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Research Article

Influence of insecticides on entomopathogenic fungus, *Lecanicillium fusisporum*

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ABSTRACT: The compatibility of insecticides with entomopathogenic fungi is essential for their effective integration in biological and integrated pest management programmes. The present study assessed the *in vitro* effects of selected insecticides on the mycelial growth of *Lecanicillium fusisporum* using the poisoned food technique. Nineteen insecticides along with an untreated control were evaluated at three dose levels, namely 0.5×, 1× and 2× of the recommended dose, under a completely randomised design. Colony diameter was recorded, and per cent growth inhibition was calculated to determine the fungitoxic effects of insecticides. Significant differences in colony diameter and growth inhibition were observed among insecticide treatments at all dose levels. Growth inhibition ranged from 5.6 to 71.5%, 17.5 to 78.0%, and 31.6 to 85.3% at 0.5×, 1× and 2× RD, respectively. Differences in colony diameter and growth inhibition were observed among insecticides across the tested concentration levels. Clothianidin recorded the lowest growth inhibition of 5.6, 17.5 and 31.6% at 0.5×, 1× and 2× RD, respectively, whereas tolfenpyrad caused the highest inhibition of 71.5, 78.0 and 85.3% at the corresponding concentrations. Compatibility classification based on IOBC evaluation categories varied across insecticides and concentration levels, with several insecticides moving from harmless to slightly or moderately harmful categories at higher tested concentrations. None of the tested insecticides resulted in complete inhibition of fungal growth at any dose level. The findings emphasise that judicious selection of insecticides and adherence to recommended dose levels are critical for conserving the biological potential of *L. fusisporum* and support further validation of compatible combinations under *in planta* and field conditions.

KEYWORDS: Entomopathogenic fungi, growth inhibition, insecticide compatibility, integrated pest management, *Lecanicillium fusisporum*

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INTRODUCTION

Insect pests remain one of the principal constraints to agricultural productivity worldwide, and chemical insecticides continue to be widely relied upon because of their rapid action, ease of application, and immediate pest suppression. However, the intensive and indiscriminate use of insecticides has resulted in several adverse consequences, including environmental contamination, disruption of ecological balance, decline of beneficial organisms, and the development of insecticide resistance in pest populations. These challenges have intensified global efforts to develop pest management strategies that are effective, economically viable, and environmentally sustainable (Faria & Wraight, 2007; Chen *et al*., 2021).

Entomopathogenic Fungi (EPF) constitute a major group of microbial biological control agents that play a critical role in the natural regulation of insect populations. Unlike chemical insecticides, EPF infect their hosts through direct penetration of the cuticle and therefore do not require ingestion, making them effective against a wide range of insect pests. Their attributes such as host specificity, environmental safety, and compatibility with sustainable agriculture have positioned EPF as valuable components of Integrated Pest Management (IPM) programs (Inglis *et al.*, 2001). In recent years, advances in fungal taxonomy, molecular identification, and formulation technologies have further strengthened the potential of EPF as alternatives or complements to chemical control (Liu *et al.*, 2023).

Among EPF, species belonging to the genus *Lecanicillium* (Hypocreales: Cordycipitaceae) are well known for their pathogenicity against soft-bodied insect pests and have been widely evaluated under laboratory and applied conditions. Molecular studies have improved the taxonomic resolution of *Lecanicillium* species, enabling more accurate identification and assessment of strain-level variability in virulence and growth characteristics (Zhou *et al.*, 2020). These fungi are known to produce a range of extracellular enzymes, including chitinases, proteases, lipases, and esterases, which facilitate host cuticle degradation and successful infection.

Lecanicillium fusisporum (W. Gams) Zare and W. Gams has emerged as a promising EPF with notable biological and enzymatic attributes relevant to insect control. Its importance has been underscored by recent efforts in India, where ICAR-National Bureau of Agricultural Insect Resources (NBAIR) identified *L. fusisporum* as one of the potential fungal biocontrol agents during systematic screening of microbial resources. These studies highlighted its strong enzymatic activity and consistent performance in experimental evaluations, emphasising its relevance in biologically based pest management approaches (Kandan *et al.*, 2022). Such findings reinforce the need to generate complementary information on factors influencing the successful use of *L. fusisporum* in pest management systems.

Despite the advantages of EPF, their practical utilisation in IPM programs is often influenced by their interaction with chemical insecticides. In many cropping systems, EPF are applied in environments where insecticides are already in use, either concurrently or sequentially. Certain insecticides may adversely affect fungal growth, conidial germination, sporulation, and overall viability, thereby reducing their biological effectiveness. Conversely, insecticides that exhibit compatibility with EPF may allow combined or rotational use, contributing to reduced chemical inputs and improved sustainability (Chen *et al.*, 2021).

Laboratory-based compatibility studies are therefore essential to assess the influence of insecticides on EPF prior to their integration into IPM programs. Such *in vitro* evaluations provide baseline information on fungal tolerance to insecticides and help identify chemical products that are least disruptive to fungal growth. Recent studies have demonstrated that compatibility responses vary considerably depending on fungal species or strain, insecticide chemistry, formulation, and concentration (Gowda & Rani, 2022), highlighting the importance of species- and strain-specific assessments.

In this context, the present laboratory investigation was undertaken to evaluate the influence of selected insecticides on the vegetative growth of *L. fusisporum* under *in vitro* conditions. The study aimed to generate compatibility information using standardised growth inhibition assays, thereby contributing to evidence-based integration of chemical and fungal components in sustainable pest management strategies.

MATERIALS AND METHODS

Fungal isolate and culture maintenance

The laboratory experiment was conducted at the Biocontrol Laboratory, Department of Entomology, N. M. College of Agriculture, Navsari Agricultural University, Navsari, Gujarat, India, under controlled conditions. The entomopathogenic fungus, *Lecanicillium fusisporum* isolate BCLAUG18_3 used in the present investigation was originally obtained from naturally infected western flower thrips, *Frankliniella occidentalis* (Pergande), collected from chilli fields in Navsari, Gujarat, India during 2018. The isolate was authenticated through molecular characterisation of the ribosomal DNA region comprising partial Internal Transcribed Spacer 1 (ITS1), complete 5.8S rRNA gene, complete Internal Transcribed Spacer 2 (ITS2), and partial Large Subunit (LSU) rRNA gene. Sequencing was performed using the Sanger dideoxy sequencing method, and the nucleotide sequence was deposited in the NCBI GenBank database under accession number PX658537. The authenticated fungal culture was maintained on Czapek-Dox Agar (CZA) medium and sub-cultured periodically to ensure purity and viability.

Insecticides and concentrations

The insecticides selected for the present study were commonly used chemical insecticides registered for agricultural use in India. The concentrations evaluated were calculated based on the Recommended Dose (RD) prescribed by the Central Insecticides Board and Registration Committee (CIB&RC, 2026). Assessing the compatibility of EPF at field-recommended concentrations is essential for determining their suitability for integration into IPM programs. Details of the insecticides, their formulations, and the recommended doses are provided in Table 1. Each insecticide was tested at three concentration levels, namely lower concentration (0.5 × RD), recommended concentration (1.0 × RD), and higher concentration (2.0 × RD).

Table 1. Details of the insecticides used in the study

T. No.	Insecticides	Chemical class	Conc. (%)		
			0.5 × RD	1 × RD	2 × RD
T1	Afidopyropen 50DC	Pyridine azomethine derivative	0.003	0.005	0.010
T2	Buprofezin 25SC	Thiadiazinone	0.017	0.033	0.067
T3	Clothianidin 50WDG	Neonicotinoid	0.003	0.005	0.010
T4	Cyantraniliprole 10.26OD	Diamide	0.009	0.018	0.036
T5	Dinotefuran 20SG	Neonicotinoid	0.004	0.008	0.016
T6	Emamectin benzoate 5SG	Avermectin	0.0013	0.003	0.005
T7	Fenpyroximate 5EC	Pyrazole acaricide	0.0025	0.005	0.010
T8	Thiacloprid 21.7SC	Neonicotinoid	0.014	0.029	0.058
T9	Tolfenpyrad 15EC	Pyridazinone	0.015	0.030	0.060
T10	Spiromesifen 22.90SC	Tetronic acid derivative	0.010	0.019	0.038
T11	Flonicamid 50WG	Pyridine carboxamide	0.008	0.015	0.030
T12	Fipronil 5SC	Phenylpyrazole	0.005	0.010	0.020
T13	Dimethoate 30EC	Organophosphate	0.020	0.040	0.080
T14	Spinosad 45SC	Spinosyn	0.0068	0.014	0.027
T15	Diafenthiuron 50WP	Thiourea	0.025	0.050	0.100
T16	Chlorantraniliprole 18.5SC	Diamide	0.0028	0.006	0.011
T17	Imidacloprid 17.8SL	Neonicotinoid	0.0027	0.005	0.011
T18	Acetamiprid 20SP	Neonicotinoid	0.004	0.008	0.016
T19	Thiamethoxam 25WG	Neonicotinoid	0.005	0.010	0.020
T20	Control	—	—	—	—

Compatibility assay

The effect of insecticides on the vegetative growth of *L. fusisporum* was evaluated using the poisoned food technique, a widely adopted method for assessing the impact of pesticides on fungal growth. CZA medium (HiMedia Laboratories Pvt. Ltd., Mumbai, India) was prepared according to the manufacturer's instructions (49 g L^{-1} distilled water) and sterilised by autoclaving at 121°C under 15 lb pressure for 30 min. Following sterilisation, the medium was allowed to cool to approximately 45-50°C. The required quantity of each insecticide was aseptically added to 100 mL of molten CZA medium, mixed thoroughly, and poured (approximately 20 mL per plate) into sterile Petri plates (90 mm diameter). CZA medium without insecticide served as the untreated control. The use of multiple concentration levels enabled assessment of insecticide compatibility under different field-relevant application scenarios. Each Petri plate was inoculated aseptically at the centre with a 5 mm diameter mycelial disc cut from a 10-day-old actively growing culture of *L. fusisporum* using

a sterile cork borer. The plates were sealed and incubated in a BOD incubator at 25±2°C for seven days, conditions commonly recommended for optimal growth of EPF (Grover & Moore, 1962).

Radial mycelial growth was recorded on the 7th day after inoculation by measuring the average of two perpendicular colony diameters (mm). The inhibitory effect of insecticides on fungal growth was expressed as per cent growth inhibition over the untreated control, calculated using the standard formula described in compatibility studies (Grover & Moore, 1962):

$$\text{Per cent growth inhibition} = \frac{C - T}{C} \times 100$$

where C represents the colony diameter in the untreated control, and T represents the colony diameter in the respective treatment.

Compatibility classification

The compatibility of insecticides with *L. fusisporum* was evaluated following the IOBC/WPRS classification proposed by Hassan (1994), with modifications suitable for EPF. In the present study, insecticides were categorised based on per cent growth inhibition of the fungus into four classes: harmless (Class 1: <30% growth inhibition), slightly harmful (Class 2: 30-79% growth inhibition), moderately harmful (Class 3: 80-99% growth inhibition), and harmful (Class 4: >99% growth inhibition).

Statistical analysis

The experiment was analysed under a Completely Randomised Design with three replications, and statistical analysis was performed separately for each concentration level (0.5 × RD, 1.0 × RD, and 2.0 × RD). Data on colony diameter were subjected to analysis of variance (ANOVA), and treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5 per cent level of significance (p = 0.05). The Coefficient of Variation (CV%), Standard Error of Difference [SE(d)], and Critical Difference (CD) were calculated to assess experimental precision.

Per cent growth inhibition data were subjected to arcsine square-root transformation prior to statistical analysis, while original (untransformed) mean values are presented for interpretation. As the untreated control served as the reference for computation, it was excluded from statistical analysis. Box plots were constructed using original per cent growth inhibition values to illustrate treatment-wise variability across dose levels, whereas heat maps were generated using treatment-wise mean per cent growth inhibition values to depict dose-response patterns and compatibility classes. All statistical analyses and graphical visualisations were performed using R version 4.4.0 through RStudio 2024.04 (RStudio Integrated Development Environment for R; Posit Software, PBC, Boston, MA, USA) (R Core Team, 2024).

RESULTS

Effect of insecticides on colony diameter of *L. fusisporum*

The colony diameter of *L. fusisporum* differed significantly among insecticide treatments at all dose levels. At 0.5 × RD, significant variation in colony diameter was observed among treatments ($F = 290.8$; $df = 19, 40$; $p < 0.01$). The untreated control (T20) recorded the maximum colony diameter (83.43 mm) and was significantly superior to all insecticide treatments. Among insecticides, T3: clothianidin 50WDG (78.74 mm) was statistically at par with T11: flonicamid 50WG (76.10 mm) and T5: dinotefuran 20SG (74.58 mm), followed by T16: chlorantraniliprole 18.5SC (72.84 mm) and T14: spinosad 45SC (71.10 mm). Moderate colony diameters were observed with T19: thiamethoxam 25WG (69.08 mm) and T15: diafenthiuron 50WP (66.42 mm). Lower colony diameters were recorded with T2: buprofezin 25SC (64.48 mm) and T17: imidacloprid 17.8SL (62.18 mm). The minimum colony diameter was observed with T9: tolfenpyrad 15EC (23.78 mm), which was statistically at par with T4: cyantraniliprole 10.26OD (28.99 mm) and T13: dimethoate 30EC (33.93 mm), indicating strong inhibition of fungal growth.

At the recommended dose (1.0 × RD), colony diameter varied significantly among insecticide treatments ($F = 369.9$; $df = 19, 40$; $p < 0.01$). The untreated control again recorded the maximum colony diameter (83.43 mm). Among insecticides, T3: clothianidin 50WDG (68.84 mm) recorded the highest colony diameter, followed by T11: flonicamid 50WG (65.27 mm), T5: dinotefuran 20SG (61.60 mm) and T14: spinosad 45SC (57.80 mm). Comparable colony diameters were observed with T16: chlorantraniliprole 18.5SC (56.69 mm) and T19: thiamethoxam 25WG (54.69 mm). Significantly lower colony diameters were recorded with T15: diafenthiuron 50WP (50.98 mm) and T2: buprofezin 25SC (48.65 mm). The lowest colony diameters were observed with T9: tolfenpyrad 15EC (18.37 mm), followed by T4: cyantraniliprole 10.26OD (22.19 mm) and T13: dimethoate 30EC (25.79 mm), which were statistically at par.

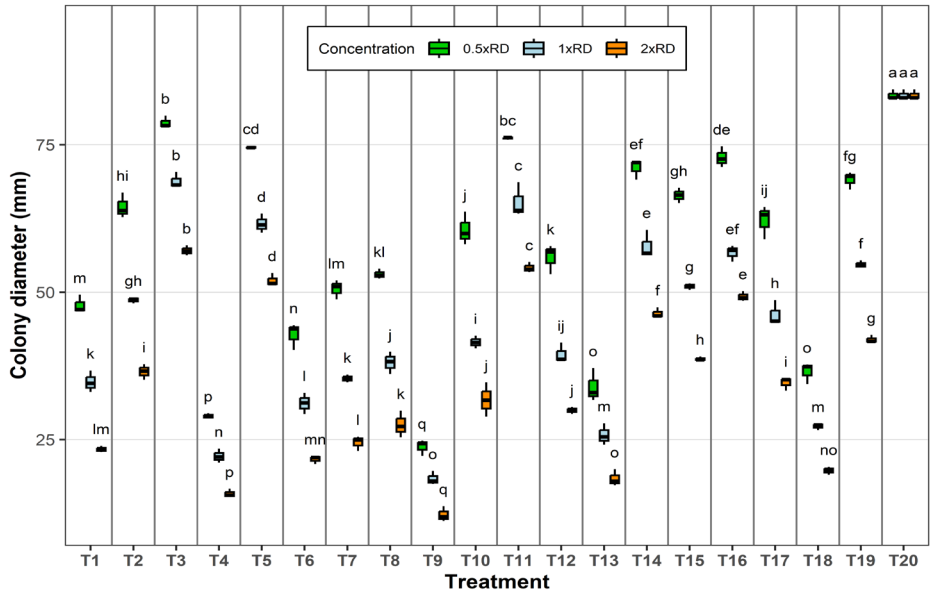


Figure 1. Effect of insecticides on colony diameter of *L. fusisporum*.

At the highest dose (2.0 × RD), colony diameter differed markedly among insecticide treatments (F = 620.4; df = 19, 40; p < 0.01). The untreated control consistently maintained the highest colony diameter (83.43 mm). Among insecticides, T3: clothianidin 50WDG (57.05 mm) recorded the maximum colony diameter, followed by T11: flonicamid 50WG (54.13 mm), which was statistically at par with T5: dinotefuran 20SG (51.98 mm), followed by T16: chlorantraniliprole 18.5SC (49.25 mm). Moderate inhibition was recorded with T14: spinosad 45SC (46.41 mm) and T19: thiamethoxam 25WG (41.99 mm). The minimum colony diameter was recorded with T9: tolfenpyrad 15EC (12.27 mm), followed by T4: cyantraniliprole 10.26OD (15.83 mm) and T13: dimethoate 30EC (18.38 mm), indicating maximum suppression of mycelial growth.

Numerically lower colony diameters were observed at higher concentration levels for several insecticide treatments. However, statistical comparisons were restricted to insecticide treatments within each concentration level. Low coefficients of variation (3.08-3.40%) along with small SE(d) and CD values indicated high experimental precision. Treatment-wise variation in colony diameter across the tested concentration levels is illustrated in Figure 1.

Colony diameter (mm) of *L. fusisporum* under different insecticide treatments at 0.5×, 1× and 2× of the recommended dose. Values sharing the same lowercase letters are not significantly different as per Duncan's Multiple Range Test (DMRT) at p ≤ 0.05.

Effect of insecticides on per cent growth inhibition of *L. fusisporum*

The per cent growth inhibition of *Lecanicillium fusisporum* differed significantly among insecticide treatments at all dose levels (Figure 2). At 0.5 × RD, growth inhibition ranged from 5.6% to 71.5% (F = 227.0; df = 18, 38; p < 0.001). The highest inhibition was recorded with T9: tolfenpyrad 15EC (71.5%), followed by T4: cyantraniliprole 10.26OD (65.3%), T13: dimethoate 30EC (59.3%) and T18: acetamiprid 20SP (56.2%). Moderate inhibition was observed with T6: emamectin benzoate 5SG (48.7%), T1: afidopyropen 50DC (42.7%) and T7: fenpyroximate 5EC (39.4%). The lowest inhibition was recorded with T3: clothianidin 50WDG (5.6%), followed by T11: flonicamid 50WG (8.8%) and T5: dinotefuran 20SG (10.6%).

At the recommended dose (1.0 × RD), per cent growth inhibition ranged from 17.5% to 78.0% (F = 179.3; df = 18, 38; p < 0.001). Maximum inhibition was observed with T9: tolfenpyrad 15EC (78.0%), followed by T4: cyantraniliprole 10.26OD (73.4%), T13: dimethoate 30EC (69.1%) and T18: acetamiprid 20SP (67.4%). Intermediate inhibition levels were recorded with T6: emamectin benzoate 5SG (62.7%), T1: afidopyropen 50DC (58.3%) and T7: fenpyroximate 5EC (57.6%). The lowest inhibition was observed with

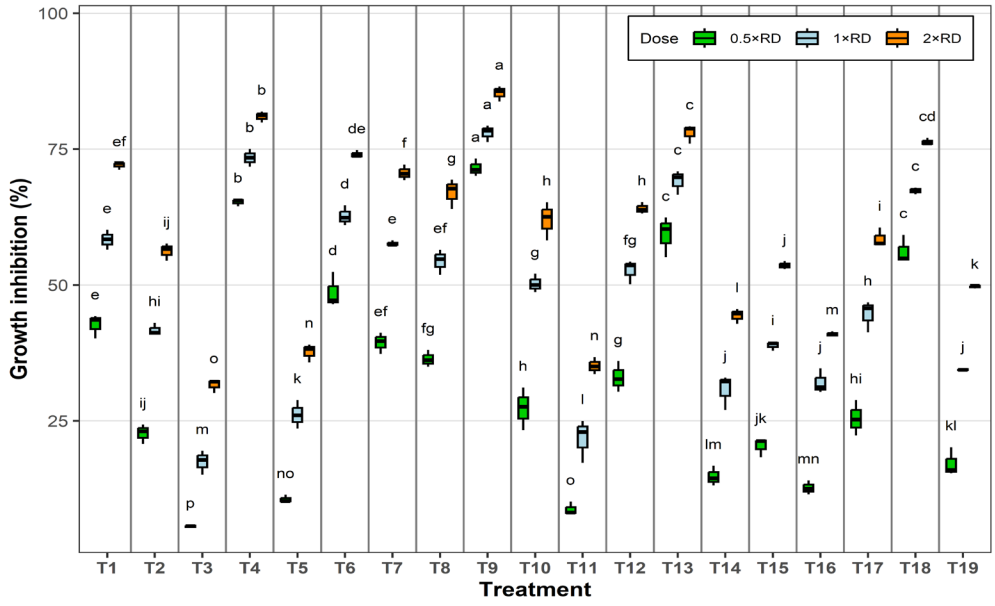


Figure 2. Effect of insecticides on growth inhibition of *L. fusisporum*.

T3: clothianidin 50WDG (17.5%), T11: flonicamid 50WG (21.7%) and T5: dinotefuran 20SG (26.1%).

At 2.0 × RD, growth inhibition increased markedly and ranged from 31.6% to 85.3% ($F = 316.2$; $df = 18, 38$; $p < 0.001$). T9: tolfenpyrad 15EC (85.3%) recorded the highest inhibition, followed by T4: cyantraniliprole 10.26OD (81.0%) and T13: dimethoate 30EC (78.0%). Considerable inhibition was also observed with T18: acetamiprid 20SP (76.3%), T6: emamectin benzoate 5SG (74.0%), T1: afidopyropen 50DC (72.0%) and T7: fenpyroximate 5EC (70.6%). The lowest inhibition was recorded with T3: clothianidin 50WDG (31.6%) and T11: flonicamid 50WG (35.1%).

Per cent growth inhibition of *Lecanicillium fusisporum* under different insecticide treatments at 0.5×, 1× and 2× of the recommended dose. Values sharing the same lowercase letters are not significantly different as per Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

Compatibility classification based on per cent growth inhibition

Compatibility classification based on IOBC/Hassan evaluation categories revealed a clear dose-dependent reduction in compatibility (Figure 3). At 0.5 × RD, several insecticides were categorised as harmless (<30% inhibition), including clothianidin, flonicamid, dinotefuran, chlorantraniliprole, spinosad, thiamethoxam, diafenthiuron,

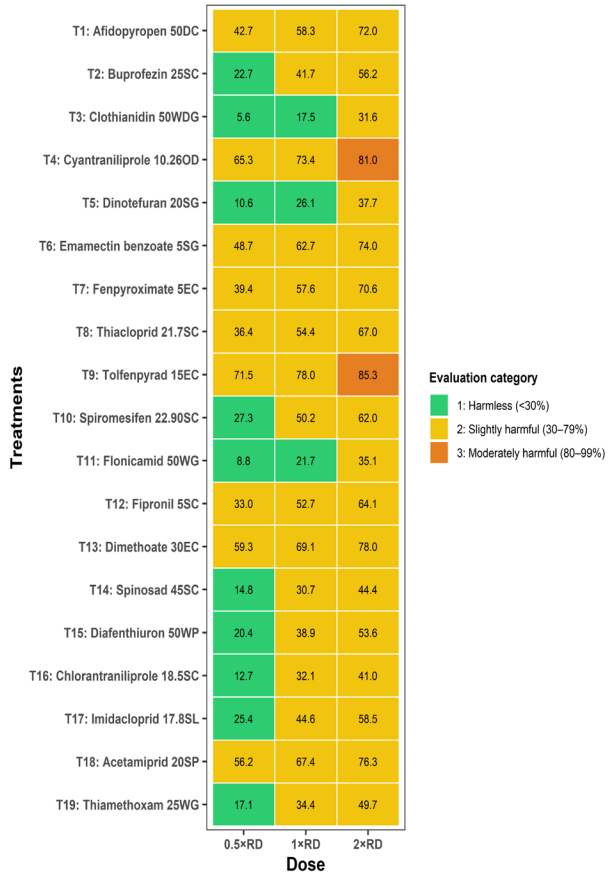


Figure 3. Compatibility classification of insecticides with *L. fusisporum*.

buprofezin, imidacloprid and spiromesifen. All remaining insecticides at this dose were classified as slightly harmful (30-79%).

At 1 × RD, only clothianidin, flonicamid and dinotefuran remained in the harmless category, while all other insecticides were classified as slightly harmful. At 2 × RD, none of the insecticides was categorised as harmless; most were slightly harmful, while tolfenpyrad and cyantraniliprole were categorised as moderately harmful (>80% inhibition). None of the insecticides was classified as harmful (>99%) at any dose level.

Heat map showing per cent growth inhibition of *L. fusisporum* at 0.5 ×, 1 × and 2 × of the recommended dose. Compatibility classes are based on IOBC evaluation categories: harmless (<30%), slightly harmful (30-79%), moderately harmful (80-99%) and harmful (>99%).

DISCUSSION

The present study demonstrated significant differences among insecticides in their compatibility with *L. fusisporum* under *in vitro* conditions. Considerable variation in colony diameter and per cent growth inhibition was observed among treatments at each tested concentration level, indicating differential fungitoxic effects of the evaluated insecticides. Numerically lower colony diameters and higher growth inhibition values were observed at higher concentration levels for several insecticides; however, statistical comparisons were restricted to insecticide treatments within each concentration level. Similar variations in compatibility among insecticides and concentration levels have been reported previously for entomopathogenic fungi, emphasising the importance of selecting insecticides that are less disruptive to fungal growth and survival (Gowda & Rani, 2022; Zhang *et al*., 2024). These findings highlight the importance of evaluating insecticide compatibility prior to integrating chemical and biological control components in pest management programmes.

Among the insecticides evaluated, clothianidin, flonicamid and dinotefuran consistently exhibited higher colony diameters and lower growth inhibition across all dose levels, indicating greater compatibility with *L. fusisporum*. These insecticides remained within the harmless category (<30% inhibition) at lower and recommended doses and showed only moderate suppression at higher concentrations. Similar compatibility of neonicotinoids with *Lecanicillium* spp. has been reported earlier, where imidacloprid, thiamethoxam and dinotefuran caused minimal adverse effects on mycelial growth and sporulation (Shinde *et al.*, 2023; Gowda & Rani, 2022; Zhang *et al.*, 2024). The relatively low fungitoxicity of neonicotinoids is attributed to their high selectivity towards insect nicotinic acetylcholine receptors, with limited direct impact on fungal cellular targets.

Diamide and biologically derived insecticides such as chlorantraniliprole and spinosad also showed comparatively lower inhibition at reduced doses, shifting to slightly harmful categories only at higher concentrations. Earlier studies have similarly reported that diamides and spinosyns are generally compatible with EPF due to their insect-specific modes of action (Shinde *et al.*, 2023; Gowda & Rani, 2022). The moderate inhibition observed at higher doses in the present study further reinforces the importance of dose optimisation when integrating these insecticides with fungal biocontrol agents.

In contrast, tolfenpyrad consistently recorded the lowest colony diameter and highest growth inhibition across all dose levels, reaching the moderately harmful category (>80%) at 2 × RD. Cyantraniliprole and dimethoate also exhibited pronounced inhibitory effects at higher concentrations. The strong fungitoxicity of tolfenpyrad may be attributed to its action on mitochondrial electron transport, which directly disrupts fungal respiration and energy production. Similar high inhibitory effects of tolfenpyrad and broad-spectrum insecticides against *Lecanicillium* spp. have been reported earlier (Nikhade *et al.*, 2024; Shinde *et al*., 2023). The moderate to high inhibition observed with dimethoate is consistent with its non-specific biochemical activity, which can adversely affect multiple enzymatic pathways in fungi (Gowda & Rani, 2022; Zhang *et al.*, 2024).

Compatibility classification based on IOBC/Hassan categories provided a clear and practical assessment of insecticide-fungus interactions. Several insecticides categorised as harmless at 0.5 × RD shifted to slightly or moderately harmful categories with increasing concentration, indicating that compatibility classifications may vary across the concentration levels evaluated. Importantly, none of the insecticides was classified as harmful (>99% inhibition), suggesting that *L. fusisporum* retained a degree of tolerance even under elevated chemical stress. Similar observations have been emphasised by Cuthbertson *et al.* (2005) and Gurulingappa *et al.* (2011), who reported that *in vitro* toxicity does not necessarily translate into reduced fungal efficacy under field or in planta conditions, particularly when insecticides and fungi are applied sequentially.

Overall, the present findings indicate that clothianidin, flonicamid, dinotefuran, chlorantraniliprole and spinosad are comparatively more compatible with *L. fusisporum*, especially at lower and recommended doses, and therefore hold promise for inclusion in integrated pest management programmes. Conversely, insecticides such as tolfenpyrad and dimethoate should be used cautiously in systems relying on *Lecanicillium*-based biological control. The study underscores the importance of dose selection and judicious integration of chemical and biological inputs to ensure sustainable and effective pest management, as advocated by earlier workers (Gurulingappa *et al.*, 2011; Zhang *et al.*, 2024).

CONCLUSION

The present study demonstrated significant differences among insecticides in their compatibility with *L. fusisporum* at the tested concentration levels. Considerable variation in colony diameter and per cent growth inhibition among treatments indicated differential fungitoxic effects of the evaluated insecticides on fungal growth.

At lower and recommended doses, clothianidin, flonicamid and dinotefuran were found to be comparatively safer, consistently exhibiting lower growth inhibition and remaining within the harmless category. In contrast, tolfenpyrad, cyantraniliprole and dimethoate caused pronounced suppression of fungal growth, particularly at higher concentrations, indicating reduced compatibility with *L. fusisporum*. The IOBC-based classification varied among insecticides and concentration levels, providing useful information on their relative compatibility with *L. fusisporum* under laboratory conditions. Importantly, none of the tested insecticides caused complete inhibition of fungal growth, indicating an inherent tolerance of *L. fusisporum* to chemical stress under *in vitro* conditions.

Overall, the findings emphasise that judicious selection of insecticides and adherence to recommended dose levels are critical for preserving the biological potential of *L. fusisporum* in pest management programmes. The results generated from this laboratory study provide a scientific basis for further in planta and field-level validation of compatible insecticide-fungus combinations to facilitate their effective integration in sustainable pest management strategies.

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AUTHOR CONTRIBUTION

M. R. Siddhapara conducted the experiments, collected the data, performed formal data analysis and statistical analysis, and reviewed the manuscript. C. U. Shinde assisted in data interpretation and thoroughly reviewed and edited the manuscript. A. D. Patel and I. M. Hirapara assisted in conducting the experiments, interpreting the results, and preparing the initial draft of the manuscript. All authors have read and agreed to the published version of the manuscript.