disease development adequately. Though they were not as ineffective as the positive control, their higher levels of disease severity make them less attractive options for managing the disease.

Lastly, the positive control (PC) exhibited the highest disease severity at 80 %, confirming the expectation that, without any treatment or with minimal intervention, the disease would spread extensively. This serves as a baseline, underscoring the critical need for effective disease control strategies to minimize crop damage and loss.

Overall, the results demonstrate a clear gradient in disease control efficacy, with T3 and T4 completely preventing disease, followed by the strong performance of T5. Treatments like T6, T9, T1, and T11 provide moderate control, while treatments with higher severity levels (T7, T10, T8, T2) show minimal effectiveness. Understanding these varying levels of efficacy can guide agricultural decision-making, enabling the selection of the most appropriate treatment for disease management in specific contexts.

The results shown in Fig. 4, indicate that the most effective treatments were T4 and T9 (8 % severity) with the highest disease inhibition (92 %) (Fig. 5). These treatments showed the lowest disease severity, suggesting they were the most effective in controlling the disease. Both T2 and T5 treatments (12 % severity and 88 % inhibition) were also quite effective with relatively low disease severity. T3, T7, and T11 (20 % severity and inhibition of 80 %) showed moderate efficacy in controlling crown and root rot of strawberries with around 20 % disease severity, providing a decent level of disease control. T1 (32 % severity) on the other hand, although not as effective as the others, this treatment still controlled the disease to a moderate extent. T6, T10, and T8 with disease severities of 36, 48, and 52 %, exhibited relatively high disease severity, indicating they were among the least effective treatments. Positive Control as expected, had the highest disease severity at 80 %, demonstrating the impact of disease when no treatment or minimal intervention is applied.

The results presented in Fig. 4 illustrate the varying degrees of effectiveness of the treatments in

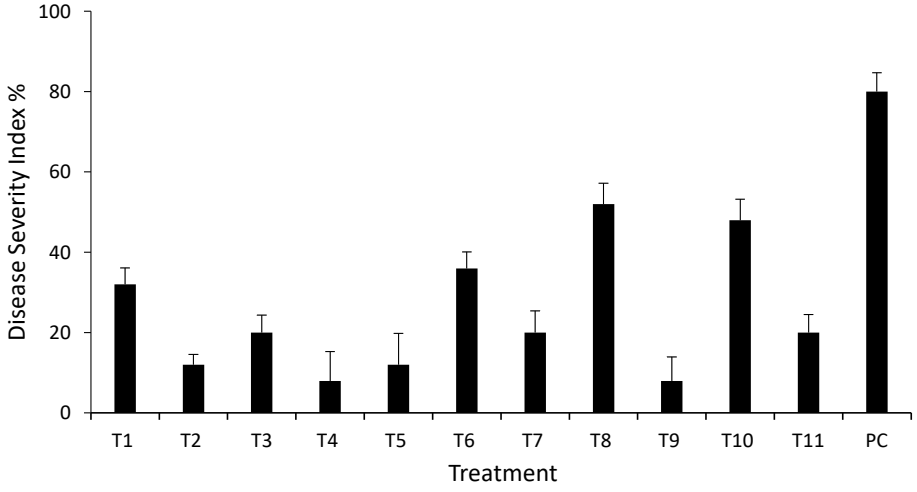

Fig. 4. The efficacy of integrated options on the severity of root rot symptoms on the strawberry root and crown. Where: the inoculated strawberry seedlings treated with: P. flaorescens *(T1),* T. harzianum *(T2), Sumac (*Rhus coriaria*) extract (T3), Pristine fungicide (T4),* P. flaorescens *and* T. harzianum *(T5),* P. flaorescens *and Sumac extract (T6),* T. harzianum *and Sumac extract (T7),* P. flaorescens *and Pristine (T8),* T. harzianum *and Pristine (T9), Sumac extract and Pristine (T10), Integration of* T. harzianum, P. flaorescens, *Sumac extract, and Pristine (T11), PC representing untreated control where seedlings inoculated with the pathogen only, and NC representing negative control where seedlings immersed in water only. Error bars represent standard deviation, deviation and Fischer's least significant difference (LSD) test at P = 0.05 is 43.49.*

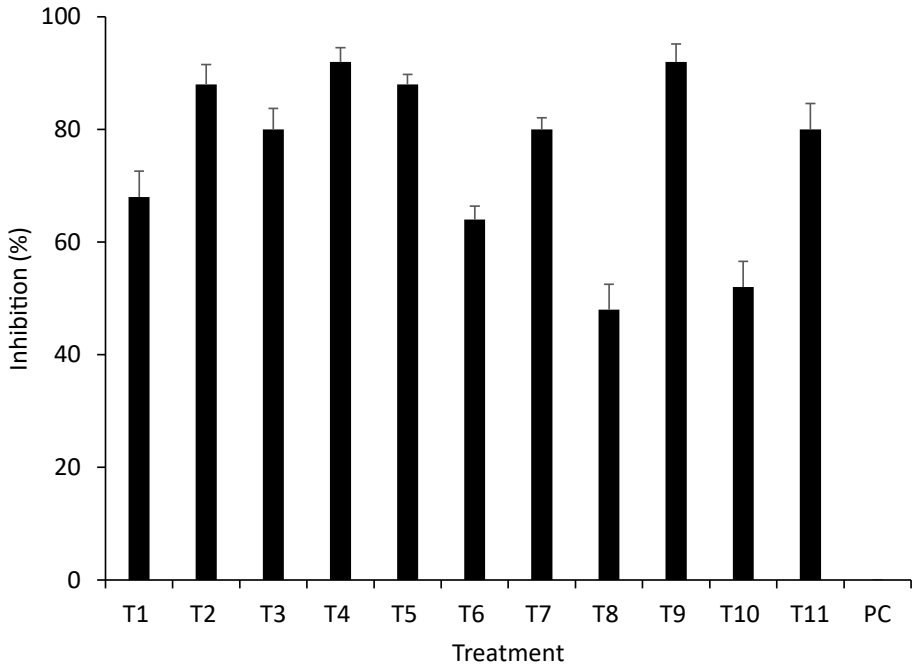

Fig. 5. The efficacy of treatments on inhibition disease severity on root and crown strawberry plants. Where: the inoculated strawberry seedlings treated with: P. flaorescens *(T1),* T. harzianum *(T2), Sumac (*Rhus coriaria*) extract (T3), Pristine fungicide (T4),* P. flaorescens *and* T. harzianum *(T5),* P. flaorescens *and Sumac extract (T6),* T. harzianum *and Sumac extract (T7),* P. flaorescens *and Pristine (T8),* T. harzianum *and Pristine (T9), Sumac extract and Pristine (T10), Integration of* T. harzianum, P. flaorescens, Sumac extract, and Pristine (T11), PC representing untreated control where seedlings inoculated with the pathogen only, and NC representing negative control where seedlings immersed in water only. Error bars represent standard deviation, deviation and Fischer's least significant difference (LSD) test at $P = 0.05$ is 46.61.

controlling crown and root rot of strawberries. The standout treatments were T4 and T9, both achieving the lowest disease severity at 8 %, demonstrating superior disease control. This indicates that these treatments were highly effective in either preventing the pathogen from infecting the plants or boosting the plants' natural defenses. Their effectiveness makes them the top candidates for managing this disease in practical agricultural settings. These findings imply that, when used prophylactically, some therapies may be effective in preventing strawberry root and crown rot caused by fungal infections. These findings will help to create strawberry root and crown rot management plans that are more successful [42]. Next in line were treatments T2 and T5, with a disease severity of 12 %. These treatments, while not as perfect as T4 and T9, still performed exceptionally well, offering strong protection against the disease. With a relatively low severity rate, they provide a robust option for disease management where T4 and T9 may not be available or suitable.

Treatments T3, T7, and T11 demonstrated moderate control, with a disease severity of around 20 %. Though less effective than the top treatments, these results show that these treatments provided a reasonable level of disease suppression. For growers dealing with moderate disease pressure, these treatments may still be viable, offering some control over the disease.

T1, with a 32 % disease severity, was less effective than the above treatments but still provided a moderate level of control. While it cannot be relied on to significantly reduce the disease under high-pressure conditions, it may be of use in conjunction with other management strategies or in environments where disease pressure is lower. In this regard, Koike and Gordon [43] stated that standard integrated pest management practices remain important measures that can reduce the risk of damage from Fusarium root and crown rot.

The treatments T6 (36 %), T10 (48 %), and T8 (52 %) exhibited relatively high levels of disease severity, indicating poor performance in controlling crown and root rot. These treatments did not provide sufficient protection and would not be ideal for disease management. Their higher disease severity suggests that either their mode of action was not strong enough, or the disease was able to bypass their protective mechanisms more easily compared to the more effective treatments.

As expected, the positive control (PC) had the highest disease severity at 80 %, demonstrating the

high susceptibility of strawberries to crown and root rot in the absence of effective treatments. This serves as a reminder of the significant impact the disease can have on crops without intervention, further highlighting the importance of effective disease management strategies.

In summary, the results show a clear distinction in the effectiveness of the treatments, with T4 and T9 emerging as the best options for disease control, followed by T2 and T5. Treatments like T3, T7, T11, and T1 offer moderate efficacy, while T6, T10, and T8 were among the least effective. These findings provide valuable insights into which treatments are most promising for managing crown and root rot in strawberries, helping guide future recommendations for disease control in the field. Previous literature indicate that integrated management was successful by incorporating different control methods in protecting strawberries against the main diseases [44]. Due to the advantages, integrated disease management approaches should be adopted for the effective and sustainable management of plant diseases [45].

4. Conclusions

In summary, the findings show a distinct gradient in the efficacy of disease control, with plant extract only, fungicide alone, and combination of *Trichoderma harzianum* and Pristine continuously showing the best performance to prevent the disease. However, combining *Pseudomonas flaorescens* and sumac extract, sumac extract and Pristine, and gathering of *Pseudomonas flaorescens* and Pristine were the least effective. Other treatments, including a combination of *Pseudomonas flaorescens* and *Trichoderma harzianum*, *Trichoderma harzianum* only, had different degrees of efficacy and provided moderate control. To prevent crown root rot in strawberries by combining various control materials that require the least amount of fungicide input, these insights are very important for guiding agricultural decisions and improving disease management techniques.

5. Study highlights

- Plant extract and *T. harzianum*, when combined with Pristine, consistently demonstrated the highest efficacy in disease prevention.
- Treatments involving *P. fluorescens* and sumac extract, sumac extract with Pristine, or the combination of *P. fluorescens* and Pristine were the least effective.
- Lower efficacy levels were observed in treatments using either *T. harzianum* alone or in combination with *P. fluorescens.*
- These findings underscore the potential of integrating biological agents like *T. harzianum* with minimal fungicide application to achieve effective disease management.
- This integrated approach provides critical insights for optimizing agricultural practices and developing sustainable strategies to manage crown and root rot in strawberries.

Author contribution

All authors have made equal contributions to this research work.

Ethics information

Ethics approval was not required for this research.

AI usage declaration

The authors declare that the content of this work was not generated using AI.

Funding information

No specific funding was received for conducting this research.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare that there is no conflict of interest.

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