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ORIGINAL RESEARCH

Eco-friendly management of tomato wilt disease caused by *Fusarium* sp. in Sindh Province, Pakistan

Gul Bahar Poussio[1*], Manzoor Ali Abro[2], Rehana Naz Syed[2], Muhammad Ibrahim Khaskheli[3], Jamal- U-Ddin Hajano[2]

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Abstract

Purpose The investigation of the different plant waste parts for ecofriendly management of *Fusarium* sp. was carried out.

Method The disease associated fungus was isolated from the diseased specimen and purified. The twelve different aqueous plant extracts were prepared and evaluated against test pathogen in laboratory, pots and in filed conditions.

Results Among the tested aqueous plant extracts the neem seed, thorn apple, garlic, neem leaves and eucalyptus were found the most effective providing highest growth inhibition percent of test fungus. The lowest plant mortality and disease incidence percent, maximum plant biomass and minimum root infection percent were observed in plans treated with neem leaves, neem seed, garlic, thorn apple and eucalyptus extracts in pot experiment. In field experiment, the extracts of neem leaves, thorn apple and neem seed produced the lowest disease incidence and mortality percentage as compared to other extracts. The extract of garlic was noted as moderate effective among the treatments. The eucalyptus extract was found as less effective. The maximum height and weight of individual plant was observed in the treatment of neem leaves than in neem seed, garlic, eucalyptus, and thorn apple extracts. Significantly, the highest fruit yield was recorded in plant treated with neem leaves extracts followed by neem seed, garlic, eucalyptus, and thorn apple.

Conclusion The study showed that neem leaves, neem seed and garlic, eucalyptus and thorn apple extracts are potential aqueous extracts for ecofriendly management of tomato fusarium wilt disease.

Keywords Tomato, Fusarium wilt, Control, Extracts, Sindh

Introduction

Among widely cultivated vegetable crops in the world, tomato (*Lycopersicum esculentum L*) is the most important horticultural commodity (Haghighi et al. 2016). It ranked second after potato among the vegetables, used as fresh fruit and salad whereas many fruit items are also prepared from tomato such as tomato juice, tomato ketchup, soup, drinks, and many other dishes (Ansley 2018). The fruit of tomato possesses 95.3 percent water, 0.07 percent calcium and niacin, vitamin A, C, E, and few more important sources of nutrients like sodium, potassium, iron, and lycopene as well salicylate as antioxidants. All have great importance in human metabolic system (Chaudhary et al. 2018). Almost 144 countries are growing tomato on large scale such as China, India, Turkey, United States and Egypt which are the top tomato producing countries in the world (FAOSTAT 2019).

Tomato is an important vegetable crop of Pakistan; grown on area of 55.25 thousand hectares which produce 561.2 thousand tones with average yield of 10.15 thousand tons per hectare (FAOSTAT 2019). Sindh province is major tomato producing region of Pakistan,

✉ Gul Bahar Poussio
gulbahar.2008@gmail.com

[1] Plant Disease Research Institute, Agriculture Research Center Sindh, Tandojam, Pakistan
[2] Department of Plant Pathology, Faculty of Crop Protection, Sindh Agriculture University Tandojam, Pakistan
[3] Department of Plant Protection, Faculty of Crop Protection, Sindh Agriculture University Tandojam, Pakistan

where 21.0 thousand hectares are under cultivation with overall production of 153.2 thousand tones and 7.29 thousand tones yield per hectare (GOP 2019). This average yield is at a low level as compared to other tomato cultivating countries for example USA (98.04 t/ha), Turkey (70.75 t/ha), China (57. 84 t/ha), Egypt (38.96 t/ha) and India (24.33 t/ha) (FAOSTAT 2019). The reasons of low yields are several biotic and abiotic disorders. As the crop is sensitive to more than 200 diseases caused by pathogenic fungi, nematodes, bacteria, and responsible to cause the diseases (Singh et al. 2017). It is susceptible to large number of diseases including early blight, anthracnose, bacterial wilt, bacterial canker, tomato spotted wilt, verticillium wilt and fusarium wilt (Esse et al. 2019). Fusarium wilt disease is caused by pathogenic *formae speciales* of the soil borne fungus *Fusarium oxysporum* Schltdl., produces significant yield losses in tomatoes all over the world (Carmona et al. 2020). It almost affects the root and generating production losses between 30 and 40 percent and it may even reach up to 80 percent if climatic conditions favor the growth of the fungus (Nirmaladevi et al. 2016). It is a serious disease of tomato especially in warmer areas because the pathogen requires a soil temperature around 28°C for its growth (Srinivas et al. 2019).

Fusarium wilt is a challenging disease to control. Various strategies have been suggested to control this fungal pathogen. It is mostly controlled by the uses of fungicides applications of Prochloraz and Carbendazim (Song et al. 2004). Recently Patiyal et al. (2020) evaluated six different fungicides against fusarium wilt disease of tomato *in-vitro* conditions and recommended Custodia fungicide as a possible control measure. The chemical fungicides are no longer with comfort eco-friendly and have a tendency of persisting for years in the environment and creating physicochemical and biological weakening of the soils and upsetting the agro-ecosystems worldwide (Singh et al. 2019). As a result, the usage of natural plant material for managing the fungal diseases in plants is believed a sensible substitute for synthetic fungicides (Ramaiah and Garampalli 2015). The extracts from the natural plant parts are used as nutrient supplements or biofertilizers as an alternative to chemical fertilizers in agriculture (Ramya et al. 2015). In order to overcome the disadvantages of chemical fungicides, alternative strategies are needed to tackle with the attack of various fungi on different crops. It has great potential to use different botanical fungicides to control tomato Fusarium wilt disease. The excessive misuse and wide range of fungicides results the harmful effect to the environment and enhances the resistant to pathogen and these chemicals not only affect the nutritional contents of tomato but also the texture or productivity of soil (Ozgonen et al. 2001). Continuous usage of chemical products may produce soil and water pollution to environment. The management of the pathogen by implementing various methods, among them the uses of different plant extracts, is the long lasting, economical, eco-friendly, and safe to target organisms (Verma et al. 2018). Kala et al. (2016) studied on the ecofriendly management of *Fusarium oxysporum* f. sp. *ciceri* in chickpea by using different bioagents, farmyard manure, vermicompost and mustard cake and found that they are effective against wilt disease. The advanced ecofriendly management of fusarium wilt of tomato by using different fungal, bacterial endophytes and biopesticides are supposed to be environmentally safe and highly effective protection measures (Abdallah et al. 2020; Cotes et al. 2018; Fatima and Anjum 2017). However, due to the emergence of new pathogenic races, attempts to control the disease have experienced limited success. Early strategies to deal with this devastating plant disease include the use of cultural, physical and chemical control. None of these strategies can provide the best results, except for cultural methods, which are mainly preventive (Ajilogba and Babalola 2013). Now the Scholars and scientists are looking for the alternative disease management plans mainly based on natural resources, which are eco-friendly environment (Javaid et al. 2015). Alternative approaches for controlling the diseases have been studied highlighting the use of different types of plant parts extracts and antifungal compounds from plants (Shoib et al. 2018). Recently, different reports specified that some plant extracts and essential oils are highly efficient antimicrobial agents against food and stored grain fungi, foliar pathogens, and soil-borne fungal Phyto-pathogens (Hassan 2020). Keeping in view the importance and losses due to this important fungal disease, the environmentally safe, cheap, and eco-friendly management practice was carried out in laboratory as well as in the field by utilizing the aqueous extracts prepared from waste plant parts for the sustainable and eco-friendly management of Fusarium wilt disease of tomato to minimize the economic loss in tomato crop.

Materials and methods

Isolation of disease-causing pathogen

The isolation of pathogen was carried from diseased specimen showing fusarium wilt disease symptoms (Plate 1). The isolation was carried out on potato dextrose agar (PDA) medium through tissue isolation technique (Agrios 2005)**.** The infected parts of tomato plant including roots, stem and branches were cut into slight pieces of about 0.5-2.0 cm longitudinally. The pieces were cleaned in running tap water followed by surface sterilization in 0.1 percent mercuric chloride solution for half minute and rinsed frequently twice in sterilized distilled water to eliminate mercuric chloride solution. The pieces were dried on filter paper. Five to eight tissues were placed to petri plates having sterilized PDA. These plates were incubated at 25±2°C for 7 days for recovery of target pathogen. The isolated fungus was characterized by using taxonomic keys (Booth 1971; Nelson et al. 1983).

Plate 1 Fusarium wilt diseased specimen collected from the tomato field for the isolation purpose

Preparation of aqueous plants extract.

The plant materials such as Bitter apple *(Citrullus colocynthis)* mature fruit, leaves of Eucalyptus (*Eucalyptus globulus*), Neem *(Azadirachta indica)* Leaves, Neem Seeds, Ginger (*Zingiber officinale)* Rhizome, Garlic (*Allium sativum)* Tuber, Tobacco (*Nicotiana tabacum)* leaves, Aloe vera *(Aloe* indica) gel, Milkweed (*Asclepias)* leaves, Mint (*Mentha)* leaves, Thorn apple (*Datura stramonium)* leaves and Marigold (*Calendula officinalis)* leaves were cleaned thoroughly with normal tape water and surface sterilized with 0.1 percent sodium hypochlorite and repeatedly washed in sterilized distill water and air dried (Plate 2). The extracts were prepared by adding 20 ml of sterile water with 20 grams of selected plant material and grinded with pestle and mortar. A 100 percent w/v stock solution of all selected plant parts was prepared, filtrated through muslin cloth followed by Whatman filter paper No.1 (Plate 2). The extracts were centrifuged at 10,000 rpm for 5 minutes and supernatant was sterilized at 40°C for 10 min and stored at 4°C for further use (Jaganathan and Narasimhan 1988; Ramaiah and Garampalli 2015).

In-vitro assay of different plant extracts

The selected prepared plant extracts were used in the laboratory in aseptic conditions by food poison method. The four different concentrations 2, 4, 6 and 8 percent were prepared from the 100 percent stock solutions in separate conical flasks having sterilized potato dextrose agar (PDA) medium at the time of pouring. PDA medium plates without extract considered as control. After the solidification of the medium, the (5mm) disc of pure culture of target fungus was inoculated with the help of sterilized cork borer in the center of Petri plate containing sterilized PDA and incubated at 25±2°C. The colony mycelial growth of fungus was noted after every 24 hours in millimeter until the mycelial growth of the control plates formed fully. The effect of all tested plant extracts against the mycelial growth of *Fusarium* sp. was calculated by using standard percent inhibition formulae (Vincent 1947).

$$PI=C-T/C \times 100$$

PI= Percent inhibition, C= Mycelial growth in control plate, T= Mycelial growth in treated plate

Plate 2 Plant parts and prepared aqueous extracts

Pot experiment assay

The tested extracts found most effective in laboratory experiment were further selected for greenhouse trial in pots. The plant extracts such as Neem leaves, Neem seed, Thorn apple, Garlic, and Eucalyptus were used at 4, 6 and 8 percent concentrations. The seed of the widely growing local tomato variety "Desi local" was surface sterilized for 2 minutes with 5 percent commercial bleach followed by cleaning with sterile water. Ten seeds per pot were grown in each earthen pot (20 cm diameter) comprising of 2 kg steam sterilized soil. The soil was artificially infested with the test pathogen suspension of 10^5conidia/1 gram of soil. These seeds were slightly covered with thin coating of soil. The pots were kept in green house. The prepared concentrations of the selected plant extracts were drenched into the earthen pots after seven days of sowing. The experiment was designed as complete randomized design (CRD) with four replications. The irrigation water was applied to earthen pots whenever required. Plant mortality percentage, disease incidence percentage, plant biomass (plant height + weight), root infection percentage were noted after 40 days of sowing by uprooting the plants. The plant mortality, disease incidence and root infection percentage were calculated by using the following formula.

$$\text{Mortality percentage} = \frac{\text{Number of dead plants}}{\text{Total number of plants under observation}} \times 100$$

$$\text{Disease incidence percentage} = \frac{\text{Number of infected plants}}{\text{Total number of plants under observation}} \times 100$$

$$\text{Root infection percentage} = \frac{\text{Number of root pieces colonized by the fungus}}{\text{Total number of pieces studied}} \times 100$$

Field experiment assay

The seed of tomato variety "Desi local" was collected from Tomato Station of Agriculture Research Panghrio Sindh, Pakistan. The trial was designed as Randomized complete block design (RCBD) with four replications. Five rows of ten meters each were the length of the plot. The Distance between row to row and plant to plant was kept 75 and 15 cm, respectively.

Seed dressing

The seeds of commonly growing variety "Desi local" was treated with selected plant extracts such as neem leaves, neem seed, thorn apple, garlic, and eucalyptus at 8 percent concentration at the dose of 10 ml per kg of seed. The seeds without treatment were named as control. The plant mortality percentage, disease incidence percentage, plant biomass (plant height + weight), root infection percentage and fruit yields were noted. The agronomical activities were also continued as per recommendations.

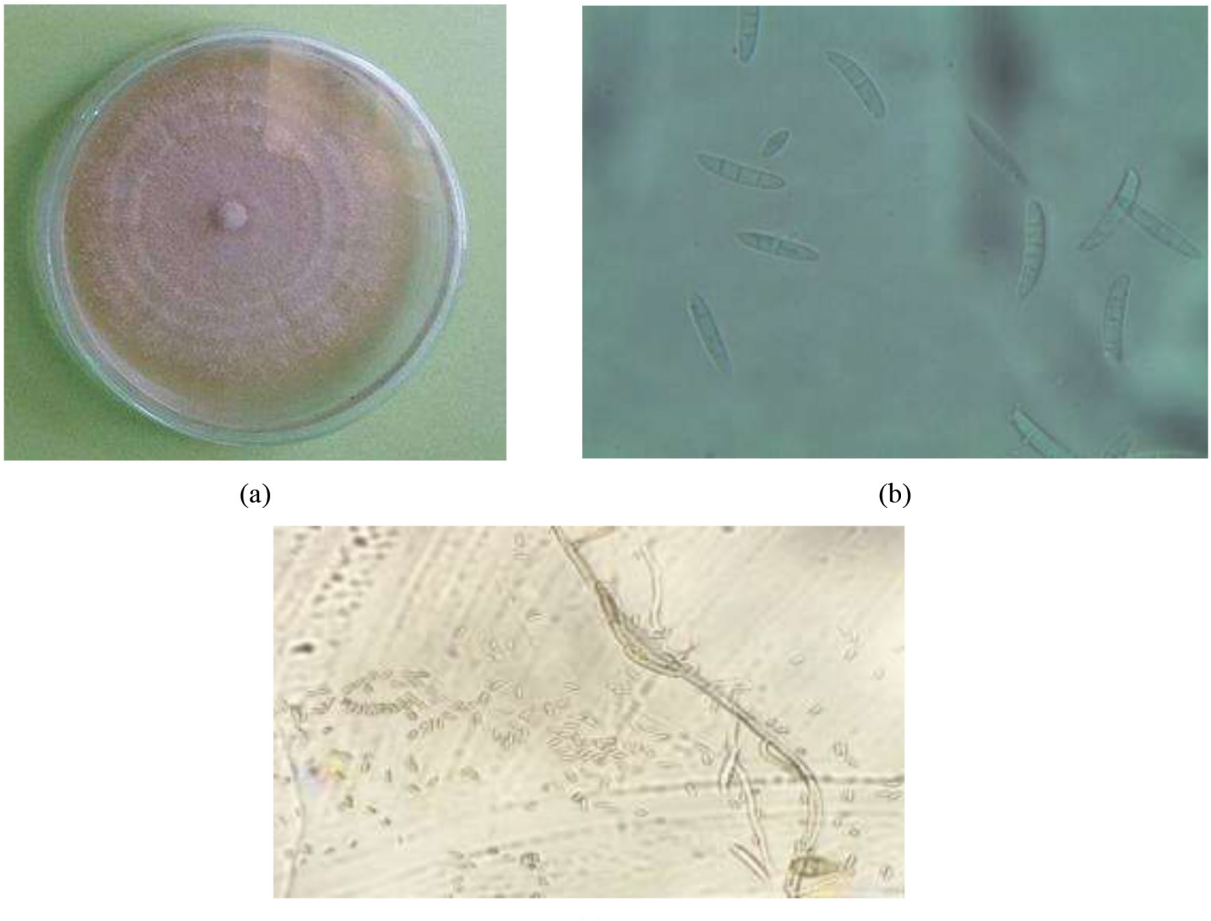
Data analysis

The Statistix 8.1 software was used for the analysis of data. The analysis of variance (ANOVA) was used to differentiate the impact of treatments. The Least Significant Difference (LSD) test was used for mean separation, and a $P < 0.05$ was used for significant differences between treatments. The experiments were repeated twice within two years.

Results and discussion

Morphological identifications of *Fusarium* sp.

The identification of isolated pathogen was carried out according to the colony morphology, morphological characteristics of macro and microconidia as described by Booth (1971). The colony mycelial growth of *F. oxysporum* f.sp. *lycopersici* is fast growing cover (90 mm) Petri-dish at almost seven days, having white color aerial mycelium with orange colony color under the lower surface of the Petri-dish (Plate 3a). It formed three types of asexual spores such as Macroconidia which are mostly observed in large quantities as long and like sickle-shape and thin-walled, spores having numerous septation (Plate 3b). The microconidia are too profuse, small single- celled and oval type shape (Plate 3c). Chlamydospores are round shaped individually or in pairs terminal or intercalary. The morphological characteristics of the isolated fungus from tomato plant are the indications that the fungus is *Fusarium* sp.



(a) (b)

(c)

Plate 3 Morphological characteristics of *Fusarium* sp. (a) the colony mycelial growth, (b) the macroconidia and (c) the microconidia

In-vitro efficacy

All tested aqueous plant extracts have ability to inhabit the mycelial colony growth of *F. oxysporum* f.sp. *lycopersici.* The higher doses are found highly effective as compared to medium and lower doses. The neem seed extract was found the most effective extracts recording (72.96) mycelial growth inhibition percent of test fungus followed by thorn apple (66.66), garlic (66.29) and neem leaves (66.29) at 8 percent concentrations. The minimum (29.03) colony mycelial growth inhibition percent was recorded by mint extracts at 2 percent concentrations (Table 1). Interestingly, the plant extracts including milk weed, bitter apple, ginger, tobacco, and

eucalyptus were found as moderate effective at their higher 8 percent concentrations. The lower doses of all tested plant extracts were found partially ineffective to check the mycelial colony growth of test fungus in laboratory conditions (Plate 4). Ngegba et al. (2017) specified that increase in the concentration of the plant extracts have the potential of antifungal activities. Another study was carried out for the potential of few plant extracts for managing the Fusarium wilt associated fungus. The results indicated that approximately all used plant extracts were effective in falling the mycelium growth of *Fusarium oxysporum* f. sp. *lycopersici* by using 25 percent concentration (Nasrin et al. 2018). Chohan et al. (2011) studied on different plants' extracts at 2, 4, 6 and 8 percent concentration against *Fusarium oxysporum* f. sp. *gladioli in* lab conditions. Out of tested plants extracts the neem extract resulted the highest mycelial growth inhibition both at 8 and 2 percent concentration.

Pot experiment efficacy

Significantly, the lowest plant mortality percent (21 and 26) was noted in plants treated with neem leaves extracts at 8 and 6 percent concentrations followed by neem seed (27.66) and garlic extracts (28.66) at 8 percent concentrations. The extracts of eucalyptus, and thorn apple recorded as less effective at their lowest concentrations; however, the higher concentration of thorn apple found as moderate effective as compared to other extracts. The maximum plant mortality percentage (93.66) was recorded in untreated (control) plant (Fig. 1). The plants treated with extracts found with less disease attack. The lowest disease incidence percentage (23.66 and 25.33) was recorded in plants treated with neem leaves and neem seed extracts at 8 percent concentrations. The extract of the neem leaves was found the most effective at all tested concentrations. The extracts of the eucalyptus and thorn apple were found less effective and produced

Table 1 Effect of different plant extracts on the growth inhibition percent of *Fusarium* sp

Plant Extracts	Growth Inhibition percent at different concentration of plant extracts			
	2%	4%	6%	8%
Bitter apple	35.556 s	44.444 o p	50.000 m	55.556 i
Aloe vera	46.667 n	52.222 l	57.778 f g	63.333 c
Marigold	43.333 p	50.000 m	55.185 i j	58.519 f
Neem leaves	53.704 k	58.889 f	63.333 c	66.296 b
Ginger	40.000 q r	44.815 o	50.741 m	55.926 h i
Tobacco	43.704 o p	50.741 m	55.926 h I	60.741 e
Eucalyptus	47.778 n	54.074 j k	55.556 i	61.852 d e
Milkweed	33.333 t	41.111 q	47.778 n	51.111 l m
Neem seed	52.222 l	61.111 de	67.407 b	72.963 a
Garlic	50.370 m	55.556 i	62.222 c d	66.296 b
Mint	29.630 u	39.259 r	44.444 o p	47.407 n
	47.037 n	57.037 g h	61.111 d e	66.667 b

Note: Figures following the similar letter within a column are not significantly different according to the LSD (least significant difference) test at $P<0.05$.

maximum disease incidence percentage at their lowest 4 and 6 percent tested concentrations as compared to other extracts (Fig. 2). Hassanein et al. (2010) studied on different concentrations of aqueous neem extract and found that it suppressed wilt pathogen and the degree of suppression gradually increased with increasing concentration. Another study conducted by Hadian et al. (2011) showed that neem seed powder reduces the wilt disease of tomato. Jatav et al. (2019) studied on different extracts of Neem, Tulsi, Aak, Eucalyptus, Onion and Garlic clove and found that the neem leaf extract is highly effective providing lowest wilt disease incidence in brinjal.

Generally, the higher concentrations of plant extracts were observed highly efficient for encouraging the growth of plant as compared to lower and medium

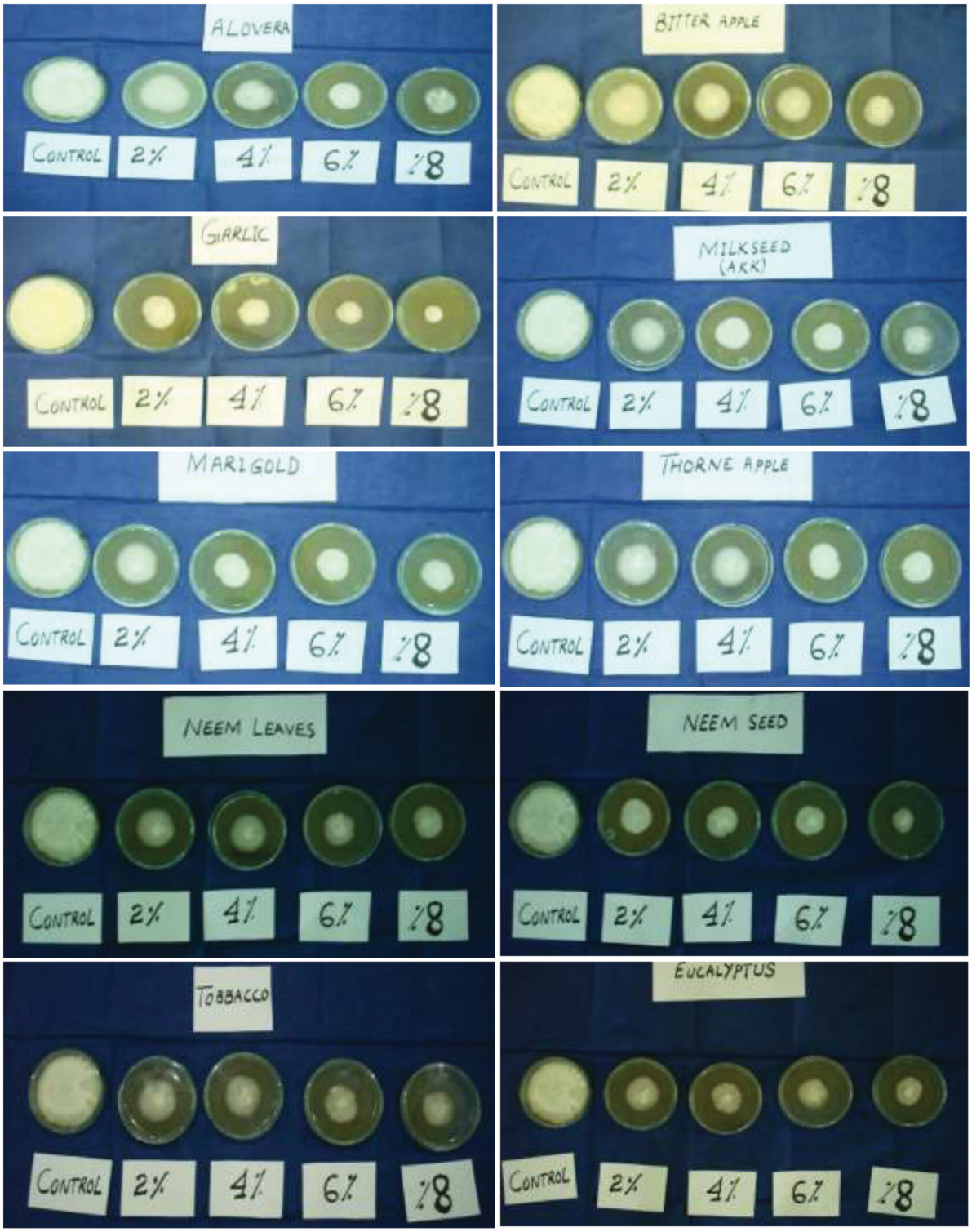


Plate 4 Effect of different plant extracts on the growth inhibition percent of *Fusarium* sp

doses. The maximum (28.33 and 27.66 cm) plant height was noted in plants treated with neem leaves and neem seed extracts at higher 8 percent concentrations. The garlic, thorn apple and eucalyptus extracts were also found effective at their higher concentrations. The medium 6 percent concentration of all tested extracts were also recorded effective against fusarium wilt disease of tomato in pot experiment. The plant height ranging from (21 to 24 cm) was noted in treated plants at 6 percent concentrations. The lowest plant height (18.66 cm) was observed in plants treated with eucalyptus extracts at 4 percent concentration (Table 2). Our results are in

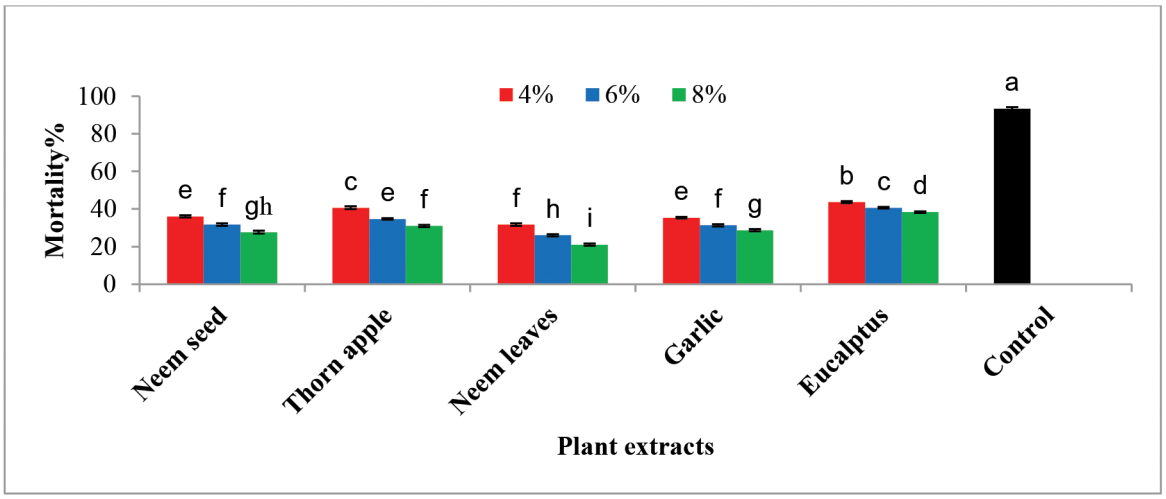


Fig. 1 Effect of different plant extracts on mortality percentage of tomato plants inoculated with *Fusarium* sp. in pot experiment

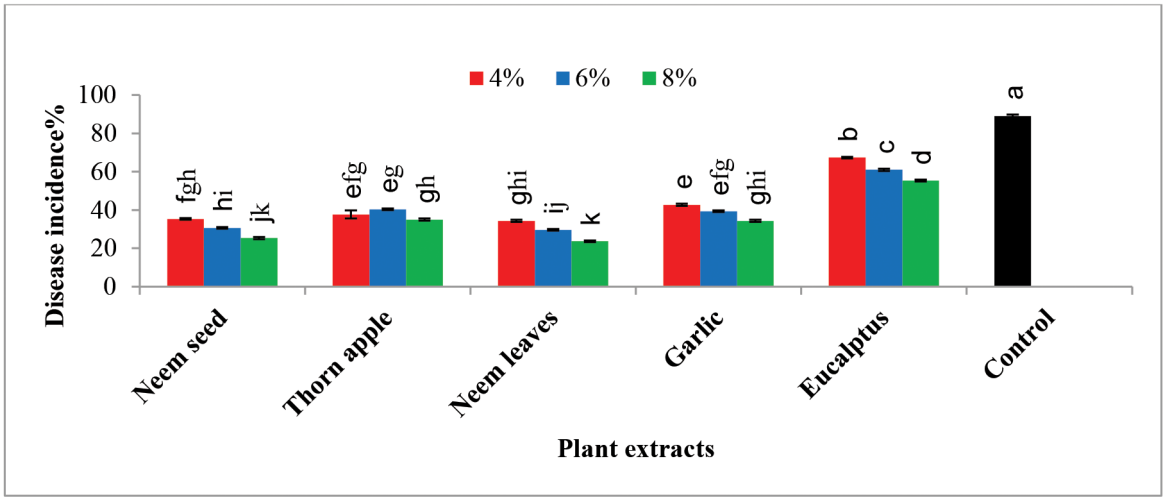


Fig. 2 Effect of different plant extracts on disease incidence percentage of tomato plants inoculated with *Fusarium* sp. in pot experiment

line with Hanna et al. (2011) who studied on fusarium wilt disease in tomato seedlings and found lowest disease incidence and highest plant growth with the application of aqueous extracts of neem and willow. Etaware et al. (2019) also reported that the height of tomato plant increases with the applications of plant extracts.

In case of the weight of plants, the maximum plant weight (0.73 and 0.70 gm) was noted in plant treated with neem leaves and neem seed extracts at 8 percent concentrations whereas the lowest weight of plant was noted in plants treated with eucalyptus extracts at 4 percent concentrations as compared to other extracts (Table 2) Moreover, the root infection percentage was also recorded and found that the highest (97) percent was in untreated plant. Generally, the highest concentrations of all tested extracts did not produce any root infection in inoculated plant. Interestingly, no root infection was recorded by neem leaves, need seed and thorn apple extracts even at 6 percent concentrations. However, the maximum root infection percentage (38) was noted by eucalyptus between the treatments (Fig. 3). Elgubbi et al. (2019) investigated the effects of various aqueous extracts on tomato plants and discovered that the extracts can boost growth percentage, vegetative growth, and yield. The use of botanicals eliminated disease symptoms, according to Etaware et al. (2019). Tomato plants treated with extracts showed an improvement in plant height.

Table 2 Effect of different plant extracts on height and weight of tomato plant inoculated with *Fusarium* sp. in pot experiment

Treatments	Concentration of extracts					
	4%		6%		8%	
	Plant height (cm)	Plant weight (g)	Plant height (cm)	Plant weight (g)	Plant height (cm)	Plant weight (g)
Neem seed	21 hi	0.51 fg	24 ef	0.59 de	27.66 ab	0.7 ab
Thorn apple	19.66 ijk	0.43 hi	22.66 fg	0.55 ef	26.66 bc	0.66 bc
Neem leaves	22 gh	0.54 ef	24.66 de	0.62 cd	28.33 a	0.73 a
Garlic	20.33 ij	0.47 gh	23.66 ef	0.59 de	27 abc	0.66 bc
Eucalyptus	18.66 k	0.36 j	21 hi	0.48 gh	25 de	0.62 cd
Control	10.33 l	0.20 k	10.33 l	0.20 k	10.33 l	0.20 k

Note: Figures following the similar letter within a column are not significantly different according to the LSD (least significant difference) test at $P<0.05$.

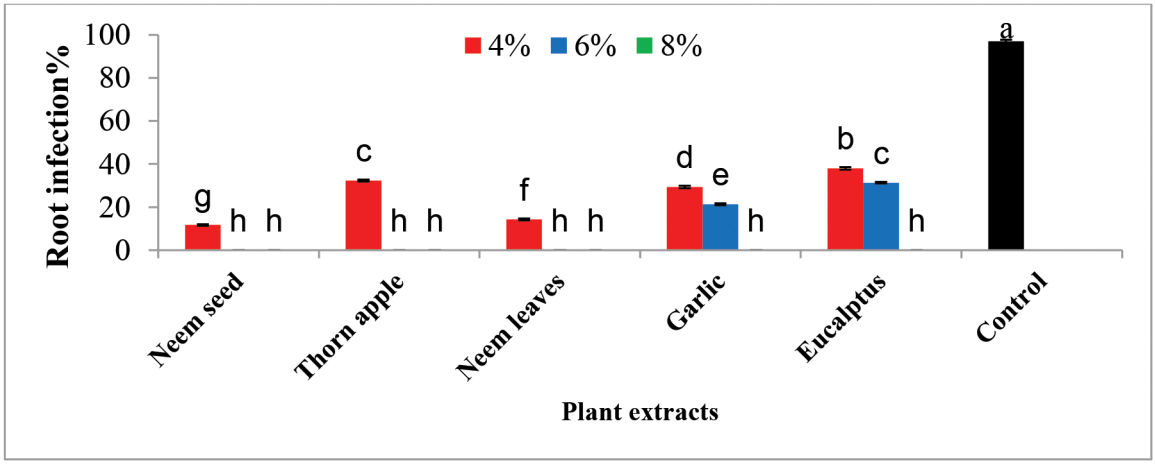


Fig. 3 Effect of different plant extracts on root infection of tomato plants inoculated with *Fusarium* sp. in pot experiment

Field experiment efficacy

The results of the field experiments revealed significant differences among each other for their efficacy against fusarium wilt disease incidence and mortality percentage of the tomato plant. The highest mortality percentage (78.33) was recorded in untreated plant. The lowest mortality percentage (9.33) was noted in neem leaves treated plant followed by thorn apple (13), neem seed (15.33) and garlic (18) percent, respectively. The eucalyptus provided the maximum mortality percentage among the treatments (Fig. 4). Very similar trends have been observed in case of disease incidence percentage; however, the maximum disease incidence percentage (86) was noted in control plant. The extracts of neem leaves, thorn apple and neem seed produced the lowest disease incidence percentage as compared to other extracts. The extract of garlic was noted as moderate effective providing (23) percent disease incidence among the treatments. The eucalyptus extract was found as less effective as compared to other tested extracts (Fig. 5). Pattnaik et al. (2012) studied on some plant extracts against the different pathogens of *Lycopersicon esculentum* and found that disease incidence decreases and the growth of plant as well as yield increases with the application of plant extracts.

All tested plant extracts enhanced the pathogen action in plants as the significantly lowest pathogen infection percentage (17.66 to 23) was recorded in treated plants as compared to untreated (control) plants (89.66). The minimum pathogen infection percentage was recorded in neem leaves (17.66) followed by garlic (19) neem seed (20.66) and thorn apple (22.66), whereas the maximum pathogen root infection percentage (23) was noted in plants treated

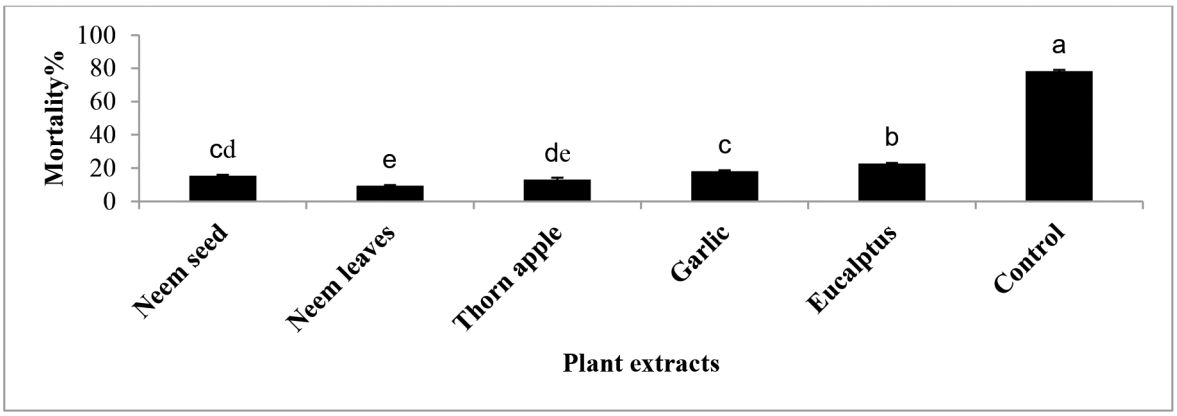


Fig. 4 Effect of different plant extracts on mortality percentage of tomato plants inoculated with *Fusarium* sp. in field conditions

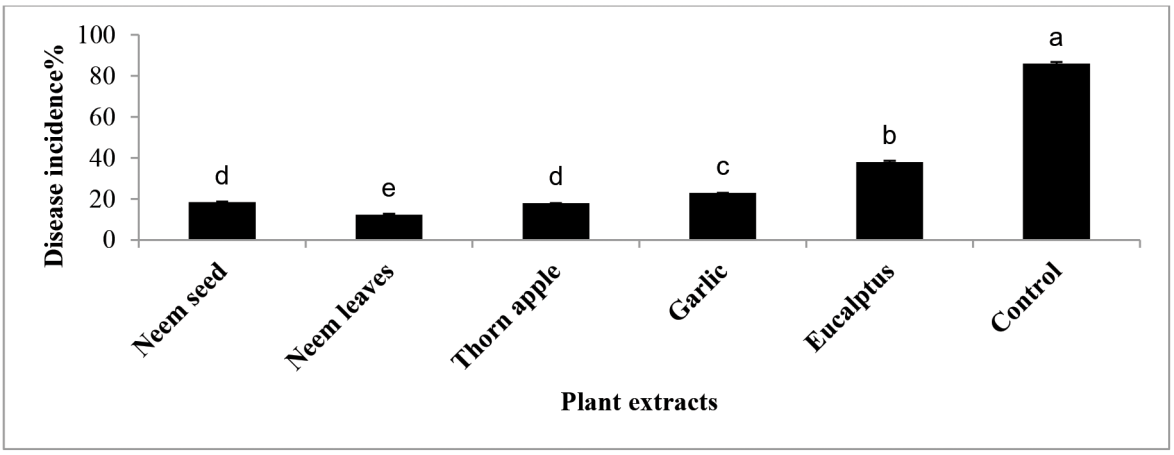


Fig. 5 Effect of different plant extracts on disease incidence percentage of tomato plants inoculated with *Fusarium* sp. in field conditions

with eucalyptus extracts (Fig. 6). Hassanein et al. (2010) tested different concentrations of aqueous neem extract against two tomato pathogens and discovered that aqueous extract of neem leaves reduces the wilt disease incidence and boosts the tomato plant growth.

Moreover, the applications of tested extract also improved the growth of tomato plants as compared to untreated plants. The highest plant height (106.00 cm) was recorded in plants treated with Neem leaves followed by Neem seed (103.33 cm), Garlic (97.00 cm), Eucalyptus (96.00 cm) and thorn apple (94.00 cm), whereas, significantly, the lowest plant height (89.33 cm) was recorded in untreated plants (Table 3). Similarly, the highest plant weight (606.67 gm) was noted in neem leaves treated plants followed by neem seed (588.67 gm), garlic (569.67 gm), eucalyptus (568.00 gm) and thorn apple (551.67 gm). The untreated plants (control) significantly produced the lowest plant weight (477.67 gm) as compared to treated plants (Table 3). The uses of aqueous extracts of garlic as foliar spray and root drenching ensures the better yield and growth performance of tomato plants grown under plastic tunnel conditions (Hayat et al. 2018). Bashir et al. (2014) reported that the height, number of branches, number of flowers in tomato plants increase with the uses of plant extracts.

The application of plant extracts also improved the yield of tomato as compared to untreated plants. The highest fruit yield (8 kg) was recorded in plant treated with neem leaves extracts followed by Neem seed, garlic, eucalyptus (6.33 kg) and thorn apple (6 kg). The remarkable lowest fruit yield (2.9 kg) was recorded in untreated plants (Fig. 7).

The 2 percent concentration of neem leaves are highly effective against collar rot disease in chickpea *in-vivo* and

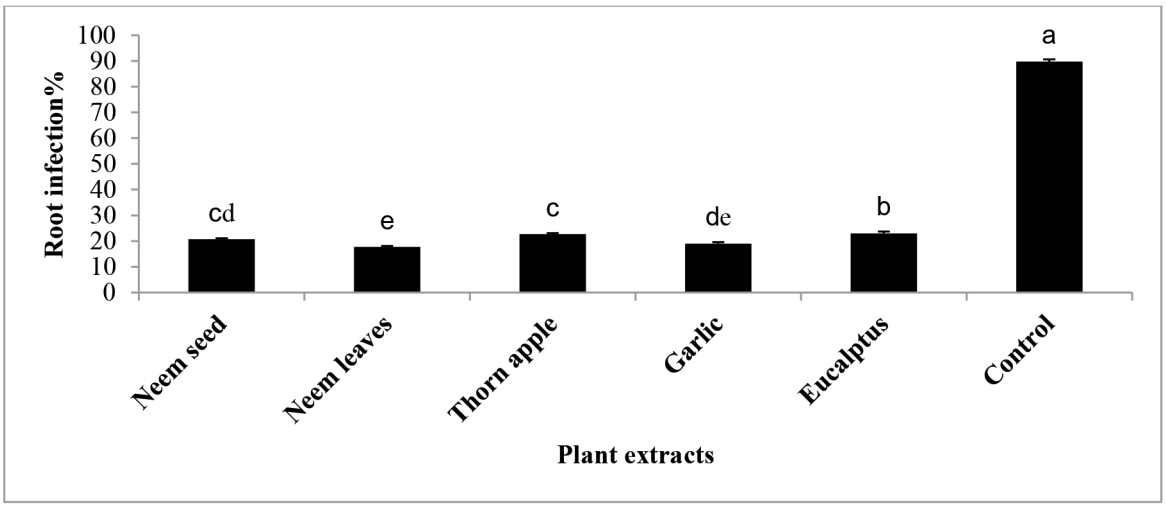


Fig. 6 Effect of different plant extracts on root infection percentage of tomato plants inoculated with *Fusarium* sp. in field conditions

Table 3 Effect of different plant extracts on height and weight of tomato plant inoculated with *Fusarium* sp. in field experiment

Treatments	Plant height (cm)	Plant weight (gm)
Neem seed	103.33 b	588.67 b
Neem leaves	106.00 a	606.67 a
Thorn apple	94.00 d	551.67 d
Garlic	97.00 c	569.67 c
Eucalyptus	96.00 c	568.00 c
Control	89.33 e	477.67 e

Note: Figures following the similar letter within a column are not significantly different according to the LSD (least significant difference) test at $P<0.05$

in-vitro conditions (Khan et al. 2020). Similarly, Castellanos et al. (2020) studied on clove and pepper essential oils and functional extracts against *Fusarium oxysporum* and *Aspergillus niger* in tomato under *in-vivo* and *in-vitro* conditions and found essential oils and extracts are highly effective against both phytopathogenic fungi.

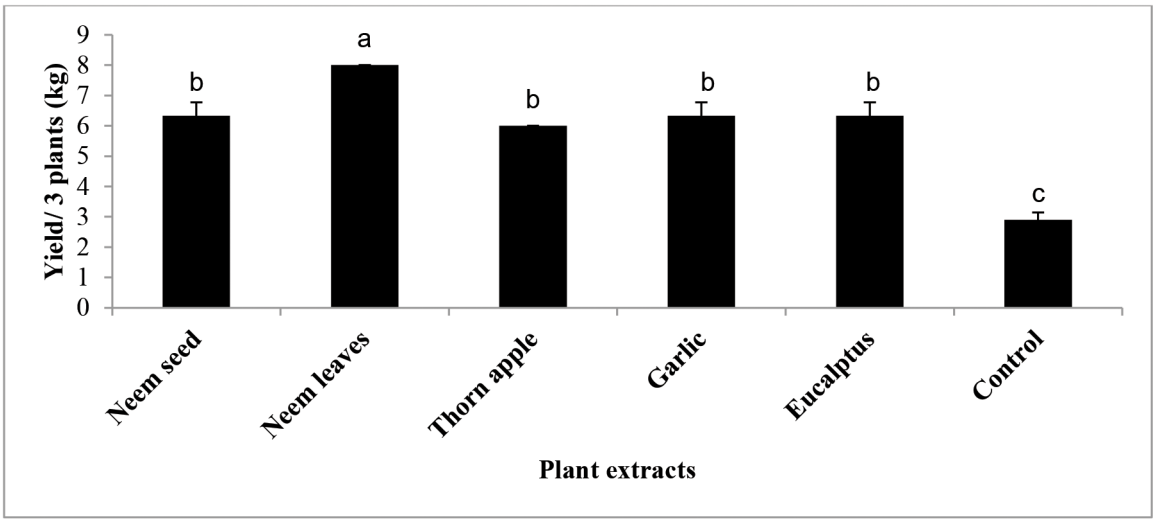


Fig. 7 Effect of different plant extracts on fruit yield per plant inoculated with *Fusarium* sp. in field conditions

Conclusion

The plant extracts of the neem leaves, neem seed, thorn apple, garlic and eucalyptus were found highly effective at 8 percent concentrations in terms of reducing the disease mortality, disease incidence, root infection percentage. The use of these extracts improved plant biomass and yields in tomato plant. These plant extracts are highly recommended as a possible alternate control measures against fusarium wilt disease of tomato and it is also suggested that the assessment of plant extracts concentrations must be carried out at field level.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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