

***In Vitro* Compatibility of Elite Indigenous *Trichoderma* Isolates with Commonly Used Agrochemicals for Sustainable Integrated Disease Management**

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Received: July 11, 2026 | Review began: July 30, 2026 | Review ended: August 11, 2026 | Published: September 01, 2026

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Abstract

The compatibility of biological control agents with agrochemicals is critical for creating successful and long-lasting integrated disease management strategies. Five elite indigenous *Trichoderma* isolates (Tr79, Tr80, Tr44, Tr42, and Tr46), previously selected based on their superior antagonistic activity against three major soil-borne fungal pathogens (*Fusarium oxysporum*, *Macrophomina phaseolina*, and *Sclerotium rolfsii*), which pose significant threats to crop production in the Saurashtra region of Gujarat, India, were evaluated for their *in vitro* compatibility with 21 commercially available agrochemicals, including fungicides, insecticides, and herbicides. Agrochemicals were evaluated at four different concentrations, and compatibility was determined by calculating the percentage suppression of radial mycelial growth. The data were analyzed using two-way analysis of variance (ANOVA), followed by Tukey's Honest Significant Difference test. Agrochemical treatment, *Trichoderma* isolate, and their interaction significantly affected mycelial growth inhibition (two-way ANOVA, $P < 0.05$). Carbendazim 12% + Mancozeb 63% Wettable Powder resulted in total inhibition (100%), but Prochloraz + Tebuconazole (99.91%) and Carbendazim + Flusilazole (99.81%) both showed significant toxicity, showing poor compatibility with the tested isolates. In contrast, Imazethapyr 10% Soluble Concentrate showed no measurable inhibition and was found to be the most compatible agrochemical. Pyriproxyfen + Diafenthiuron, Fluazifop-p-butyl + Fomesafen, Carbofuran, Imazethapyr + Imazamox, and Pendimethalin were similarly very compatible, with less than 10% mycelial inhibition. The interaction between agrochemicals and isolates revealed distinct variances in chemical tolerance. These findings give significant information for determining appropriate pesticide and *Trichoderma* combinations that can be included in sustainable crop protection systems while limiting harmful impacts on beneficial soil microorganisms.

Categories: Plant-pathogen interaction, Disease & pests of crops, Use of biostimulants, biofertilizers, bioinoculants in sustainable agriculture

Keywords: trichoderma, agrochemical compatibility, biological control, integrated disease management, sustainable agriculture

Introduction

Global agriculture faces the challenge of increasing food production while minimizing the environmental impacts of intensive farming. Plant diseases remain a major constraint to crop productivity, and synthetic pesticides have long been relied upon for their management. Although these chemicals have substantially improved agricultural production, their excessive and prolonged use has resulted in environmental contamination, pesticide residues, disruption of beneficial

How to cite this article:

Suvagiya D K, Kothari R K (September 01, 2026) *In Vitro* Compatibility of Elite Indigenous *Trichoderma* Isolates with Commonly Used Agrochemicals for Sustainable Integrated Disease Management. Cureus J. Agri. Food Sci 2 : es44497-026-00256-9. DOI <https://doi.org/10.7759/s44497-026-00256-9>

soil microorganisms, pathogen resistance, biodiversity loss, and potential risks to human and animal health [1-3]. Consequently, sustainable crop protection strategies that reduce dependence on chemical pesticides have become a global priority.

Integrated Disease Management (IDM) combines biological control with cultural practices, host resistance, and the judicious use of pesticides to achieve effective and environmentally sustainable disease management [4]. Among biological control agents, *Trichoderma* species are widely recognized for their ability to suppress numerous plant pathogens while simultaneously promoting plant growth and improving tolerance to environmental stresses, making them an important component of modern sustainable agriculture [5-10].

Despite the increasing adoption of microbial biocontrol agents, synthetic fungicides, insecticides, and herbicides remain indispensable in crop production. Therefore, identifying agrochemicals that are compatible with beneficial microorganisms is essential for their successful integration into IDM programs. Agrochemicals that adversely affect *Trichoderma* can reduce fungal growth, sporulation, rhizosphere colonization, and biocontrol efficacy, whereas compatible products enable their combined or sequential application without compromising biological performance [11,12].

Previous studies have demonstrated that compatibility between *Trichoderma* and agrochemicals varies considerably depending on the isolate, active ingredient, formulation, and concentration [7,8,13]. However, most investigations have focused on a limited number of isolates or individual pesticide groups, particularly fungicides, with comparatively little information available on recently introduced commercial formulations, combination products, and the simultaneous evaluation of fungicides, insecticides and, herbicides. Furthermore, studies evaluating multiple indigenous *Trichoderma* isolates against a broad spectrum of commercially available agrochemicals at different application concentrations remain scarce. Consequently, comprehensive isolate-specific compatibility data required for the successful integration of *Trichoderma*-based bioformulations into regional crop protection programs are still limited.

To address this knowledge gap, the present study provides the first comprehensive agrochemical compatibility assessment of elite indigenous *Trichoderma* isolates from the Saurashtra region of Gujarat, India. To the best of our knowledge, this is the first study from the Saurashtra region to simultaneously evaluate five elite indigenous *Trichoderma* isolates against 21 commercially available agrochemicals representing fungicides, insecticides, and herbicides, each tested at four concentrations. The five elite isolates (Tr79, Tr80, Tr44, Tr42, and Tr46), previously selected based on their superior antagonistic activity against the major soil-borne pathogens, *Fusarium oxysporum*, *Macrophomina phaseolina*, and *Sclerotium rolfsii*, were evaluated *in vitro* to generate comprehensive isolate-specific compatibility profiles. This integrated assessment of multiple *Trichoderma* isolates, diverse agrochemical classes, and concentration gradients in a single study provides valuable baseline information for selecting compatible agrochemical-bioagent combinations. The findings will facilitate the effective integration of *Trichoderma*-based bioformulations into integrated disease management programs and support the development of environmentally sustainable crop protection strategies.

Materials And Methods

Source of isolates

Five indigenous *Trichoderma* isolates (Tr79, Tr80, Tr44, Tr42, and Tr46) were selected for the present investigation based on their superior antagonistic activity against three economically important soil-borne phytopathogens, *Fusarium oxysporum*, *Macrophomina phaseolina*, and *Sclerotium rolfsii*, under *in vitro* dual culture assays [14] conducted in a previous screening study. These isolates consistently exhibited the highest levels of pathogen growth inhibition and were therefore considered elite candidates for compatibility evaluation with agrochemicals.

The isolates were maintained on potato dextrose agar (PDA) slants at $4 \pm 1^\circ\text{C}$ and subcultured at 30-day intervals onto fresh PDA slants to maintain viability and purity. Before each experiment, the isolates were transferred onto fresh PDA plates and incubated at $28 \pm 2^\circ\text{C}$ for 5 days. Actively growing colonies from the peripheral region were used for all compatibility assays.

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Agrochemical treatments

Twenty-one commercially available agrochemicals, comprising seven fungicides, seven insecticides, and seven herbicides, were selected for this study based on their widespread use in the cultivation of major agricultural crops in the Saurashtra region of Gujarat, India. The selected products represent commonly recommended commercial formulations with different active ingredients and modes of action that are routinely employed by farmers for managing fungal diseases, insect pests, and weeds. Since these agrochemicals are frequently applied either before, during, or after the application of microbial biocontrol agents, evaluating their compatibility with *Trichoderma* is essential for developing practical IDM strategies. Similar approaches for selecting representative agrochemicals have been adopted in previous compatibility studies [15]. Details of the commercial formulations, active ingredients, and agrochemical groups are presented in Table 1.

Fungicides were evaluated at 100, 200, 300, and 400 ppm, whereas insecticides and herbicides were tested at 250, 500, 750, and 1000 ppm. These concentration ranges were selected to represent the recommended field dose together with proportionally lower and higher concentrations that may occur due to variations in field preparation, application practices, or residual exposure. Evaluating four concentration levels enabled the assessment of concentration-dependent responses, determination of isolate tolerance over a realistic exposure range, and identification of agrochemicals that remain compatible with *Trichoderma* under different application scenarios. The selected concentration ranges are also consistent with those commonly employed in previous *Trichoderma*-agrochemical compatibility studies [15].

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Sr. No.	Commercial Product	Active Ingredient(s)	Agro Chemical
1	Carbendazim 25% + Flusilazole 12.5% SE	Carbendazim + Flusilazole	Fungicide
2	Carbendazim 12% + Mancozeb 63% WP	Carbendazim + Mancozeb	
3	Prochloraz 5.7% + Tebuconazole 1.4% w/w ES	Prochloraz + Tebuconazole	
4	Metiram 55% + Pyraclostrobin 5%	Metiram + Pyraclostrobin	
5	Azoxystrobin 18.2% + Difenoconazole 11.4%	Azoxystrobin + Difenoconazole	
6	Carboxin 37.5% + Thiram 37.5% WS	Carboxin + Thiram	
7	Penflufen 13.28% w/w + Trifloxystrobin 13.28% w/w FS	Penflufen + Trifloxystrobin	
8	Chlorpyrifos 10%	Chlorpyrifos	Insecticide
9	Carbosulfan 25% EC	Carbosulfan	
10	Cartap hydrochloride 50% SP	Cartap Hydrochloride	
11	Fipronil 5% SC	Fipronil	
12	Imidacloprid 600 FS	Imidacloprid	
13	Carbofuran 3%	Carbofuran	
14	Pyriproxyfen 5% + Diafenthiuron 25% EC	Pyriproxyfen + Diafenthiuron	
15	Quizalofop-ethyl 5% EC	Quizalofop-ethyl	Herbicide
16	Sodium Acifluorfen 16.5% + Clodinafop-propargyl 8%	Sodium acifluorfen + Clodinafop-propargyl	
17	Propaquizafop 3.75% + Imazethapyr 2.5%	Propaquizafop + Imazethapyr	
18	Fluazifop-P-butyl 13.4% + Fomesafen 11.1%	Fluazifop-p-butyl + Fomesafen	

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19	a { text-decoration: none; color: #464feb; } tr th, tr td { border: 1px solid #e6e6e6; } tr th { background-color: #f5f5f5; } Pendimethalin 30% EC	Pendimethalin	
20	Imazethapyr 35% + Imazamox 35%	Imazethapyr + Imazamox	
21	Imazethapyr 10% SL	Imazethapyr	

TABLE 1: Agrochemicals used in the compatibility study; their active ingredients and agrochemical groups tested against selected *Trichoderma* isolates

WP, Wettable Powder; ES, Emulsion for Seed Treatment; SE, Suspo-Emulsion; SL, Soluble Concentrate; EC, Emulsifiable Concentrate; FS, Flowable Concentrate for Seed Treatment; SP, Water-Soluble Powder; WS, Water-Soluble Powder for Seed Treatment; SC, Suspension Concentrate

The inclusion of fungicides, insecticides, and herbicides within a single experimental design enabled a comprehensive comparison of isolate-specific compatibility across the major agrochemical groups commonly encountered under field conditions.

***In vitro* compatibility assay**

The poisoned food technique was used to determine the agrochemical compatibility of the selected *Trichoderma* isolates following the method of Vincent (1947) and methods used in recent *Trichoderma*-agrochemical compatibility studies [15]. Potato Dextrose Agar (PDA) medium was produced and sterilized at 121°C under 15 psi pressure for 20 minutes. After cooling to around 45-50°C, the needed amount of each agrochemical was aseptically added to the molten medium to achieve the desired concentrations. The altered medium was well mixed before being placed into sterile 90-mm Petri dishes. PDA plates without agrochemical amendment served as the untreated control. A 5-mm-diameter mycelial disc from the actively growing periphery of a five-day-old culture was aseptically transferred to the center of each plate. Plates were incubated at 28 ± 2°C until the untreated control plates reached complete colony coverage (approximately 5 days). Radial colony growth was measured when the untreated control plates reached complete colony coverage (approximately 5 days), thereby ensuring a uniform experimental endpoint across all treatments.

The experiment was conducted in a factorial Completely Randomized Design (CRD) with three biological replicates for each treatment.

Assessment of mycelial growth inhibition

Following incubation, radial colony growth was measured along two perpendicular axes, and the mean colony diameter was calculated. The percentage inhibition of mycelial growth was determined according to the formula, following the method described previously [16].

$$I = (C - T)/C \times 100$$

where I is the percentage inhibition of mycelial growth, C is the radial colony growth in the untreated control (mm), and T is the radial colony growth in the agrochemical-amended medium (mm). Lower inhibition values indicated greater compatibility of the agrochemical with *Trichoderma*, whereas higher inhibition values indicated greater toxicity.

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Statistical analysis

The effects of *Trichoderma* isolate, agrochemical, and their interaction on mycelial growth inhibition were evaluated using two-way analysis of variance (ANOVA) [17]. When significant differences were detected, means were separated using Tukey's honestly significant difference test at $P \leq 0.05$ [18].

All statistical analyses were performed using R statistical software, and results are presented as mean $\pm$ standard error (SE).

Results And Discussion

Results

In Vitro Compatibility of *Trichoderma* Isolates with Agrochemicals

The *in vitro* compatibility of five selected *Trichoderma* isolates (Tr79, Tr80, Tr44, Tr42, and Tr46) with 21 commercially available agrochemicals was evaluated using the poisoned food technique. The tested agrochemicals included seven fungicides, seven insecticides, and seven herbicides. Considerable variation in mycelial growth inhibition was observed among both agrochemical treatments and *Trichoderma* isolates, indicating differential compatibility.

Two-way ANOVA revealed highly significant effects of *Trichoderma* isolate, agrochemical treatment and their interaction on mycelial growth inhibition ($P < 0.05$) (Table 2). Agrochemical treatment accounted for the largest proportion of the observed variation ($F = 120.10$), followed by the isolate $\times$ agrochemical interaction ($F = 2.96$) and the main effect of isolate ($F = 3.19$). These results demonstrate that compatibility depended on both the agrochemical formulation and the individual *Trichoderma* isolate.

Source of Variation	df	Sum of Squares	Mean Square	F-value	P-value
Isolate (I)	4	2582.32	645.58	3.19	<0.05
Agrochemical (A)	20	486889.14	24344.46	120.10	<0.05
I $\times$ A	80	48018.68	600.23	2.96	<0.05
Error	210	42565.05	202.69	—	—
Total	314	580055.19	—	—	—

TABLE 2: Two-way ANOVA for mycelial growth inhibition (%) of *Trichoderma* isolates exposed to different agrochemicals
ANOVA, Analysis of Variance

Quantitative Classification of Agrochemical Compatibility

To facilitate interpretation, agrochemicals were classified according to mycelial growth inhibition as highly compatible (0-10%), compatible (>10-30%), moderately compatible (>30-50%), poorly compatible (>50-75%), and incompatible (>75-100%).

Mean inhibition values ranged from 0.00 to 100.00% (Table 3), demonstrating a wide range of compatibility among the tested agrochemicals. Carbendazim 12% + Mancozeb 63% Wettable Powder (100.00%), Prochloraz 5.7% + Tebuconazole 1.4% Emulsion for Seed Treatment (99.91%) and Carbendazim 25% + Flusilazole 12.5% Suspo-Emulsion (99.81%) caused complete or near-complete inhibition and were classified as incompatible. Metiram + Pyraclostrobin and Azoxystrobin + Difenconazole also produced high inhibition (>75%). Quizalofop-ethyl, Carboxin + Thiram, Chlorpyrifos, Carbosulfan and Fipronil were poorly compatible, whereas Penflufen + Trifloxystrobin, Imidacloprid and Sodium Acifluorfen + Clodinafop-propargyl showed moderate compatibility. Propaquizafop + Imazethapyr and Cartap hydrochloride were classified as compatible. In contrast, Imazethapyr 10% Soluble Concentrate, Pyriproxyfen + Difenthiuron, Fluazifop-P-butyl + Fomesafen, Carbofuran, Imazethapyr + Imazamox and Pendimethalin caused less than 10% inhibition and were therefore considered highly compatible.

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Agrochemical	Mean inhibition (%) $\pm$ SE	Tukey Group*
Carbendazim 12% + Mancozeb 63% WP	100.00 $\pm$ 0.00	a
Prochloraz 5.7% + Tebuconazole 1.4% ES	99.91 $\pm$ 0.09	a
Carbendazim 25% + Flusilazole 12.5% SE	99.81 $\pm$ 0.13	a
Metiram 55% + Pyraclostrobin 5%	85.70 $\pm$ 3.22	b
Azoxystrobin 18.2% + Difenoconazole 11.4%	80.06 $\pm$ 1.95	c
Quizalofop-ethyl 5% EC	74.93 $\pm$ 4.51	d
Carboxin 37.5% + Thiram 37.5% WS	59.59 $\pm$ 6.61	e
Chlorpyrifos 10%	59.31 $\pm$ 4.17	e
Carbosulfan 25% EC	54.48 $\pm$ 2.38	ef
Fipronil 5% SC	53.61 $\pm$ 2.45	ef
Penflufen + Trifloxystrobin	43.81 $\pm$ 6.98	fg
Imidacloprid 600 FS	38.69 $\pm$ 5.67	gh
Sodium Acifluorfen + Clodinafop-propargyl	32.17 $\pm$ 4.36	hi
Propaquizafop + Imazethapyr	23.48 $\pm$ 4.30	ij
Cartap hydrochloride 50% SP	18.57 $\pm$ 3.37	jk
Pendimethalin 30% EC	7.89 $\pm$ 1.21	kl
Imazethapyr + Imazamox	6.46 $\pm$ 1.31	kl
Carbofuran 3G	6.26 $\pm$ 1.49	kl
Fluazifop-P-butyl + Fomesafen	6.17 $\pm$ 1.25	kl
Pyriproxyfen + Diafenthiuron	4.04 $\pm$ 1.04	l
Imazethapyr 10% SL	0.00 $\pm$ 0.00	l

TABLE 3: Mean mycelial inhibition (%) of five *Trichoderma* isolates exposed to different agrochemicals (pooled across isolates). Values are presented as mean $\pm$ SE. Means followed by different lowercase letters (a–l) differ significantly

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according to Tukey's honestly significant difference (HSD) test at $P \leq 0.05$, whereas means sharing at least one common letter are not significantly different

WP, Wettable Powder; ES, Emulsion for Seed Treatment; SE, Suspo-Emulsion; SL, Soluble Concentrate; EC, Emulsifiable Concentrate; FS, Flowable Concentrate for Seed Treatment; SP, Water-Soluble Powder; WS, Water-Soluble Powder for Seed Treatment

Representative colony growth patterns observed in the poisoned food assay (Figure 1) closely corresponded with the quantitative inhibition data. Agrochemicals classified as incompatible produced little or no colony growth, whereas highly compatible treatments supported colony development comparable to the untreated control.

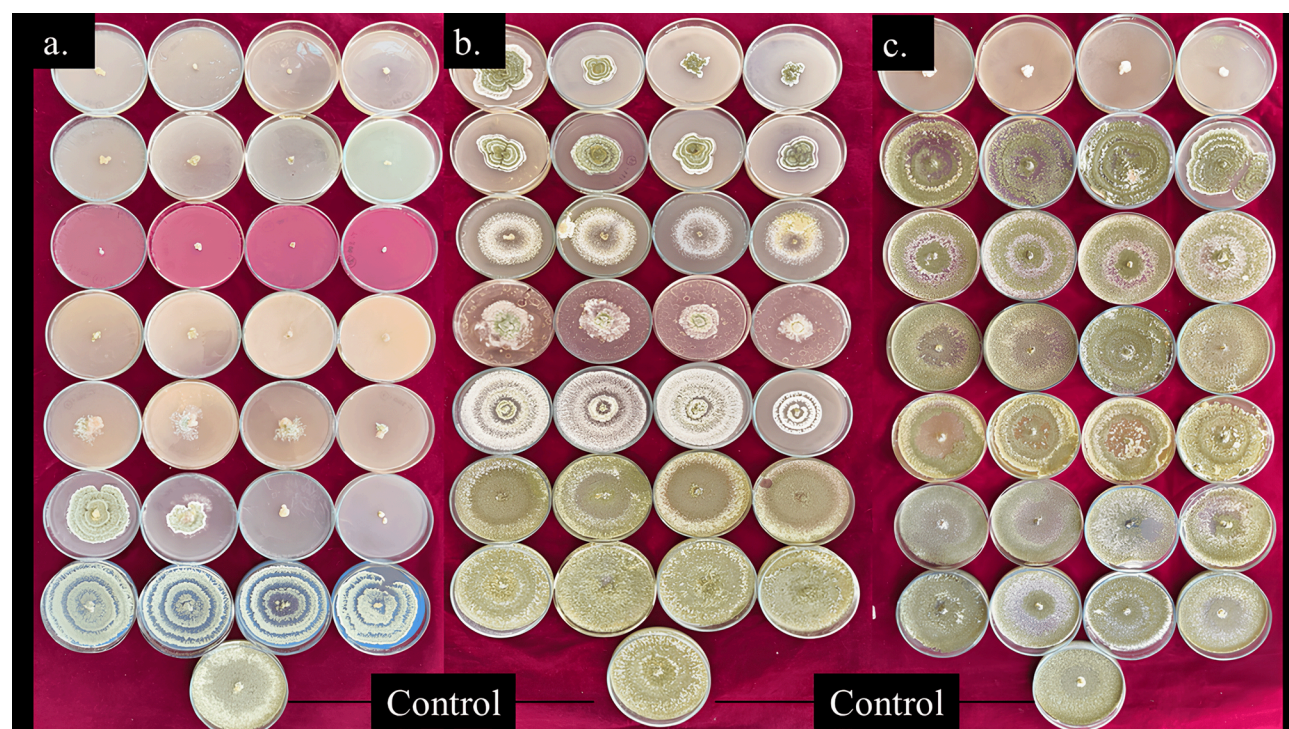


FIGURE 1: Representative images of *Trichoderma* colony growth on potato dextrose agar supplemented with different agrochemicals. (a) Fungicides, (b) insecticides, and (c) herbicides, illustrating differential compatibility responses ranging from strong inhibition to normal colony development under in vitro conditions

Isolate-Specific Responses to Agrochemicals

The significant isolate $\times$ agrochemical interaction observed in the ANOVA was reflected in distinct compatibility responses among the five *Trichoderma* isolates (Table 4 in Appendix). Penflufen + Trifloxystrobin exhibited the greatest variability, with inhibition ranging from 7.3% in Tr80 to 81.9% in Tr42, while intermediate responses were recorded for Tr79 (12.3%), Tr44 (64.4%), and Tr46 (53.1%). Similarly, Quizalofop-ethyl 5% EC caused severe inhibition in Tr79 (95.1%) and Tr80 (93.1%), whereas Tr44, Tr42, and Tr46 showed comparatively lower inhibition (56.0–66.8%). Sodium Acifluorfen + Clodinafop-propargyl and Propaquizafop + Imazethapyr also exhibited marked isolate-dependent variation, whereas Pyriproxyfen + Diafenthiuron and Imazethapyr 10% SL remained consistently compatible across all five isolates.

These findings demonstrate that agrochemical compatibility is isolate-specific, with individual *Trichoderma* strains differing considerably in their tolerance to particular agrochemical formulations.

Overall Compatibility Pattern

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Overall, fungicides produced the greatest inhibition of *Trichoderma* growth, followed by insecticides, whereas most herbicides showed comparatively lower inhibitory effects. Nevertheless, compatibility varied substantially among formulations within each agrochemical group, indicating that responses were formulation-specific rather than determined solely by agrochemical category. The combined evaluation of five elite indigenous *Trichoderma* isolates against 21 commercially available agrochemicals identified several formulations with consistently high compatibility, providing a practical basis for selecting agrochemical-*Trichoderma* combinations suitable for integrated disease management.

Discussion

The compatibility of biological control agents with chemical crop protection techniques is critical to their success in practice. The current study found that *Trichoderma*'s compatibility with agrochemicals is extremely formulation- and isolate-dependent, as proven by the strong effects of agrochemical treatment, *Trichoderma* isolate, and their interaction. These data show that compatibility cannot be generalized across *Trichoderma* species or agrochemical classes, necessitating experimental testing for each bioagent-agrochemical combination planned for IDM.

Among the agrochemicals evaluated, fungicides generally exerted the greatest inhibitory effects on *Trichoderma* growth, whereas most insecticides and herbicides showed comparatively lower toxicity. This trend is expected because fungicides are specifically designed to inhibit fungal growth by targeting essential cellular processes that are common to both pathogenic and beneficial fungi. Carbendazim-based formulations produced complete or nearly complete inhibition, which can be attributed to their disruption of β -tubulin polymerization and mitotic spindle formation, thereby preventing hyphal growth and cell division. Similarly, triazole fungicides such as tebuconazole, flusilazole, and prochloraz inhibit ergosterol biosynthesis by blocking the cytochrome P450-dependent C14-demethylase enzyme, resulting in impaired membrane integrity and fungal development. Multi-site fungicides such as mancozeb further enhance toxicity by interfering with sulfhydryl-containing enzymes involved in several metabolic pathways. These mechanisms explain the poor compatibility of these formulations with *Trichoderma* and are consistent with previous reports describing the high sensitivity of beneficial fungi to systemic and broad-spectrum fungicides [15,17,19].

Although fungicides were generally more inhibitory, variances were visible even among formulations from the same pesticide group, demonstrating that compatibility is influenced by the specific active ingredients, formulation type, and concentration rather than the agrochemical category. For example, Penflufen + Trifloxystrobin showed only modest suppression when compared to other fungicides, implying that certain fungicidal combinations may allow *Trichoderma* to survive in some cases. Such observations underscore the significance of examining commercial formulations separately, since changes in active ingredient combinations, formulation chemistry and bioavailability might have a significant impact on fungal tolerance.

Compared to fungicides, most insecticides and herbicides were relatively compatible with the *Trichoderma* isolates studied. This is explained by their major mechanisms of action, which focus on physiological pathways unique to insects or plants rather than fungal metabolism. Insecticides often disrupt insect nervous system function, whereas herbicides primarily hinder plant-specific biochemical activities such as amino acid synthesis, photosynthesis, and lipid metabolism. As a result, many of these chemicals have relatively little direct toxicity for fungal cells. Nonetheless, the mild inhibition reported with certain pesticides suggests that some formulations may still affect fungal growth indirectly via changes in membrane function, oxidative stress, or other non-specific metabolic disruptions. As a result, compatibility should be tested separately for each formulation rather than assuming identical responses within an agrochemical group.

One of the most important outcomes of the current investigation was the strong isolate-specific variation in pesticide tolerance. The substantial isolate $\times$ agrochemical interaction shows that genetically diverse *Trichoderma* isolates react differentially to identical chemical formulations. Previous research has reported similar variations, which are most likely due to intrinsic physiological and genetic characteristics such as differences in cell wall composition, membrane permeability, antioxidant defense systems, detoxification enzymes, efflux transporters, and overall metabolic adaptability [8,17]. These adaptive systems may reduce intracellular toxic compound buildup or improve detoxification, resulting in

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increased survival under agrochemical stress. As a result, agrochemical compatibility should be considered a significant consideration when selecting elite biocontrol strains, complementing antagonistic potential, rhizosphere competence and environmental adaptation.

The compatibility profiles developed in this study have significant practical implications for integrated disease management. Agrochemicals that are highly compatible with *Trichoderma* can be used concurrently or sequentially with microbial bioformulations without significantly affecting fungal establishment or biological control activity. To reduce negative effects on beneficial fungal populations, extremely inhibitory formulations should be avoided or applied with adequate temporal separation. This information is critical for developing efficient pesticide-bioagent integration methods that enhance disease suppression while lowering reliance on chemical inputs.

Conclusions

The current work presents a thorough evaluation of the compatibility of elite indigenous *Trichoderma* isolates with commercially relevant fungicides, insecticides, and herbicides utilized in agricultural production. The data show that agrochemical compatibility is not a universal feature of *Trichoderma* but is regulated by both the chemical formulation and the specific fungal isolate. These findings underscore the significance of compatibility testing as an essential component of selecting microbial biocontrol agents for use in IDM programs.

The study also shows that compatibility cannot be deduced just from the agrochemical category, as there is significant variance among formulations with diverse active ingredients and mechanisms of action. This stresses the importance of formulation-specific evaluation before mixing agrochemicals and biological control agents in practical crop production systems. Such information is useful for lowering the possibility of unanticipated negative effects on beneficial microorganisms while preserving the efficacy of chemical disease treatment techniques.

A major strength of this study is the simultaneous testing of many indigenous *Trichoderma* isolates against a wide variety of commercially available agrochemicals at various concentration levels. This approach produced a complete compatibility dataset that may be used to determine appropriate agrochemical-bioagent combinations for future study and field applications. Furthermore, the study provides region-specific information for Gujarat's Saurashtra region, where such compatibility data have been scarce despite increased use of biological management measures.

From an applied standpoint, the compatibility data gathered in this study can help researchers, extension professionals, and crop protection practitioners build IDM programs that combine microbial biocontrol agents with acceptable agrochemicals. Careful formulation selection and application tactics can increase the durability and performance of *Trichoderma*-based bioformulations while promoting more sustainable crop protection practices.

As the present investigation was conducted under *in vitro* conditions, the observed compatibility patterns should be interpreted as a foundation for further validation rather than as direct recommendations for field use. Environmental conditions, soil characteristics, microbial interactions, and agrochemical persistence may influence the performance of both *Trichoderma* and agrochemicals under natural conditions. Therefore, future studies should focus on greenhouse and field validation of the compatible agrochemical-*Trichoderma* combinations identified in this work, together with assessments of rhizosphere colonization, disease suppression, and crop productivity under different cropping systems.

Overall, this work adds to the expanding body of evidence supporting the use of microbial biocontrol agents alongside traditional crop protection techniques. The compatibility data provided a scientific foundation for the logical selection of agrochemical-*Trichoderma* combinations, thereby facilitating the creation of more effective and environmentally sustainable IDM methods.

Appendices

The percent mycelial inhibition of the five selected *Trichoderma* isolates at different concentrations of the tested fungicides is presented in Table 4.

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Sr n o.	Trea t m e n t s	Percent mycelial inhibition(%)																			
		Concentrations																			
		Isolate 79				Isolate 80				Isolate 44				Isolate 42				Isolate 46			
		Fu n g i c i d e s	10 0 p p m	20 0 p p m	30 0 p p m	40 0 p p m	10 0 p p m	20 0 p p m	30 0 p p m	40 0 p p m	10 0 p p m	20 0 p p m	30 0 p p m	40 0 p p m	10 0 p p m	20 0 p p m	30 0 p p m	40 0 p p m	10 0 p p m	20 0 p p m	30 0 p p m
1	Ca rb en da zi m 25 % + Fl us ila zo le 12 .5 % SE	98 .1 5	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	98 .1 5	10 0. 00	10 0. 00	10 0. 00	
2	Ca rb en da zi m 12 % + M an co ze b 63	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	

In Vitro Compatibility of Elite Indigenous *Trichoderma* Isolates with Commonly Used Agrochemicals for Sustainable Integrated Disease Management

	% W P																				
3	Pr oc hl or az 5. 7 % + Te b uc on az ol e 1. 4 % w/ w ES	10 0. 00	10 0. 00	10 0. 00	10 0. 00	98 .1 5	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	
4	M eti ra m 55 % + Py ra cl os tr o bi n 5 %	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	10 0. 00	61 .1 1	73 .3 3	80 .3 7	84 .4 4	77 .7 8	81 .1 1	88 .8 9	91 .1 1	55 .9 3	68 .5 2	72 .2 2	79 .2 6
5	Az ox ys tr o bi	74 .0 7	77 .4 1	77 .4 1	82 .2 2	61 .1 1	72 .9 6	82 .9 6	88 .1 5	76 .6 7	87 .0 4	87 .7 8	88 .5 2	77 .7 8	86 .6 7	90 .0 0	92 .2 2	62 .2 2	71 .8 5	78 .8 9	85 .1 9

How to cite this article:

Suvagiya D K, Kothari R K (September 01, 2026) *In Vitro* Compatibility of Elite Indigenous *Trichoderma* Isolates with Commonly Used Agrochemicals for Sustainable Integrated Disease Management. *Cureus J. Agri. Food Sci* 2 : es44497-026-00256-9. DOI <https://doi.org/10.7759/s44497-026-00256-9>

	n 18 .2 % + Di fe no co na zo le 11 .4 %																				
6	Ca rb ox in 37 .5 % + Th ira m 37 .5 % W S	10 .0 0	64 .0 7	10 0. 00	10 0. 00	32 .9 6	49 .2 6	10 0. 00	10 0. 00	22 .5 9	50 .0 0	75 .5 6	85 .9 3	34 .4 4	51 .8 5	61 .1 1	84 .8 1	18 .5 2	33 .3 3	40 .3 7	77 .0 4
7	Pe nfl uf en 13 .2 8 % w/ w + Tri flo xy str o bi n	5. 93	11 .1 1	15 .1 9	17 .0 4	2. 96	2. 59	7. 04	16 .6 7	52 .5 9	61 .8 5	62 .9 6	80 .0 0	73 .3 3	77 .7 8	86 .6 7	90 .0 0	32 .9 6	54 .8 1	58 .1 5	66 .6 7

		13.28% w/w FS																			
		Insecticide s	250 ppm	500 ppm	750 ppm	1000 ppm	250 ppm	500 ppm	750 ppm	1000 ppm	250 ppm	500 ppm	750 ppm	1000 ppm	250 ppm	500 ppm	750 ppm	1000 ppm	250 ppm	500 ppm	750 ppm
8		Chlorpyrifos 10%	7.049	65.100	70.506	29.633	63.700	66.607	75.506	43.303	55.506	67.708	74.007	40.000	60.000	75.506	77.708	40.000	55.506	67.708	75.506
9		Carbosulfan 25% EC	28.15	44.81	53.303	61.101	44.404	50.000	51.408	54.007	50.000	61.101	65.506	72.509	45.506	56.607	61.101	73.303	45.506	51.101	55.506
10		Cartap hydrochloride 50% SP	28.89	32.202	38.502	41.101	28.502	30.307	39.603	43.303	0.37	3.70	4.44	5.19	3.33	5.56	14.404	16.300	4.44	4.07	11.48
11		Fipronil	31.48	32.906	45.506	55.506	41.101	45.506	57.401	64.404	50.000	51.101	60.704	74.007	51.101	62.202	64.007	68.105	49.206	51.805	56.607

In Vitro Compatibility of Elite Indigenous *Trichoderma* Isolates with Commonly Used Agrochemicals for Sustainable Integrated Disease Management

	5 % SC																				
12	Im id ac lo pr id 60 0 FS	0. 74	5. 56	14 .4 4	38 .8 9	5. 19	8. 52	15 .1 9	50 .0 0	21 .1 1	50 .7 4	62 .5 9	72 .2 2	33 .3 3	51 .1 1	66 .6 7	77 .4 1	24 .0 7	48 .8 9	53 .7 0	73 .3 3
13	Ca rb of ur an 3 %	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	4. 44	3. 70	11 .4 8	14 .8 1	5. 56	14 .4 4	14 .4 4	16 .3 0	4. 44	4. 81	12 .9 6	17 .7 8
14	Py ri pr ox yf en 5 % + Di af en th iu ro n 25 % EC	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	3. 33	4. 44	6. 67	6. 67	2. 59	6. 67	6. 30	8. 89	1. 48	6. 30	9. 63	17 .7 8
	H er bi ci de s	25 0 p p m	50 0 p p m	75 0 p p m	10 00 p p m	25 0 p p m	50 0 p p m	75 0 p p m	10 00 p p m	25 0 p p m	50 0 p p m	75 0 p p m	10 00 p p m	25 0 p p m	50 0 p p m	75 0 p p m	10 00 p p m	25 0 p p m	50 0 p p m	75 0 p p m	10 00 p p m
15	Q ui	80 .3	10 0.	10 0.	10 0.	87 .0	88 .8	96 .3	10 0.	45 .5	53 .3	73 .7	82 .2	42 .2	45 .5	61 .4	74 .8	48 .8	64 .4	69 .6	84 .0

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	za lof o p- et hy l 5 % EC	7	00	00	00	4	9	0	00	6	3	0	2	2	6	8	1	9	4	3	7	
16	So di u m ac ifl uo rf en 16 .5 % + Cl o di na fo p- pr o pa rg yl 8 %	29 .2 6	46 .3 0	61 .1 1	60 .3 7	0. 00	0. 74	2. 22	10 .0 0	17 .7 8	34 .4 4	48 .1 5	54 .8 1	26 .3 0	28 .8 9	41 .1 1	54 .4 4	22 .2 2	23 .3 3	36 .3 0	45 .5 6	
17	Pr o pa q ui za fo p 3. 75 % + Im	24 .8 1	40 .0 0	47 .0 4	62 .5 9	0. 00	0. 00	0. 00	0. 00	5. 56	12 .2 2	16 .6 7	24 .4 4	15 .1 9	31 .1 1	43 .3 3	44 .8 1	10 .0 0	19 .2 6	21 .1 1	51 .4 8	

In Vitro Compatibility of Elite Indigenous *Trichoderma* Isolates with Commonly Used Agrochemicals for Sustainable Integrated Disease Management

	az et ha py r 2. 5 %																				
18	Fl ua zif o p- p- b ut yl 13 .4 % + Fo m es af en 11 .1 %	5. 93	7. 04	8. 89	19 .6 3	0. 00	0. 00	0. 00	0. 00	2. 22	3. 33	8. 89	11 .1 1	1. 48	3. 33	5. 19	16 .6 7	2. 96	5. 56	8. 89	12 .2 2
19	Pe n di ne th ali n 30 % EC	2. 96	8. 52	10 .0 0	17 .7 8	0. 00	3. 33	6. 30	7. 41	2. 59	5. 56	9. 26	17 .7 8	2. 96	4. 81	5. 19	8. 89	3. 33	10 .0 0	12 .2 2	18 .8 9
20	Im az et ha py r 35 % +	1. 11	1. 85	11 .1 1	11 .1 1	0. 00	1. 11	2. 22	3. 70	1. 11	3. 33	6. 67	10 .0 0	0. 37	10 .7 4	16 .6 7	17 .7 8	1. 11	5. 56	7. 78	15 .9 3

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	Im az a m ox 35 %																				
21	Im az et ha py r 10 % SL	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00	0. 00

TABLE 4: Details of all five potent isolates percent mycelial inhibition at four different concentrations
WP, Wettable Powder; ES, Emulsion for Seed Treatment; SE, Suspo-Emulsion; SL, Soluble Concentrate; EC, Emulsifiable Concentrate; FS, Flowable Concentrate for Seed Treatment; SP, Water-Soluble Powder; WS, Water-Soluble Powder for Seed Treatment

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Dhruvi K. Suvagiya

Acquisition, analysis, or interpretation of data: Dhruvi K. Suvagiya, Ramesh K. Kothari

Drafting of the manuscript: Dhruvi K. Suvagiya

Critical review of the manuscript for important intellectual content: Ramesh K. Kothari

Supervision: Ramesh K. Kothari

Disclosures

Plant subjects: All authors have confirmed that this study did not involve any herbarium specimen. **Human subjects:** All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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