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Research Article

Evaluation of Organic and Vermicompost-based *Trichoderma harzianum* Formulation for Seedling Disease Management and Yield Enhancement in Chickpea (*Cicer arietinum* L.)

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Abstract

Seedling diseases caused by soil-borne pathogens pose a significant threat to chickpea (*Cicer arietinum* L.) production, often resulting in poor plant stand, reduced growth, and substantial yield losses. Eco-friendly and sustainable disease management strategies are therefore essential to minimize chemical inputs while enhancing soil and plant health. In this study, organic composts and vermicompost were screened as carrier materials for the formulation of *Trichoderma harzianum*, an effective biocontrol agent, to evaluate their efficacy in managing seedling diseases caused by soil-borne pathogens, *Sclerotium rolfsii* and *Fusarium oxysporum* f. sp. *ciceri*, and promoting growth and yield of chickpea. The experiments were conducted in the fields of the Plant Pathology Division, Bangladesh Agricultural Research Institute, Gazipur, during 2018-19, 2019-20, and 2020-21 cropping years to evaluate the antagonistic potential of organic composts and vermicompost-based *T. harzianum* formulations designated as Tricho-organic-compost and Tricho-vermi-compost on seedling emergence, disease incidence, plant growth, and grain yield of chickpea. Seed treatment with fungicide Provax 200 WP was also tested. Results revealed that *T. harzianum* enriched organic composts and vermicompost, viz. Tricho-organic-compost and Tricho-vermi-compost soil, seed treatment by Provax 200 WP, and soil amendment with organic-compost and vermi-compost were effective in reducing seedling mortality and increasing plant growth and yield of chickpea compared to the control. Among the treatments, *T. harzianum* enriched organic composts and vermicompost, viz. Tricho-organic-compost and Tricho-vermi-compost exhibited superior for significant reduction in seedling mortality, and enhancement in plant growth parameters, and increased yield of chickpea compared to untreated control and other treatments. The study underscores the potential of compost-based *T. harzianum* formulations as sustainable tools for integrated management of chickpea seedling diseases while enhancing crop productivity. Seed treatment with the chemical fungicide Provax 200 WP was also a better treatment for managing seedling disease and increasing plant growth and yield of chickpea.

Introduction

Chickpea (*Cicer arietinum* L.) belongs to the family Fabaceae and is an important legume crop globally, and it is the third most important pulse crop in the world, including Bangladesh [1,2]. It is one of the major sources of plant-derived edible quality protein, minerals, folate, and contributes to food security and soil fertility through its nitrogen-fixing ability [3]. However, its production is often hindered by many factors, whereas several biotic stresses, particularly soilborne diseases, are the most important ones [4-7].

There are more than 50 diseases that have been reported in different regions across the world, which affect this particular crop [7,8]. So far, 17 chickpea diseases have been identified in Bangladesh, 12 of which are caused by fungus [9]. The yield loss of chickpea due to insects and diseases varies depending on the region, in temperate regions yield loss of 5% - 10% and in tropical regions, higher loss of 50% - 100% [10].

Soil-borne diseases, notably seedling diseases caused by pathogens like *Fusarium oxysporum f. sp. ciceris* and *Sclerotium rolfsii,* are one of the major constraints for chickpea production in Bangladesh, which contributes 55% - 95% seedling mortality of chickpea [11]. These pathogens can lead to substantial yield losses, making effective disease management crucial for sustainable chickpea cultivation. However, under favorable environmental conditions for the pathogens, yield losses have been estimated as high as 100% [12,13].

Traditional chemical fungicides have been employed to manage these diseases. However, their prolonged use can lead to environmental degradation, the development of pathogen resistance, and adverse effects on non-target organisms. Consequently, there is a growing interest in integrating biological control agents (BCAs) with organic farming practices to develop eco-friendly and sustainable disease management strategies. In this context, alternative approaches like crop rotation, use of soil amendment, bio-fumigation, biological soil disinfestations, and application of biocontrol agents are growing in interest to develop eco-friendly and sustainable disease management strategies [14-17].

Biological control agents such as *Trichoderma harzianum* offer an environmentally friendly and economically viable alternative. *T. harzianum* is well known for its antagonistic activities as well as its ability to trigger systemic resistance and promote plant growth [18,19]. In chickpea, *T. harzianum* has been successfully used to reduce wilt and root rot incidence and to enhance yield under both greenhouse and field conditions [20,21]. A major limitation of biocontrol by *Trichoderma* strains is the production of inoculum on a large scale.

However, the success of *Trichoderma*-based bioformulations depends on the choice of carrier material, which influences spore viability, shelf-life, and field performance. Conventional carriers like talc and peat are effective but may not always be sustainable or locally available, and often show reduced viability over time. Organic carriers such as compost and vermicompost are rich in nutrients and beneficial microbes, providing a favorable environment for *Trichoderma* survival and multiplication [22,23]. Vermicompost in particular has been shown to suppress soil-borne pathogens directly through microbial antagonism and indirectly by enhancing soil fertility and host resistance [24,25]. Enriching compost and vermicompost with *Trichoderma* further enhances their efficacy, resulting in improved rhizosphere competence, disease suppression, and yield benefits [21,25].

A few works have been done on the management of soil-borne seedling diseases of chickpea with bio-control microorganisms in Bangladesh. Yet information on *Trichoderma* formulation in different composts and their effectiveness against soil-borne disease of chickpea is inadequate under Bangladeshi conditions. So, evaluation of organic and vermicompost-based *T. harzianum* formulations offers a promising avenue for sustainable management of seedling diseases in chickpea. Such approaches not only improve disease control efficacy but also contribute to soil health and long-term productivity under integrated pest management systems. Therefore, the present study was undertaken to evaluate organic compost and vermi-compost-based *T. harzianum* formulation for the management of seedling disease caused by soil-borne fungal pathogen *S. rolfsii* Sacc and *F. oxysporum* f. sp. *ciceri,* and to increase the yield of chickpea.

Materials and methods

The effect of organic compost and vermi-compost-based *T. harhianum* formulation designated as Tricho-organic-compost and Tricho-vermi-compost against seedling disease of chickpea caused by *S. rolfsii* and *F. oxysporum* f. sp. *ciceri* was investigated in the field of Plant Pathology Division of Bangladesh Agricultural Research Institute at three cropping seasons during 2018-19, 2019-20, and 2020-21. Native *T. harzianum* isolate TKC-3 was tested against *S. rolfsii* and *F. oxysporum* f. sp. *ciceri* in the laboratory and found to be more vigorous in suppressing the growth of these pathogens.

Tricho-organic-compost and Tricho-vermi-compost preparation

The pure culture of *T. harzianum* (TKC-3) was grown in potato dextrose agar (PDA) medium. The culture was used to formulated in the substrates containing a mixture of rice bran, wheat bran, and mustard oilcake. The formulated *T. harzianum* was used for mass multiplication in organic compost and vermi-compost. The formulated *T. harzianum* was properly mixed with organic compost and vermi-compost and kept under the shed for 7-10 days for multiplication of *Trichoderma* in the mixture. Based on the compost materials used in composting, these composts were designated as Tricho-organic-compost and Tricho-vermi-compost.

Pathogenic fungal inocula preparation

The pure cultures of the pathogenic fungi *S. rolfsii* and *F. oxysporum* f. sp. *ciceri* were prepared on potato dextrose agar (PDA) medium. The inoculum of *S. rolfsii* and *F. oxysporum* f. sp. *ciceri* was multiplied on a mixture of wheat bran, khesari bran, and mustard oilcake (MOC).

Field experiment

The experiment was conducted in the field of the Plant Pathology Division, Bangladesh Agricultural Research Institute, Gazipur. There were 6 treatments viz. (i) Seed treatment with Provax 200 WP @ 2.5 g/kg seed (ii) Soil amendment with organic compost @ 2.5 t/ha (iii) Soil amendment with Tricho-organic compost @ 2.5 t/ha (iv) Soil amendment with vermi-compost @ 2.5 t/ha, (v) Soil amendment with Tricho-vermi-compost @ 2.5 t/ha and (vi) Untreated control. The unit plot size was 2 m x 3 m. RCB design was followed with 3 replications. The field soil was inoculated with *S. rolfsii* and *F. oxysporum* inocula colonized in the substrate consisting of khesari bran, wheat bran, and mustard oilcake @ 100g/m^2 of soil, and allowed the pathogen establishment in the soil for 7 days. Then the inoculated soil was again treated with organic compost, vermi-compost, Tricho-organic-compost, and Tricho-vermi-compost applied in the soil @ 2.5 t/ha and properly mixed with the soil, kept for 5 days for *Trichoderma* establishment in the soil. Seeds were treated with Provax @ 2.5 g/kg seeds before seed sowing. The seeds of chickpea var. BARI Chola 5 were sown @ 45 kg ha^{-1} in the experimental plots, maintaining row to row distance of 40 cm. Proper intercultural operations were done for better growth of chickpea in the field. No plant-protecting chemicals (insecticides or fungicides) were applied in the field.

Determination of seedling disease

The experimental plots were routinely inspected to observe the initiation of seedling disease of chickpea in the field. The infected plants were collected from the field and brought to the laboratory, and the pathogens were isolated following tissue planting methods [26]. The isolated fungi were purified by the hyphal tip culture method and identified as *S. rolfsii* and *F. oxysporum* f. sp. *ciceri* according to reference mycology books and manuals [27,28].

Data collection and analysis

Data on different parameters, viz., seedling mortality, shoot height, shoot weight, root length, root weight, and yield of chickpea, were recorded. The incidence of seedling mortality data was started at the time of disease appeared, and it continued until 40 days of seed sowing. Plant growth parameters, shoot height, shoot weight, root length, and root weight were recorded 40 days after seed sowing. The percent data were converted into arcsine transformation values before statistical analysis. Data were analyzed statistically by using the MSTATC program following ANOVA. The treatment effects were compared by applying the least significant difference (LSD) test at a $p = 0.05$ level.

Results and discussion

Seedling emergence and pre-emergence mortality

Soil amendment with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic compost, and seed treatment with Provax 200 WP gave significantly higher seedling emergence of chickpea compared to the control in all the years (Table 1). In the 1st year, seedling emergence varied from 78.67% - 84.67% among the treatments, where control gave comparatively lower 55.67% seedling emergence of chickpea (Table 1). Soil amendment with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic compost, and seed treatment with Provax 200 WP gave significantly higher seedling emergence in the 2nd year and 3rd year trials, ranging from 71.67% - 83.33% and 76.67% - 81.67%, respectively, and it was the lowest of 48.33% in the 2nd year and 49.33% in the 3rd year in control treatment.

On the contrary, soil amendment with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic compost, and seed treatment with Provax 200 WP caused a significant reduction in pre-emergence seedling mortality of chickpea compared to the control. The range of pre-emergence seedling mortality was 15.33% - 21.33% in the 1st year, 16.67% - 28.33% in the second year, and 18.33% - 23.33% in the third year. The corresponding mortality under control was 44.33%, 51.67% and 50.67% in the 1st year, 2nd year, and 3rd year, respectively (Table 1).

Several studies have shown similar outcomes where seed treatment or soil application of *T. harzianum* formulations improved seed germination, vigor index, and reduced pre- and post-emergence damping-off in legumes and other crops [29,30]. Hossain and Fakir [31] reported that seed treatment with *Trichoderma* increased the germination of different crops. Several other studies have shown that soil amendments with Organic compost and vermicompost promote higher germination rates [32-34]. *Trichoderma* species as bio-control agents significant increase in seedling emergence and suppression of pre-emergence mortality of tomato seedlings have also been reported by Mishra and Sinha [35], Prasad and Anes [36], and Mukhtar [37]. The earlier research also suggests that the combined application of biocontrol agents with organic amendments represents an eco-friendly and sustainable strategy for improving seed germination, plant growth, and disease suppression in chickpea and other crops [38,39].

Post-emergence seedling mortality

Soil amendment with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic compost, and seed treatment with Provax 200 WP sharply reduced the post-emergence seedling mortality of chickpea during three cropping years (Table 2). Under control treatment, the highest seedling mortality, 27.67%, 30.00% and 36.67% in the 1st year, 2nd year, and 3rd year, respectively, was recorded. Soil amendment with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic compost, and seed treatment with Provax 200 WP gave significantly lower seedling mortality, ranging from 9.67% - 17.33% in the 1st year, 8.67% - 15.00% in the 2nd year, and 12.33% - 22.33% in the 3rd year. The reduction of seedling mortality was from 37.37% - 65.05% in 1st year, 50.00% - 71.10% in 2nd second year, and 39.11% - 66.38% in 3rd year due to various treatments as compared to the untreated control. Soil amendment with Tricho-vermi-compost gave the highest

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Table 1: Effect of *Trichoderma harzianum* enriched Tricho-organic-compost and Tricho-vermi-compost on the plant growth of chickpea during three consecutive years.

Treatments	Average shoot length (cmplant-1)			Average shoot weight (gplant-1)		
	2018-19	2019-20	2020-21	2018-19	2019-20	2020-21
Seed treatment with Provax	33.33 b	39.53 b	33.53 b	31.40 ab	37.83 b	34.03 b
Soil amendments with organic compost	33.67 b	38.87 b	30.67 b	29.60 b	37.33 b	28.53 b
Soil amendments with Tricho-organic-compost	38.33 a	45.73 a	41.60 a	33.50 a	42.33 a	41.80 a
Soil amendments with vermi-compost	34.00 b	39.07 b	29.27 c	28.73 b	37.73 b	29.47 b
Soil amendments with Tricho-vermi-compost	39.33 a	46.07 a	41.07 a	33.43 a	42.27 a	41.60 a
Control	26.67 c	30.40 c	24.54 d	23.93 c	26.60 c	20.73 c
LSD (p = 0.05)	2.522	2.529	2.312	3.248	3.258	3.512

Values in a column having the same letter did not differ significantly (p = 0.05) by LSD.

Table 2: Effect of *Trichoderma harzianum* enriched Tricho-organic-compost and Tricho-vermi-compost on the root growth of chickpea during three consecutive years.

Treatments	Average root length (cmplant-1)			Average root weight (gplant-1)		
	2018-19	2019-20	2020-21	2018-19	2019-20	2020-21
Seed treatment with Provax	10.77 a	11.00 b	12.33 b	4.43 a	4.18 b	3.73 b
Soil amendments with organic compost	10.53 a	11.60 ab	11.87 b	4.37 a	4.27 ab	3.67 b
Soil amendments with Tricho-organic-compost	11.40 a	13.07ab	15.07 a	4.73 a	4.58 ab	4.37 a
Soil amendments with vermi-compost	10.73 a	11.80 ab	10.47 b	4.20 a	4.20 b	3.30 b
Soil amendments with Tricho-vermi-compost	12.13 a	13.47 a	14.53 a	4.57 a	4.73 a	4.33 a
Control	7.47 b	8.67 c	7.93 c	3.17 b	3.38 c	2.77 c
LSD (p = 0.05)	1.714	2.185	1.834	0.746	0.477	1.031

Values in a column having the same letter did not differ significantly (p = 0.05) by LSD.

reduction of seedling mortality by 76.87% in the 1st year, 80.00% in the 2nd year and 65.61% in the 3rd year followed by soil amendment with Tricho-organic-compost, seed treatment with Provax 200 WP, soil amendment with vermi-compost and organic-compost where the reduction of seedling mortality 72.40%, 68.66%, 67.92% and 61.94, respectively in the 1st year, 78.18%, 70.91%, 59.40% and 67.27, respectively in the 2nd year and 61.60%, 61.60%, 57.59% and 44.01, respectively in the 3rd year. Fungicidal seed treatments (eg, carbendazim, thiram, captan) have been widely used to manage seedling diseases, and their effectiveness in reducing seed and seedling infections has been well-documented [29,40]. The application of *T. harzianum* through organic and vermicompost formulations provides an eco-friendly approach to reduce seedling mortality. Sharma, et al. [38] reported that *T. harzianum* in compost-based formulations not only reduced seedling mortality but also enhanced plant vigor and survival, supporting the idea that biocontrol agents offer both disease suppression and plant growth promotion. Podder, et al. [41] and Rojo, et al. [42] recorded the efficacy of *Trichoderma* spp. as bio-control agents against phytopathogenic fungi, especially to *Rhizoctonia* spp. and *Fusarium* spp., to formulate bio-fungicides after colonization on organic materials. Tricho-compost was found to be most effective in controlling soil-borne diseases of cabbage [43]. Uzun [44] and Younis [45] also reported that *Trichoderma* isolates potentially reduced the disease caused by phytopathogenic fungi such as *R. solani, F. oxysporum,* and *S. rolfsii.* Previous studies also reported that *T. harzianum* in combination with organic amendments was more effective than fungicides alone in reducing root rot and wilt in legumes [29,39].

Shoot growth and Root growth

Shoot growth, such as shoot length and shoot weight of chickpea, was significantly enhanced by different treatments in all the years compared to the control (Table 3). The lowest shoot length 26.67 cmplant-1, 30.40 cmplant-1, and 24.54 cmplant-1 in the 1st year, 2nd year, and 3rd year, respectively, was recorded under the control plot. Soil amendment with Tricho-organic-compost and Tricho-vermi-compost gave the higher shoot length of 39.33 cmplant-1 and 38.33 cmplant-1 in 1st year, 46.07 cmplant-1 and 45.73 cmplant-1 in 2nd year, 41.07 cmplant-1 and 41.60 cmplant-1, respectively followed by soil amendment with vermi-compost, organic compost and seed treatment with Provax 200 WP where the shoot length was 34.00 cmplant-1, 33.67 cmplant-1 and 33.33 cmplant-1 in 1st year, 39.07 cmplant-1, 38.87 cmplant-1 and 39.53 cmplant-1 in 2nd year, 33.53 cmplant-1, 30.67 cmplant-1 and 29.27 cmplant-1 in 3rd year, respectively.

Under control treatment, the shoot weight of chickpea was 23.93, 26.60, and 20.73 g plant-1 in the 1st, 2nd, and 3rd year, respectively. Soil amendment with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic-compost, and seed treatment with Provax 200 WP increased the parameter ranging from 28.73 - 33.50 gplant-1, 37.33 - 42.33 gplant-1, and 28.53 - 41.80 gplant-1 in the 1st, 2nd, and 3rd year, respectively. Every year, the shoot weight of chickpea was significantly increased due to different treatments with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic-compost, and seed treatment with Provax 200 WP compared to the control. Among the treatments, soil amendments with Tricho-vermi-compost and Tricho-organic-compost gave the highest shoot weight in all the years, followed by soil amendments with vermi-compost, organic compost, and seed treatment with Provax 200 WP. The lowest shoot weight was recorded from the control treatment in all the years (Table 3).

The root length of chickpea was significantly lower in the control by 7.47 cmplant^{-1}, 8.67 cmplant$^{-1,}$ and 7.93 cmplant^{-1} in the 1st year, 2nd year, and 3rd year, respectively. The root length of chickpea under different treatments was increased significantly compared to the control, which ranged from 10.53 - 12.13 cmplant^{-1}, 11.00 - 13.47 cmplant$^{-1,}$ and 10.47 - 15.07 cmplant^{-1} in the 1st year, 2nd year, and 3rd year, respectively (Table 4). In case of root weight, significantly higher root weight ranges from 4.20 - 4.57 gplant^{-1}, 4.18 - 4.73 gplant$^{-1,}$ and 3.30 - 4.37 gplant^{-1} in the 1st year, 2nd year, and 3rd year, respectively, were recorded in the different treatments. The lowest root weight 3.17 gplant^{-1}, 3.38 gplant$^{-1,}$ and 2.77 gplant^{-1} in the 1st year, 2nd year, and 3rd year, respectively, was recorded from the control (Table 4). The promotion of plant growth in terms of length and weight of shoot and root, due to the use of *Trichoderma* spp. as soil amendment, has been achieved by several investigators [46-49]. Sharma, et al. [38] and Kumar, et al. [50] reported that compost-based formulations of *T. harzianum* improved chickpea growth parameters alongside effective management of collar rot and wilt. Findings of the present investigation have also been in agreement with findings of other researchers [51-54].

Yield of chickpea

Every year, chickpea yield was significantly increased by soil amendment with Tricho-vermi-compost, Tricho-organic-compost, vermi-compost, organic compost, and seed treatment with Provax 200 WP compared to the control (Table 5). The lowest yield of chickpea was recorded under control by 1356 kgha^{-1}, 1407 kgha$^{-1,}$ and 11448 kgha^{-1} in the 1st year, 2nd year, and 3rd year, respectively (Table 5). The yield of chickpea was significantly increased, ranging from 1694 - 2083 kgha^{-1}, 1870 - 2148 kgha$^{-1,}$ and 1774 - 2077kgha^{-1} in the 1st year, 2nd year, and 3rd year, respectively, due to different treatments. Among them, soil amendment with Tricho-vermi-compost and Tricho-organic-compost, gave the maximum yield by 2083 kgha^{-1} and 2056 kgha^{-1} in the 1st year, 2148 kgha^{-1} and 2167 kgha^{-1} in the 2nd year, 2077 kgha^{-1} and 2040 kgha^{-1} in the 3rd year, respectively followed by seed treatment with Provax 200 WP, soil amendment with vermi-compost and organic compost where the yield was 1794 kgha^{-1}, 1750 kgha^{-1} and 1694 kgha^{-1} in the 1st year, 1907 kgha^{-1}, 1896 kgha^{-1} and 1870 kgha^{-1} in the 2nd year and 1925 kgha^{-1}, 1774 kgha^{-1} and 1779 kgha^{-1} in the 3rd year, respectively.

In the 1st year, soil amendment with Tricho-vermi-compost gave the maximum 34.90% higher yield compared to control, followed by soil amendment with Tricho-organic-compost, seed treatment with Provax 200 WP, soil amendment with vermi-compost, and organic compost, where the yield was

Table 3: Effect of *Trichoderma harzianum* enriched Tricho-organic-compost and Tricho-vermi-compost on the pre-emergence seedling mortality of chickpea during three consecutive years.

Treatments	Seed Germination (%)			Pre-emergence seedling mortality (%)		
	2018-19	2019-20	2020-21	2018-19	2019-20	2020-21
Seed treatment with Provax	81.67 a (64.71)	78.33 a (62.29)	81.67 a (65.19)	18.33	21.67	18.33
Soil amendments with organic compost	78.67 a (62.51)	71.67 a (57.87)	76.67 a (61.46)	21.33	28.33	23.33
Soil amendments with Tricho-organic-compost	82.33 a (65.16)	83.33 a (66.14)	81.67 a (65.00)	17.67	16.67	18.33
Soil amendments with vermi-compost	82.67 a (65.49)	75.00 a (60.07)	76.67 a (61.14)	17.33	25.00	23.33
Soil amendments with Tricho-vermi-compost	84.67 a (67.01)	81.67 a (64.71)	81.33 ab (64.45)	15.33	18.33	18.67
Control	55.67 b (48.26)	48.33 b (44.01)	49.33 c (44.62)	44.33	51.67	50.67
LSD (p = 0.05)	4.335	10.48	2.945	-	-	-

Table 4: Effect of *Trichoderma harzianum-enriched* Tricho-organic-compost and Tricho-vermi-compost on the post-emergence seedling mortality of chickpea during three consecutive years.

Treatments	Post-emergence seedling mortality (%)			Reduction of post-emergence seedling mortality (%)		
	2018-19	2019-20	2020-21	2018-19	2019-20	2020-21
Seed treatment with Provax	9.67 c (18.10)	8.67 c (17.05)	12.33 c (20.57)	65.05	71.10	66.38
Soil amendments with organic compost	17.33 b (24.53)	15.00 b (22.73)	22.33 b (28.23)	37.37	50.00	39.11
Soil amendments with Tricho-organic-compost	10.33 c (18.72)	9.33 c (17.75)	13.67 c (21.69)	62.67	68.90	62.72
Soil amendments with vermi-compost	16.00 b (23.41)	14.33 b (22.21)	21.00 b (27.29)	42.18	52.23	42.73
Soil amendments with Tricho-vermi-compost	10.07 c (19.04)	9.10 c (17.39)	12.33 c (20.58)	63.61	69.67	66.38
Control	27.67 a (31.74)	30.00 a (33.02)	36.67 a (37.38)	-	-	-
LSD (p = 0.05)	3.343	3.531	3.628	-	-	-

Values in a column having the same letter did not differ significantly (p = 0.05) by LSD; values within the parentheses are the arcsin-transformed value.

Table 5: Effect of *Trichoderma harzianum-enriched* Tricho-organic-compost and Tricho-vermi-compost on the yield of chickpea during three consecutive years.

Treatments	Yield (kgha^{-1})			Yield increased over control (%)		
	2018-19	2019-20	2020-21	2018-19	2019-20	2020-21
Seed treatment with Provax	1794 b	1907 b	1925 b	24.42	26.22	24.78
Soil amendments with organic compost	1694 b	1870 b	1779 c	19.95	24.76	18.61
Soil amendments with Tricho-organic-compost	2056 a	2167 a	2040 ab	34.05	35.07	29.02
Soil amendments with vermi-compost	1750 b	1896 b	1774 c	22.51	25.79	18.38
Soil amendments with Tricho-vermi-compost	2083 a	2148 a	2077 a	34.90	34.50	30.28
Control	1356 c	1407 c	1448 d	-	-	-
LSD (p = 0.05)	229.8	266.2	192.6	-	-	-

Values in a column having the same letter did not differ significantly (p = 0.05) by LSD.

34.05%, 24.42%, 22.51% and 19.95%, respectively, higher compared to control. In the 2nd year, the maximum 35.07% higher yield compared to control was achieved with Tricho-organic-compost treatment followed by soil amendment with Tricho-vermi-compost, seed treatment with Provax 200 WP, soil amendment with vermi-compost, and organic compost, where the yield was 34.50%, 26.22%, 25.79% and 24.76%, respectively, higher compared to control. In the 3rd year, soil amendment with Tricho-vermi-compost gave the maximum 30.28% higher yield compared to control, followed by soil amendment with Tricho-organic-compost, seed treatment with Provax 200 WP, soil amendment with organic compost, and vermi-compost, where the yield was 29.02%, 24.78%, 18.61% and 18.38%, respectively, higher compared to control.

Seed treatment with fungicides like carbendazim, thiram, or captan has long been recommended as an effective measure to reduce early disease incidence, ensuring better plant stand establishment and yield [29,40]. In the current evaluation, fungicide treatments effectively minimized seedling mortality and contributed to moderate yield improvement. Organic and vermicompost-based *T. harzianum* formulations, on the other hand, significantly enhanced chickpea yield by combining disease suppression with plant growth promotion. Additionally, compost substrates (organic and vermicompost) provide essential macro- and micronutrients, improve soil structure, and increase microbial activity, further enhancing yield potential [30,32,33]. Kumar, et al. [50] observed that *T. harzianum* bioformulations significantly increased yield in chickpea while reducing collar rot incidence. Sharma, et al. [38] also demonstrated enhanced pod number and seed weight in chickpea treated with improved strains of *T. harzianum*. Rahman [55] reported that *Trichoderma*-fortified composted poultry refuse was very effective in controlling several soil-borne pathogens of tomato and increased yield significantly in comparison to the untreated control. Mohiddin, et al. [56] and Sajad, et al. [57] reported that vermi-compost and organic manure are the best materials for mass formulation and biomass production of *T. harzianum*. In another study, Singh, et al. [39] highlighted that integrating organic amendments with biocontrol agents resulted in higher yield and greater sustainability compared to fungicides alone.

The present evaluation suggests that while fungicide seed treatments are useful for reducing early pathogen-induced yield losses, the integration of *T. harzianum* bioformulations with organic and vermicompost substrates offers greater yield benefits. This dual advantage, disease suppression and plant growth stimulation, makes compost-based *T. harzianum* formulations a superior, eco-friendly alternative to sole reliance on chemical fungicides for sustainable chickpea production. Therefore, it may be concluded that vermi-compost and organic compost are the promising substrates for the mass production of bio-control agent *T. harzianum*. Soil treatment with formulated *T. harzianum* designated as Tricho-vermi-compost and Tricho-organic-compost is the best treatment for the management of seedling disease caused by soil-borne fungal pathogen *S. rlfsii* and *F. oxysporum,* which also increases plant growth parameters as well as yield of chickpea.

Conclusion

From this, it was revealed that vermi-compost and organic compost are the promising substrates for the mass production of bio-control agent *T. harzianum.* Compost-based *T. harzianum* formulations are a superior, eco-friendly alternative to sole chemical fungicides for seedling disease management and sustainable chickpea production.

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