DOI: 10.54083/ResBio/8.3.2026/102-114 *Res. Bio.*, 2026, 8(3):102-114



Research Biotica

e-ISSN: 2582-6743

July-September, 2026

Article ID: RB239 Review Article

Combined Application of Biopesticides and Synthetic Pesticides for Better Pest Management

Madhusmita Mahanta[1] and Pranab Dutta[2*]

[1]*School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya (793 103), India*

[2]*College of Horticulture and Forestry, Central Agricultural University (Imphal), Pasighat, Arunachal Pradesh (791 102), India*

Open Access

Corresponding Author

Pranab Dutta

✉: pranabdutta74@gmail.com

Conflict of interests: The author has declared that no conflict of interest exists.

How to cite this article?

Mahanta, M., Dutta, P., 2026. Combined Application of Biopesticides and Synthetic Pesticides for Better Pest Management. *Research Biotica* 8(3), 102-114. DOI: 10.54083/ResBio/8.3.2026/102-114.

Copyright: © 2026 Mahanta and Dutta. This is an open access article that permits unrestricted use, distribution and reproduction in any medium after the author(s) and source are credited.

Abstract

Agriculture is the prime sector that determines the global food security, rural livelihood and overall economic development of a country. With the increase in global population, maintaining the agricultural productivity to feed its population has become a major challenge. Among the biotic stresses, insect pests, phytopathogens and weeds are the major causes of yield reduction and economic losses. Although, synthetic agrochemicals such as pesticides, fungicides, weedicides *etc.* have played a significant role in mitigation of these biotic challenges but their indiscriminate use has raised serious safety concerns. Microbial biopesticides is a potential alternative to minimize these negative impacts of synthetic pesticides; however, their efficacy may be limited by slow action, environmental sensitivity and inconsistent field performance. Therefore, combined application of biological control agents/ microbial biopesticides and synthetic agrochemicals may provide an opportunity for effective pest management while minimizing their respective drawbacks. This review examines the compatibility of microbial biocontrol agents with synthetic pesticides. The combined application of compatible microbial biopesticide and synthetic pesticides create an opportunity to integrate the rapid action of chemical pesticides with the biological advantages of microbial control agents. However, the success of such combinations depends on several interacting factors, such as microbial strain, active ingredient, concentration, formulation of pesticide, duration of pesticide exposure, prevailing environmental conditions and application sequence of the biopesticide and synthetic pesticide. Thus, the combined pesticide application should primarily focus on selection of compatible combinations rather than indiscriminate mixing of biological and chemical products. Standardized compatibility testing under laboratory and greenhouse conditions, validation by pilot field trials and formulation-specific assessments are necessary before recommending these to field application.

Keywords: Biopesticide, IPM, Plant health, Synergistic effect, Synthetic pesticide

Introduction

"Everything can wait but not agriculture."-Jawaharlal Nehru

Agriculture is the prime sector that determines the global food security, rural livelihood and overall economic development of a country. A slight fluctuation in agricultural crop production, therefore, can impart a tremendous impact on a country's economy. With the increase in global population, there is a constantly growing demand for food, feed and fibre. To meet these demands, the agricultural crop production systems are under increasing pressure to achieve higher productivity from the limited agriculturally productive land and natural resources. However, the crop production is susceptible to various biotic and abiotic stresses (Oerke, 2006; Zandalinas *et al.*, 2018). The biotic stresses *i.e.*,

Article History

RECEIVED on 03rd March 2026 RECEIVED in revised form 16th September 2026 ACCEPTED in final form 23rd September 2026

insect pests, phytopathogens and weeds are the major causes of yield reduction and economic losses. Synthetic agrochemicals such as pesticides, fungicides, weedicides *etc.* have played a major role in mitigation of these biotic stresses (Sharma *et al.*, 2020).

The need for more grains, feed and fibre was met by intensification of agricultural production during the Green Revolution. The main objectives of Green Revolution *i.e.*, widespread adoption of high yielding varieties (HYVs), adequate fertilization, irrigation and crop protection measures through use of synthetic pesticides, fungicides and weedicides contributed to fulfil the food requirement of the growing population. However, the non-judicious use of agrochemicals by the farmers during that period has created the problem of pest resistance and resurgence of secondary/ minor pests along with several other harmful effects on the environment including contamination of soil and water, effects on non-target organisms and disruption of ecological interactions within agroecosystems (Shiva, 1991). The indiscriminate use of synthetic agrochemicals can exert selection pressure in pest populations and may adversely affect the natural enemies and beneficial organisms such as pollinators, parasitoids and predators essential for maintaining the ecological balance (Desneux *et al.*, 2007; Sanchez-Bayo and Wyckhuys, 2019). These negative effects have addressed the drawbacks of complete dependency on synthetic pesticides for long term crop protection and the need for a safer and sustainable alternative was realized.

The realization of the threat in solely chemocentric agriculture has promoted the concept of integrated pest management (IPM) via adoption and integration of cultural, mechanical, physical, biological and chemical approaches (Kogan, 1998). Application of biopesticides derived from nature such as micro-organisms, plants and plant parts in biological pest management approaches have emerged as an important component of integrated pest management. Microbial biopesticides obtained from beneficial fungi, bacteria and viruses can suppress the growth and population of agricultural pests and pathogens via mechanisms such as parasitism, antibiosis, competition and induction of host defense responses. These microbial biopesticides has target specific mode of action and are mostly compatible with beneficial organisms, thereby making them a valuable alternative for reducing dependence on conventional synthetic pesticides. However, the performances of the microbial biopesticides are often negatively influenced by environmental factors such as high temperature, ultra-violet radiations, heavy rainfall, *etc.* They are relatively slow in action than the conventional pesticides and may provide inadequate control when the pest populations are already high. Therefore, complete replacement of conventional synthetic agrochemicals by biopesticides may not be suitable under all agricultural conditions. Hence, the combined application of biological control agents/ microbial biopesticides and synthetic agrochemicals may provide an opportunity for effective pest management while minimizing their respective drawbacks (Galli *et al.*, 2024).

Combined or alternative application of compatible synthetic pesticide and biocontrol agent can provide complementary pest suppression by rapid reduction of pest populations via synthetic pesticide, while the biocontrol agent contributes to subsequent and potentially sustained biological suppression. Such integration, therefore have the potential to improve holistic pest-control and reduce reliance on repeated applications of synthetic pesticides (Gentz *et al.*, 2010). The interaction between the biological control agent and synthetic pesticides may be compatible, additive, synergistic or antagonistic and is mainly governed by factors such as the nature, type and strain of biological control agent, active ingredient (a.i.), concentration and formulation of the synthetic pesticide *etc.* (Folorunso *et al.*, 2024). Therefore, identification of compatible combinations of synthetic pesticide and biocontrol agent is essential for development of effective integrated pest management programmes.

In this context, this review aims to explore and discuss the available information on the compatibility and combined use of microbial biopesticides and synthetic pesticides, with emphasis on antagonistic fungi, entomopathogenic fungi, bacterial and viral biocontrol agents.

Synthetic Pesticides in Crop Protection

In the ancient times, sulphur and compounds containing heavy metals such as mercury, arsenic *etc.* were used extensively in crop protection. During the 19th century, the naturally occurring substances, like nicotine, pyrethrum, rotenone, were isolated from their natural sources and used for pest management of agricultural crops. The first synthetically produced chemical pesticide was an organochlorine, *i.e.*, DDT which was deployed during the period of 2nd World War. The insecticidal properties of DDT were realised by Paul Muller in 1939 for which he was awarded the prestigious Nobel prize in 1948. The period from 1939-1975 was considered as the era of pesticide as this was the time when pesticides were extensively used in crop production (Matthews, 2018). The widespread adoption of synthetic pesticides may be explained by their ability to provide rapid pest and disease suppression, ease of application and relatively effective over a broad range of environmental conditions. Due to this, the synthetic pesticides become the first-hand solution to farmers to save their crops during severe pest and disease outbreaks.

However, the harmful effects of pesticides were realised in 1969 when Rachel Carson wrote "Silent Spring" describing the dreadful effects of indiscriminate use of synthetic agrochemicals on the biosphere. The book draws attention of many social activists, environmentalists. The non-judicious use of pesticides can kill non-target organisms such as pollinators, parasites and predators *etc.*, contaminate water bodies and soil; thereby enter into the food web (Carson, 1962). Consumption of the food produced on pesticide contaminated soil and water bodies leads to biomagnification of chemicals which leads to severe clinical conditions such as cardio-vascular diseases, gastro-intestinal problems, cancer, liver dysfunction, neurological ailments, kidney diseases, *etc.* (Ayilara *et al.*, 2023). Further, development of

pesticide resistance due to intensive pesticide use is another important consequence. Repeated and indiscriminate application of synthetic pesticides imposes strong selection pressure on pest population, leading to faster rate of mutation and development of pesticide resistance, pest resurgence and disruption of natural enemy population. Therefore, emphasis on judicious and strategical integrated use of synthetic pesticides is important for sustainable pest management.

Biopesticides as a Component of Integrated Pest Management

A biopesticide can be defined as the natural pesticide derived from biological sources such as micro-organisms, plants and naturally occurring substances. The microbial biopesticides are produced from antagonistic microbes such as bacteria, fungi and viruses capable of suppressing agricultural pests and phytopathogens. The microbial biopesticides are one of the major components of biological management and have attained global attention due to their potential role in reducing reliance on synthetic pesticides (Mawcha *et al.*, 2025). The major advantages of biopesticides include: i) relatively lower persistence and residue concerns, however, their environmental fate is decided by the formulation type (*viz.*, liquid or solid); ii) mostly target-specific with a narrow host range, thereby, safe to the non-target and beneficial organisms; iii) potential compatibility with other beneficial organisms including pollinators, predators and parasites; iv) exhibit multiple modes of action against targeted pests and therefore exert less selection pressure on the pest population (Dutta, 2022; Ayilara *et al.*, 2023).

Despite these advantages, microbial biopesticides have several limitations. The action of microbial biopesticides is reported to be comparatively slower than the synthetic pesticides. As the biopesticides contain living micro-organisms, therefore their initial establishment and persistence post application is often affected by the prevailing weather conditions such as temperature, rainfall, humidity, ultraviolet radiations, *etc.* Under severe pest pressure, application of microbial biopesticide alone may not be sufficient for rapid pest suppression necessary to prevent economic crop loss (Hamrouni *et al.*, 2025). Therefore, these limitations provide a strong background for investigating combinations of compatible microbial biopesticide and synthetic pesticide.

Rationale for Combining Microbial Biopesticides and Synthetic Pesticides

The characteristics of microbial biopesticides and synthetic pesticides are complementary to each other and therefore, provide a potential ground for their strategic integration. Synthetic pesticides generally offer rapid suppression of pest population; whereas microbial biopesticides may provide a relatively slower yet host-specific pest management for a longer duration of time. Therefore, combined application of compatible formulations of microbial biopesticides and synthetic pesticides may improve the overall effectiveness and sustainability of the pest management programmes. However, assessment of compatibility of the microbial biocontrol agent and synthetic pesticide is necessary before advocating their combined application for pest and disease management (Gentz *et al.*, 2010).

The potential advantages of combined application of compatible microbial biopesticides and synthetic pesticides include rapid suppression of pest populations by the synthetic pesticide and continued biological suppression by the microbial agent, possible additive or synergistic effects in case of compatible interactions (Abid *et al.*, 2020; Sarwar *et al.*, 2021); reduction in the dose and/or frequency of synthetic pesticide application, conservation of ecological balance *via* preservation of beneficial organisms through reduced chemical inputs, potential delay in development of resistant pest population due to different mode of action and improved management of pests under conditions, where either component alone provides inadequate control.

Compatibility of Biopesticides with Synthetic Pesticides

The interaction between a microbial biopesticide and synthetic pesticide may be interpreted as compatible, additive, synergistic and incompatible/ antagonistic based on their outcomes. Compatibility may be broadly defined as the ability of the biological control agent to retain its viability and functional activities when exposed to a synthetic pesticide without unacceptable loss of its biocontrol efficacy (Kopparthi, 2020). Additive effects of combined application on the other hand equals to the sum of the individual effects of microbial biopesticide and synthetic pesticides when applied separately. Synergistic effects of combined application of a microbial biopesticide and synthetic pesticide is always greater than the sum of the expected effects of individual treatments, *viz.*, microbial biopesticide and synthetic pesticide. When the combined application of the microbial biopesticide and synthetic pesticide produces a lower-than-expected effect due to the interference of one component with the activity of the other, it is termed as antagonistic or incompatible interaction (Sarwar *et al.*, 2021; Mejia and Espinel, 2022; Folorunso *et al.*, 2024).

The concept of combined application of microbial biopesticide with synthetic pesticides mainly focuses on the compatible/ additive/ synergistic use of biopesticides alongside a synthetic pesticide without hampering the efficacy of the propagules of biocontrol agent present in the formulation and with a vision to effectively tackle the pest problems in a short period of time (Dutta, 2022). Combined application of compatible biocontrol agent with synthetic pesticides can reap dual benefits of both the components than their separate application. Biologically, the compatibility of a formulation containing living micro-organism with synthetic pesticide is determined by three parameters, *viz.*, germinability of propagules, vegetative growth and further propagule production (Asi *et al.*, 2010).

Compatibility between microbial biopesticide and synthetic pesticide is known to be influenced by several factors such as microbial strain, active ingredient, concentration, formulation, duration of exposure to synthetic pesticide

and application sequence (Dutta *et al.*, 2017; Garcia-Riano *et al.*, 2022). It has been reported that the compatibility to synthetic pesticide may vary among the strains of the same biocontrol agent. This difference in compatibility may be attributed to the unique mutation in biocontrol agent leading to development of some strains with resistance or tolerance to synthetic pesticides than their wild types (Samal *et al.*, 2024). The chemical nature *i.e.*, active ingredient and mode of action of the synthetic pesticide can determine its effect on the biological agent. For example, the fungal biocontrol agents often are more susceptible to fungicides than certain insecticides. Different study has indicated that a low concentration of synthetic pesticide may be compatible with microbial biopesticide but inhibitory at higher concentrations, thereby suggesting compatibility may be concentration dependent (Niassy *et al.*, 2012; Mohiddin and Khan, 2013; Dutta *et al.*, 2015; Hadimani and Kulkarni, 2017). The synthetic pesticide formulation is a specified mixture of the active ingredient having pesticidal activity with other adjuvants such as solvent, surfactant, emulsifier, carriers, stickers *etc.* The pesticide formulations may be classified as liquid (including emulsifiable concentrates-EC, suspension concentrates-SC, solutions-S, ultra-low volume concentrates-ULV *etc.*); solid (such as wettable powder-WP, water dispersible granules-WDG, soluble powders-SP, granules-G, dust-D, *etc.*); and miscellaneous (fumigants). The response of a microbial biocontrol agent on exposure to synthetic pesticide therefore may be governed by the different formulation type of synthetic pesticide. Further, duration of exposure to synthetic pesticide can also influence the effect on microbial biopesticide (Garcia-Riano *et al.*, 2022). The application sequence of the biopesticide and synthetic pesticide such as simultaneous application, application of the biopesticide before the chemical pesticide and vice versa may produce different outcomes (Mejia and Espinel, 2022). The sequence of application should therefore be optimized for the specific combination. The environmental factors such as temperature, humidity, ultraviolet radiation, soil characteristics *etc.* may affect both the persistence and functioning of the microbial agent and the activity of the synthetic pesticide (Folorunso *et al.*, 2024). Therefore, study on compatibility of microbial biopesticide and synthetic pesticide is rather complex and requires careful investigation and interpretation with regard to the discussed factors.

Compatibility of Antagonistic Biological Control Agents with Synthetic Agrochemicals

Antagonistic microorganisms such as *Trichoderma* spp., *Ampelomyces quisqualis*, *Pseudomonas fluorescens* and *Bacillus subtilis* are widely used for management of plant diseases. They are available in the market in the form of talc- and liquid-based bioformulations prepared with either whole organism or spore suspension of biocontrol agent. Although, these biocontrol agents are well known for effective disease management, but their performance might decline under adverse climatic conditions or in severe cases of disease pressure (Keswani *et al.*, 2014). In such crisis, integration of the biocontrol agent with a compatible synthetic pesticide may provide rapid disease suppression while maintaining the functional contribution of the microbial biocontrol agent (Table 1).

1. Trichoderma spp.

Trichoderma is a widely known genera of ascomycetous fungus with many species exhibiting mycoparasitic and antagonistic activity against phytopathogens. Therefore, *Trichoderma* species plays a key role in plant disease management. Further, *Trichoderma* are reported to have endophytic association with the host plant (Dutta *et al.*, 2023).

Table 1: Compatibility of microbial biocontrol agents with different synthetic pesticides

Biocontrol agent	Synthetic pesticide	Formulation	Dose of synthetic pesticide	Parameter evaluated	Interaction	Nature of Experiment	References
Trichoderma asperellum	Metalaxyl	35% SD	250-750 ppm	Mycelial growth	Highly compatible	*In vitro*	Kumari *et al*. (2025)
	Mancozeb	75% WP					
	Copper oxychloride	50% WP					
	Thiram	75% WP	50-200 ppm		Compatible		
	Thiram + Carboxin	37.5% WS					
T. asperellum	Azoxystrobin	23% SC	0.05-0.15%	Mycelial growth	Compatible	*In vitro*	Sunkad *et al*. (2023)
	Propineb	70% WP	0.1-0.3%				
	Copper oxychloride	50% WP	0.1-0.2%				
	Copper hydroxide	77% WP	0.1-0.3%				
T. viride	Polyoxin D zinc salt	5% SC	600-1200 ppm	-	Compatible	*In vitro*	Saha *et al*. (2020)

Biocontrol agent	Synthetic pesticide	Formulation	Dose of synthetic pesticide	Parameter evaluated	Interaction	Nature of Experiment	References
T. pseudokoningii	Mancozeb	75% WP	0.125-0.5%	Mycelial growth		*In vitro*	Dutta *et al*. (2017)
	Methomyl	40% W/W	0.02-0.04%				
	Thiamethoxam	25% WG	0.125%, 0.05%				
	Diafenthiurn	50% WP	0.02%				
	Glyphosate	41% SL	0.15%				
T. harzianum	Metalaxyl	35% SD	1050 µg ml^{-1}	Mycelial growth	Compatible	*In vitro*	Mohiddin and Khan (2013)
	Thiram	75% WP	25 µg ml^{-1}				
T. virens	Metalaxyl	35% SD	1000 µg ml^{-1}	Mycelial growth	Compatible	*In vitro*	
	Thiram	75% WP	9 µg ml^{-1}				
T. harzianum with CMC carrier	Carbendazim	50% WP	0.05%	Disease reduction, yield	Compatible	Field trial	Dutta and Das (2009)
Ampelomyces quisqualis	Polyoxin D zinc salt	5% SC	600-1200 ppm	-	Compatible	*In vitro*	Saha *et al*. (2020)
A. quisqualis M-10	Boscalid	50% WG	500 mg l^{-1}	Mycelial growth inhibition	Compatible	*In vitro*	Roberti *et al*. (2010)
	Fosety-al	80% WG	1670 mg l^{-1}				
	Dimethomorph	50% WP	200 mg l^{-1}				
	Fluazinam	39.5% SC	147 mg l^{-1}				
	Spiroxamine	30.9% SC	401.7 mg l^{-1}				
Pseudomonas fluorescens	Polyoxin D zinc salt	5% SC	600-1200 ppm	-	Compatible	*In vitro*	Saha *et al*. (2020)
P. fluorescens	Hexaconazole	5% SC	1 ml l^{-1}	Cell growth	Compatible	*In vitro*	Dhanya *et al*. (2016)
	Hexaconazole 5% SC + Potassium phosphonate 40% (3:1)	-	3 ml l^{-1}			*In vitro*	Dhanya *et al*. (2016)
	Acephate	75% SP	1.5 g l^{-1}		Highly compatible		
	Chlorantraniliprole	18.5% SC	0.3 ml l^{-1}				
	Quinalphos	25% EC	2 ml l^{-1}				
	Dimethoate	30% EC	1.5 ml l^{-1}		Moderately compatible		
	Flubendiamide	39.35% SC	0.1 ml l^{-1}				
	Imidacloprid	17.8% SL	0.5 ml l^{-1}				
Bacillus subtilis	Polyoxin D zinc salt	5% SC	600-1200 ppm	Cell growth	Compatible	*In vitro*	Saha *et al*. (2020)
B. subtilis	Carbendazim	50% WP	50-1000 mg l^{-1}	Cell growth	Highly compatible	*In vitro*	Hadimani and Kulkarni (2017)
	Hexaconazole	5% EC	50-500 µl l^{-1}				
	Kresoxim-methyl	44.3% SC	50-500 µl l^{-1}				
	Mancozeb	75% WP	50-100 mg l^{-1}		Poorly compatible		
B. subtilis	Carbendazim	50% WP	5000 mg l^{-1}	Cell growth	Highly compatible	*In vitro*	Mohiddin and Khan (2013)
	Captan	50% WP	3200 mg l^{-1}		Compatible		
B. subtilis	Azoxystrobin	25% EC	5-250 ppm	Cell growth	Compatible	*In vitro*	Ahila Devi and Prakasam (2013)

Biocontrol agent	Synthetic pesticide	Formulation	Dose of synthetic pesticide	Parameter evaluated	Interaction	Nature of Experiment	References
B. subtilis strain mbI 600	Hexaconazole	5% EC	1000 ppm	Cell growth	Compatible	*In vitro*	Vijaykrishna *et al*. (2011)
	Propiconazole	25 EC					
	Validamycin	3% L					
B. bassiana strain BV060	Chlorpyrifos	-	455 ppm	Conidial germination and viability	Compatible	*In vitro*	Garcia-Riano *et al*. (2022)
	Lambda-cyalotrine-Thiamethoxam	-	21 ppm				
	Methoxyfenozide	-	4800 ppm				
	Methomyl	-	4500 ppm				
B. bassiana	Profenofos	50% EC	0.25-0.5%	Mycelial growth and spore germination	Compatible	*In vitro*	Joshi *et al.* (2018)
B. bassiana	Thiamethoxam	25% WG	0.04%	Mycelial growth	Compatible	*In vitro*	Puzari *et al.* (2006)
	Diafenthiuron	50% WP	0.04%				
	Imidacloprid	17.8% SL	0.1%-0.2%				
	Propargite	57% EC	0.2%				
	Monocrotophos	36% SL	0.31%				
	Dichlorvos	76% EC	0.12%				
B. bassiana strain CG424	Abamectin	18% EC	650 ppm	Conidial germination, mycelial growth and sporulation	Compatible	*In vitro*	de Oliveira and Neves (2004)
Metarhizium anisopliae isolate ICIPE 69	Abamectin	18% EC	-	Vegetative growth and spore production	Compatible	*In vitro*	Niassy *et al*. (2012)
	Imidacloprid	200 SC	0.5 ml l^{-1}				
	Thiamethoxam	250 g kg^{-1} WDG	0.2 g l^{-1}				
Metarhizium anisopliae	Buprofezin	25 EC	0.015%	Mycelial growth and spore germination	Compatible	*In vitro*	Patil *et al*. (2022)
	Sulphur	80 WDG	0.2%				
M. anisopliae	Polyoxin D zinc salt	5% SC	600-1200 ppm	Mycelial growth and sporulation	Compatible	*In vitro*	Saha *et al.* (2020)
M. anisopliae	Thiamethoxam	25% WG	0.04%	Mycelial growth and spore viability	Compatible	*In vitro*	Dutta *et al*. (2015)
	Methomyl	40%W/W	0.04%				
	Diafenthiuron	50% WP	0.04%				
	Imidacloprid	17.8% SL	0.1-0.2%				
	Propargite	57% EC	0.2%				

Different species of *Trichoderma* are also used in the bioremediation of soils contaminated with excessive synthetic pesticides and herbicides. Studies have highlighted that *Trichoderma* spp. has demonstrated an active ingredient and concentration dependent response to different contact and systemic fungicide evaluated (Table 1). According to Mohiddin and Khan (2013), *T. harzianum* and *T. virens* exhibited comparatively high tolerance to metalaxyl under *in vitro* experiment, with maximum tolerance concentrations (MTCs) of 1050 and 1000 µg mL^{-1}, respectively. On the other hand, they were comparatively prone to thiram, with MTCs of only 25 and 9 µg mL^{-1}, respectively for *T. harzianum* and *T. virens*. A recent finding by Kumari *et al.* (2025) revealed that *T. asperellum* was highly compatible with different fungicides

in individual treatments such as metalaxyl, mancozeb and copper oxychloride from 250 to 750 ppm; whereas exposure to thiram and thiram + carboxin was found to be compatible from 50 to 200 ppm. Similar findings were reported in *T. pseudokoningii* which was compatible to mancozeb at 0.125% to 0.5% concentration under *in vitro* conditions (Dutta *et al.*, 2017). These findings indicate that the different species and strains behave differently to different active ingredient and concentration of synthetic pesticide. Moreover, the results obtained from *in vitro* studies may differ under field conditions; therefore, before advocating the combined or simultaneous application of *Trichoderma* with synthetic pesticide, it is important to validate these findings under natural conditions by conducting multi-location pilot field trial. Dutta and Das (2009) revealed that integration of *T. harzianum* with suitable carrier such as carboxymethyl cellulose (CMC) and sub lethal dose of carbendazim (0.05-0.1%) as seed pelleting agent and soil application produced significant reduction in the incidence of white mold disease of French bean and improved dry shoot and root mass along with increase in yield (Table 1). Bhowmick *et al.* (2015) reported better management of cabbage wire stem disease by integrating a carbendazim tolerant *T. viride* isolate compared with a wild isolate.

2. Ampelomyces quisqualis

Ampelomyces quisqualis is a hyperparasite of powdery mildews (Erysiphales). They are found in colonies in the pockets where their hosts, *i.e.*, powdery mildew pathogens are available. The mycoparasite has a broad host range within the powdery mildews and has been reported from more than 64 species belonging to several genera of Erysiphales, occurring on more than 256 plant species worldwide (Falk *et al.*, 1995; Kiss *et al.*, 2004). Compatibility of *A. quisqualis* with synthetic agrochemicals has been reported to be strain specific and varies from compound to compound. According to the study conducted by Shishkoff and McGrath (2002), simultaneous application of synthetic fungicides *viz.*, myclobutanil (10 µg ml^{-1}) and triadimefon (100 µg µg ml^{-1}) with biofungicide AQ10- prepared from the conidia of *A. quisqualis* revealed that there was no significant reduction in colonization of powdery mildew fungus by the mycoparasite in AQ-10, suggesting that the mycoparasite in the formulation AQ-10 is insensitive to myclobutanil and triadimefon at these concentrations. Buttar and Agraal (2005) demonstrated that the entomopathogenic *Beauveria bassiana* is also compatible with *A. quisqualis*. Roberti *et al.* (2010) have reported *in vitro* compatibility of *A. quisqualis* M-10 with synthetic fungicides *viz.*, boscalid 50%, cyazofamid 2.03%, dimethomorph 50%, fluazinam 39.5% and spiroxamine 30.9% in a concentration dependent manner (Table 1). Saha *et al.* (2020) evaluated the compatibility of fungicide Polyoxin D zinc salt 5% SC and reported that it is compatible with *A. quisqualis* from 600 to 1200 ppm concentration.

3. Pseudomonas fluorescens

Pseudomonas spp. is an aerobic bacterium which is used as a biocontrol agent of several pathogenic micro-organisms. On nutrient agar medium, the bacterium produces smooth edged white coloured colony with convex surface. They are ubiquitous in nature and specific in their action. They are either non-toxic or with negligible toxicity towards mammalian cell. The bacterium is highly sensitive to synthetic agrochemicals; however, appropriate stickers, emulsifiable oils, *etc.* can be used in order to increase their effectivity in biological control of pests (Bora *et al.*, 2014). Dhanya *et al.* (2016) conducted a study on compatibility of *P. fluorescens* with different synthetic insecticides and fungicides. The results demonstrated that the bacterium was highly compatible with insecticides such as acephate, chlorantraniliprole and quinalphos and moderately compatible with dimethoate, flubendiamide and imidacloprid. Further, it exhibited compatibility with hexaconazole and combined application of hexaconazole and potassium phosphonate (Table 1). Hoesain *et al.* (2021) conducted an *in vitro* compatibility study of different strains of *Pseudomonas* sp. with mixture of botanical pesticides *viz.*, *Azadirachta indica*, *Ageratum conyzoides*, *Aglaia odorata* at different doses, *i.e.*, 0%, 25%, 50%, 75% and 100% are found compatible with the botanicals from 0-100% concentrations. However, the compatibility is reported as strain specific.

4. Bacillus subtilis

Bacillus subtilis is a Gram-positive, spore forming bacterium used widely as a biological control agent against several phytopathogens. They are compatible with antagonistic fungi, entomopathogenic fungi, biofertilizers, baculoviruses/ granulosis virus-based preparation and with different synthetic agrochemicals; however, their compatibility is greatly dependent on the microbial strain and chemical/ formulation type. Several studies have revealed that fungicides such as carbendazim, captan, hexaconazole, azoxystrobin and validamycin were compatible with *B. subtilis* at different concentrations; whereas mancozeb was found to substantially inhibit bacterial growth (Vijaykrishna *et al*., 2011; Mohiddin and Khan, 2013; Ahila Devi and Prakasam, 2013) (Table 1). Similar observations were reported by Hadimani and Kulkarni (2017) where they found that *B. subtilis* was compatible with carbendazim, hexaconazole and kresoxim-methyl at their recommended concentration for disease management whereas it exhibited minimum tolerance to mancozeb. A recent study on compatibility of *B. subtilis* Bs006 against 57 different synthetic pesticides further demonstrated that compatible reaction to tested fungicides such as carbendazim, dimethomorph, flutriafol, kasugamycin, thiabendazole and validamycin A; and insecticide and acaricides such as chlorfenapyr, lambda-cyhalothrin, methoxyfenozide, sulfoxaflor, spiromesifen (Barrios-Candil *et al.*, 2026). Thus, it is important to assess compatibility before combining *B. subtilis*-based biopesticide with synthetic pesticides.

Compatibility of Entomopathogenic Biological Control Agents with Synthetic Agrochemicals

1. Beauveria bassiana

Beauveria bassiana, also known as 'white muscardine' fungus is an important entomopathogenic fungus used for

biological control of insect pests (Goettel *et al.*, 2005). The compatibility of *B. bassiana* with synthetic agrochemicals is greatly influenced by the fungal strain, pesticide molecule, concentration, formulation and method of application. Generally, fungicides pose a higher risk to *B. bassiana* than several insecticides and herbicides. de Oliveira and Neves (2004) reported that *B. bassiana* strain CG424 was compatible with acaricide abamectin at mean recommended concentration without affecting conidial germination, mycelial growth and sporulation of the biocontrol agent. Puzari *et al.* (2006) reported compatible interaction of *B. bassiana* with synthetic insecticides such as thiamethoxam, diafenthiuron, imidacloprid, propargite, monocrotophos and dichlorvos at different concentrations (Table 1). Joshi *et al.* (2018) reported that profenofos 50% EC was highly inhibitory to the growth and spore germination of *B. bassiana* at higher concentrations; however, the lower concentrations of 0.25% and 0.5% were compatible with *B. bassiana*, indicating that the compatibility of profenofos with the fungus is strongly influenced by its concentration. Garcia-Riano *et al.* (2022) reported compatibility of *B. bassiana* strain BV060 based biopesticide with several insecticide such as chlorpyrifos (455 ppm), Lambda-cyalotrine-Thiamethoxam (21 ppm), methoxyfenozide (4800 ppm) and methomyl (4500 ppm); whereas, incompatible reaction was recorded with all the fungicides evaluated *viz.*, azoxystrobin, carbendazim, difenoconazole, tebuconazole and trifloxystrobin. The incompatibility of *B. bassiana* BV060 with fungicides may be due to the mode of action exhibited by these fungicides which either interfere with mitochondrial respiration and DNA biosynthesis processes, or at the transmembrane level, thereby, hindering ergosterol biosynthesis of the biocontrol agent (Patyal *et al.*, 2013). It is also noteworthy that the compatibility of *B. bassiana* BV060 with chlorpyriphos (455 ppm) and methomyl (4500 ppm) was relatively reduced after prolonged period of exposure from 180 minutes to 360 minutes. Likewise, herbicide paraquat at 3000 ppm caused considerable reduction in germination and viability of conidia of *B. bassiana* BV060 after 360 minutes of exposure. These findings have, therefore, highlighted the critical role played by strain, exposure time and pesticidal active ingredient in their interaction. The reduction in germination and viability of conidia during exposure to paraquat may be triggered by the free radicals produced by the herbicide, which in turn might cause lipid peroxidation in the membrane of the biocontrol agent followed by dropping in NADP in cells (Suntres, 2002; Lin *et al.*, 2003).

2. Metarhizium anisopliae

Metarhizium anisopliae is an important entomopathogenic fungus commonly found in undisturbed soil environments. It is cosmopolitan in nature. The fungus produces green coloured spores and therefore called as "Green Muscardine" fungus (Goettel *et al.*, 2005). During an *in vitro* study on the interaction of *M. anisopliae* with different synthetic pesticide, such as insecticide, fungicide and weedicide, it was reported that insecticide such as deltamethrin, fungicides including captan, carbendazim, mancozeb, carbendazim + mancozeb, mancozeb + metalaxyl, weedicides like glyphosate and paraquate dichloride are highly toxic to *M. anisopliae* thereby hindering its vegetative growth and spore survivality (Dutta *et al.*, 2015). A study on the *in vitro* compatibility of *Metarhizium riley* (*Nomuraea rileyi*) with different pesticides revealed that sub lethal dose of thiomethoxam 25% WG, malathion 50% EC, bifenthrin 10% WP and chlorpyrifos 20% EC caused lowest growth inhibition of *M. riley* (Hazarika *et al.*, 2016). Khun *et al.* (2021) reported compatible reaction of trichlorfon, acephate and indoxacarb with *M. anisopliae*, while diazinon, carbendazim and pyraclostrobin were found toxic to the mycelial growth and sporulation of *M. anisopliae*. Similarly, Patil *et al.* (2022) observed relatively good compatibility of *M. anisopliae* with azadirachtin, buprofezin and sulphur. Niassy *et al.* (2012) reported compatibility of *M. anisopliae* isolate ICIPE 69 with abamectin, imidacloprid and thiamethoxam; whereas, azadirachtin, L-cyhalothrin and spiromesifen were found toxic to the bicontrol agent. Therefore, it may be concluded that the compatibility of *M. anisopliae* to different synthetic pesticides and botanical insecticide greatly determined by the active ingredient, concentration and formulation of the pesticide as well. Differential level of compatibility exhibited by different strains and isolates of *M. anisopliae* to the same active ingredient may be attributed to the development of resistance towards it due to target site mutation in the biocontrol agent (Roberti *et al.*, 2017) or the ability of the strain or isolate to flush out the toxic compound through active transport system or cellular detoxification pathways similar to plant pathogenic fungi (Samal *et al.*, 2024).

3. Lecanicillium lecanii

Lecanicillium lecanii is an important entomopathogenic fungus used for the biological management of sucking pests, such as aphids, whiteflies, mealybugs and scale insects. The fungus colonizes and sporulates on infected insects, frequently producing a characteristic white mycelial growth on the cadaver, therefore also known as 'white halo' fungus (Goettel *et al.*, 2005). Its compatibility with chemical pesticides is variable and depends on the pesticide molecule, formulation, concentration and method of application. Dhanya *et al.* (2019) and Xie *et al.* (2020) reported moderate compatibility of *L. lecanii* with neem oil and other neem-based botanicals. Ummer and Kurien (2021) demonstrated that *L. lecanii* exhibited compatible interaction with insecticide imidacloprid and fungicide copper hydroxide; whereas, carbendazim was found to be toxic to the vegetative growth and sporulation of the biocontrol agent, indicating the role of different pesticidal molecules in these interactions. Gowda and Rani (2022) reported *in vitro* compatibility of *L. lecanii* with several newer insecticides, including imidacloprid, thiamethoxam, chlorantraniliprole and flubendiamide; whereas tebuconazole, hexaconazole, carbendazim, mancozeb, malathion, quinalphos and chlorpyrifos were inhibitory to fungal growth, sporulation and conidial germination. Mejia and Espinel (2022) observed a significant difference in the results of *in vitro* and *in planta* study of *L. lecanii* with different pesticides. Although different

synthetic insecticides such as chlorfenapyr, spinetoram and pyrimethanil and fungicides such as dimethomorph and kasugamycin exhibited compatible interaction with *L. lecanii* in the *in vitro* study, it was observed that the combined application the compatible set of fungicide + *L. lecanii* and insecticide chlorfenapyr + *L. lecanni in planta* for the management of white fly (*Trialeurodes vaporariorum*) exhibited toxicity reactions; whereas, spinetoram and pyrimethanil exhibited compatible reaction in both *in vitro* and *in planta* studies. Interestingly, insecticide bifenthrin was found incompatible to *L. lecanii* in the *in vitro* study, but was found compatible under the *in planta* analysis. These results, therefore, suggested the probable influence of host plant and environmental factors and highlighted the importance of validation of the results obtained under *in vitro* study in field conditions. Shejale *et al.* (2026) conducted a study on *in vitro* compatibility of *L. lecanii* with different insecticides and fungicides. The results revealed that the biocontrol agent was highly compatible with synthetic insecticides, such as chlorantraniliprole, flupyridifurone, imidacloprid, spiromesifen and botanical insecticide azadirachtin, moderately compatible with synthetic insecticides including acetamiprid, diafenthiuron, deltamethrin, emamectin benzoate, fipronil, flonicamid, flubendamide, lambda cyhalothrin, spinosad and thiamethoxam; whereas, triazophos exhibited partial compatibility with *L. lecanii* and incompatible interaction was recorded from all the treatments with fungicides *viz.*, carbendazim, copper oxychloride and propiconazole.

4. Purpureocillium lilacinum

Purpureocillium lilacinum (formerly *Paecilomyces lilacinus*) is an important nematophagous fungus widely used as a biological control agent against plant-parasitic nematodes. The fungus is cosmopolitan in nature and can be isolated from a diverse range of habitat including estuaries sediments, decaying plants and food products (Moosavi and Zare, 2011). Earlier studies have reported variable responses of *P. lilacinum* to chemical pesticides, indicating that its compatibility is highly dependent on the nature of the pesticide, concentration and fungal isolate (Kumar and Ramya, 2014; Dhanya *et al.*, 2019).

***5. Bacillus thuringiensis* (*Bt*)**

Bacillus thuringiensis (*Bt*) is a ubiquitous, spore-forming entomopathogenic bacterium, generally found in soil, aquatic environment, plants, animal faeces and in infected insects. Integration of *B. thuringiensis* with chemical insecticides can improve pest management; however, its compatibility is greatly dependent on the active ingredient, formulation, concentration and timing of application. Earlier studies demonstrated that carbamate insecticides were generally more compatible with *B. thuringiensis* than several other insecticide groups; whereas the technical formulations were recorded less harmful to the bacterium followed by wettable powders and emulsifiable concentrates (Morris, 1977). In a study on *Tuta absoluta*, Amizadeh *et al.* (2015) reported that chlorantraniliprole, dichlorvos and abamectin exhibited synergistic interactions with *Bt* in causing mortality of *Tuta absoluta* larvae at LC_{25} concentrations and additive interaction was reported at LC_{10} concentration. Further, incompatibility of *Bt* with pesticides such as azadirachtin and metaflumizone was also reported. However, a recent study demonstrated compatible reaction of *Bt* isolates with azadirachtin and chlorantraniliprole in an *in vitro* assay; whereas emamectin benzoate showed incompatible reaction (Timmi and Joshi, 2024), indicating the strain and chemical-specific nature of these interactions. Thus, compatible agrochemicals may be incorporated into integrated pest management programmes with *Bt*, but their compatibility should be validated for the specific *Bt* strain, pesticide formulation, concentration and application sequence before combined use.

6. Nuclear Polyhedrosis Viruses

Nuclear Polyhydrosis Virus (NPVs) are species-specific entomopathogenic viruses from the family Baculoviridae and are widely used as microbial biocontrol agents against several economically important lepidopteran insect pests. They are highly host specific, eco-friendly and are known to be compatible with different synthetic insecticides; thereby, making them a suitable alternative for conventional insecticides in IPM programmes (Martinez-Balerdi *et al.*, 2025). Depending on the virus isolate, target pest, insecticide chemistry, concentration and application sequence, combined application of NPVs with synthetic insecticides may result in compatible or additive or synergistic effects (Dader *et al.*, 2020). Synergistic interactions have been reported between NPVs and modern insecticides such as spinetoram, emamectin benzoate, chlorantraniliprole, cyantraniliprole and metaflumizone, with enhanced insect mortality compared with individual treatments. Abid *et al.* (2020) demonstrated that HaNPV works synergistically with insecticides *viz.*, spinetoram and emamectin benzoate against insecticide resistant larvae of *Helicoverpa armigera* in a dose dependent manner. Likewise, Sarwar *et al.* (2021) reported that application of indigenous NPVs at sub lethal (1×10^4, 6×10^4 POB ml^{-1}) and lethal (3×10^5 POB ml^{-1}) concentrations and chlorantraniliprole insecticide (0.01 µl l^{-1}) resulted in synergistic interaction at lethal concentration and caused higher larval mortality on 2nd and 4th instar larva of *Sporoptera litura* and *S. exigua*; whereas, at sub lethal concentration on NPV, the results were found to be additive. Therefore, the integration of NPVs with selected synthetic insecticides represents a promising component of IPM; however, compatibility should be assessed for individual virus-insecticide combinations, as interactions may range from compatible to additive to synergistic to antagonistic.

Conclusion

Synthetic pesticides are an important tool for management of pest and diseases of agricultural crops, particularly under severe pest and disease pressure. However, their indiscriminate and intensive use has contributed to development of pests and pathogen resistance, environmental pollution and disruption of ecological balance. Microbial biopesticides, therefore, provide a valuable alternative and complementary tool. Different

mode of action exhibited by biological control agents exerts negligible selection pressure on the target pest, thereby making it a potential candidate for sustainable pest-management programmes. However, they are relatively slow in action and can be affected by environmental conditions.

Therefore, the combined application of compatible microbial biopesticide and synthetic pesticides create an opportunity to integrate the rapid action of chemical pesticides with the biological advantages of microbial control agents. However, the success of such combinations depends on several interacting factors, such as microbial strain, active ingredient, concentration, formulation of pesticide, duration of pesticide exposure, prevailing environmental conditions and application sequence of the biopesticide and synthetic pesticide. Thus, the combined pesticide application should primarily focus on selection of compatible combinations rather than indiscriminate mixing of biological and chemical products. Standardized compatibility testing under laboratory and greenhouse conditions, field validation by pilot field trials and formulation-specific assessments are necessary for converting these observations into reliable IPM recommendations. An appropriately designed combination has the potential to reduce dependence on synthetic pesticides, improve pest-management efficiency and therefore, can contribute to sustainable agricultural production.

Ethical Statement

The authors declare that no generative artificial intelligence tools were used in drafting or preparing this manuscript. The manuscript was written, interpreted and revised solely by the authors, who take full responsibility for its content.

References

Abid, A.D., Saeed, S., Zaka, S.M., Ali, M., Shahzad, M.S., Iqbal, M., Shahzad, U., Iqbal, N., Alghanem, S.M., 2020. Interaction of HaNPVs with two novel insecticides against *Helicoverpa armigera* Hubner (Noctuidae: Lepidoptera). *Saudi Journal of Biological Sciences* 27(8), 2124-2128. DOI: https://doi.org/10.1016/j.sjbs.2020.06.023

Ahila Devi, P., Prakasam, V., 2013. Compatibility nature of Azoxystrobin 25 SC with *Pseudomonas fluorescens* and *Bacillus subtilis* on chilli plants. *World Journal of Agricultural Sciences* 1(8), 258-264.

Amizadeh, M., Hejazi, M.J., Niknam, G., Arzanlou, M., 2015. Compatibility and interaction between *Bacillus thuringiensis* and certain insecticides: Perspective in management of *Tuta absoluta* (Lepidoptera: Gelechiidae). *Biocontrol Science and Technology* 25(6), 671-684. DOI: https://doi.org/10.1080/09583157.2015.1007030

Asi, M.R., Bashir, M.H., Afzal, M., Ashfaq, M., Sahi, S.T., 2010. Compatibility of entomopathogenic fungi, *Metarhizium anisopliae* and *Paecilomyces fumosoroseus* with selective insecticides. *Pakistan Journal of Botany* 42(6), 4207-4214.

Ayilara, M.S., Adeleke, B.S., Akinola, S.A., Fayose, C.A., Adeyemi, U.T., Gbadegesin, L.A., Omole, R.K., Johnson, R.M., Uthman, Q.O., Babalola, O.O., 2023. Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides and nanobiopesticides. *Frontiers in Microbiology* 14, 1040901. DOI: https://doi.org/10.3389/fmicb.2023.1040901.

Barrios-Candil, S.M., Zapata-Narváez, Y.A., Díaz-García, A., 2026. Effect of adjuvants, fungicides, bactericides and insecticides on the growth of *Bacillus subtilis* Bs006. *Agronomía Mesoamericana* 37(1), 4n7yym82. DOI: https://doi.org/10.15517/4n7yym82.

Bhowmick, P., Saikia, M.K., Kaushik, H., Dutta, P., 2015. Carbendazim tolerant induced *Trichoderma viride* for integrated management of wire stem of cabbage. *International Journal of Current Agricultural Research* 4(1), 115-119.

Bora, L.C., Kataki, L., Talukdar, K., 2014. *Microbial Bioagents and Biopesticides: A Guide Book*. DBT-AAU Centre, Assam Agricultural University, Jorhat, India.

Buttar, G.S., Agraal, N., 2005. Bioherbicides - A review. *Pestology* 29(6), 27-35.

Carson, R., 1962. *Silent Spring*. Penguin Books, United States. p. 336.

Dader, B., Aguirre, E., Caballero, P., Medina, P., 2020. Synergy of Lepidopteran Nucleopolyhedroviruses AcMNPV and SpliNPV with Insecticides. *Insects* 11(5), 311. DOI: https://doi.org/10.3390/insects11050316.

de Oliveira, R.C., Neves, P.M.O.J., 2004. Compatibility of *Beauveria bassiana* with acaricides. *Neotropical Entomology* 33(3), 353-358. DOI: https://doi.org/10.1590/S1519-566X2004000300013.

Desneux, N., Decourtye, A., Delpuech, J.M., 2007. The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology* 52, 81-106. DOI: https://doi.org/10.1146/annurev.ento.52.110405.091440.

Dhanya, M.K., Anjumol, K.B., Murugan, M., Deepthy, K.B., 2016. Compatibility of *Trichoderma viride* and *Pseudomonas fluorescens* with plant protection chemicals and fertilizers in cardamom. *Journal of Tropical Agriculture* 54(2), 129-129.

Dhanya, M.K., Sathyan, T., Murugan, M., Ashokkumar, K., Surya, R., 2019. *In-vitro* compatibility of entomopathogenic fungi with synthetic insecticides and neem oil. *Pesticide Research Journal* 31(2), 275-281. DOI: https://doi.org/10.5958/2249-524X.2019.00039.6.

Dutta, P., Das, B.C., 2009. Efficacy of talc-based formulation of *Trichoderma harzianum* for management of white mold of French bean (*Phaseolus vulgaris*). *Journal of Mycology and Plant Pathology* 39(2), 278-282.

Dutta, P., Puzari, K.C., Bhuyan, R.P., Nath, D.J., Gogoi, D., Pegu, J.R., Das, A., Kaushik, H., Hazarika, G.N., 2015. Compatibility of *Metarhizium anisopliae* (Metsch) Sorokin with pesticides used in tea cultivation of Assam. *Annals of Plant Protection Sciences* 23(2), 261-264.

Dutta, P., Kakati, N., Das, A., Kaushik, H., Boruah, S., Bhowmick, P., Kaman, P., Puzari, K.C., Bhuyan, R.P., Hazarika, G.N., 2017. *Trichoderma pseudokoningii*

showed compatibility with certain commonly used inorganic pesticides, fertilizer and sticker cum spreader. *International Journal of Current Microbiology and Applied Sciences* 6(2), 140-146. DOI: https://doi.org/10.20546/ijcmas.2017.602.020.

Dutta, P., 2022. Biopesticides. EBH Publishers, India. p. 234.

Dutta, P., Mahanta, M., Singh, S.B., Thakuria, D., Deb, L., Kumari, S., Upamanya, G.K., Boruah, S., Dey, U., Mishra, A.K., Vanlaltani, L., VijayReddy, E., Heisnam, P., Pandey, A.K., 2023. Molecular interaction between plants and *Trichoderma* species against soil-borne plant pathogens. *Frontiers in Plant Science* 14, 1145715. DOI: https://doi.org/10.3389/fpls.2023.1145715.

Falk, S.P., Gadoury, D.M., Pearson, R.C., Seem, R.C., 1995. Partial control of grape powdery mildew by the mycoparasite *Ampelomyces quisqualis*. *Plant Disease* 79(5), 483-490. DOI: https://doi.org/10.1094/PD-79-0483.

Folorunso, E.A., Bohata, A., Mraz, J., 2024. Factors influencing pesticide-biocontrol agent compatibility: A metadata-based review. *Pesticide Biochemistry and Physiology* 206, 106204. DOI: https://doi.org/10.1016/j.pestbp.2024.106204.

Galli, M., Feldmann, F., Vogler, U.K., Kogel, K.H., 2024. Can biocontrol be the game-changer in integrated pest management? A review of definitions, methods and strategies. *Journal of Plant Diseases and Protection* 131(2), 265-291. DOI: https://doi.org/10.1007/s41348-024-00878-1.

Garcia-Riano, J.L., Torres-Torres, L.A., Santos-Diaz, A.M., Grijalba-Bernal, E.P., 2022. *In vitro* compatibility with soybean agrochemicals and storage stability studies of the *Beauveria bassiana* biopesticide. *Biocatalysis and Agricultural Biotechnology* 40(1), 102275. DOI: https://doi.org/10.1016/j.bcab.2022.102275.

Gentz, M.C., Murdoch, G., King, G.F., 2010. Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. *Biological Control* 52(3), 208-215. DOI: https://doi.org/10.1016/j.biocontrol.2009.07.012.

Goettel, M., Eilenberg, J., Glare, T., 2005. Entomopathogenic fungi and their role in regulation of insect populations. In: *Comprehensive Molecular Insect Science*, Volume 6. (Eds.) Gilbert, L.I., Iatrou, K. and Gill, S.S. Elsevier, Amsterdam (Netherlands). pp. 361-406.

Gowda, T.G., Rani, O.P.R., 2022. *In-vitro* compatibility of entomopathogenic fungus, *Lecanicillium lecanii* (Zimm.) Zare and Gams with insecticides and fungicides. *Pest Management in Horticultural Ecosystems* 28(2), 39-47. DOI: https://doi.org/10.5958/0974-4541.2022.00036.4.

Hadimani, B., Kulkarni, S., 2017. Compatibility of *Bacillus subtilis* (Ehrenberg) Cohn with chemical fungicides. *Environment and Ecology* 35(3B), 2137-2141.

Hamrouni, R., Regus, F., Da Silva, A.M.F., Orsiere, T., Boudenne, J.L., Laffont-Schwob, I., Christen, P., Dupuy, N., 2025. Current status and future trends of microbial and nematode-based biopesticides for biocontrol of crop pathogens. *Critical Reviews in Biotechnology* 45(2), 333-352. DOI: https://doi.org/10.1080/07388551.2024.2370370.

Hazarika, S., Patgiri, P., Dutta, P., Borkataki, S., Das, K., 2016. Compatibility of *Nomuraea rileyi* (Farlow) with common pesticides used in vegetable ecosystem of Assam. *Journal of Entomological Research* 40(2), 157-159. DOI: https://doi.org/10.5958/0974-4576.2016.00029.3.

Hoesain, M., Prastowo, S., Pradana, A.P., Asyiah, I.N., Kustiawan, F., Ramadhan, F.S., Rohmah, W., Nengtyas, Y.A., 2021. *In vitro* studies on *Bacillus* sp. and *Pseudomonas* sp. compatibility with botanical pesticide. In: *IOP Conference Series: Earth and Environmental Science* 759(1), 012069. DOI: https://doi.org/10.1088/1755-1315/759/1/012069.

Joshi, M., Gaur, N., Pandey, R., 2018. Compatibility of entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae* with selective pesticides. *Journal of Entomology and Zoology Studies* 6(4), 867-872.

Keswani, C., Mishra, S., Sarma, B.K., Singh, S.P., Singh, H.B., 2014. Unraveling the efficient applications of secondary metabolites of various *Trichoderma* spp. *Applied Microbiology and Biotechnology* 98(1), 533-544. DOI: https://doi.org/10.1007/s00253-013-5344-5.

Khun, K.K., Ash, G.J., Stevens, M.M., Huwer, R.K., Wilson, B.A.L., 2021. Compatibility of *Metarhizium anisopliae* and *Beauveria bassiana* with insecticides and fungicides used in macadamia production in Australia. *Pest Management Science* 77(2), 709-718. DOI: https://doi.org/10.1002/ps.6065.

Kiss, L., Russell, J.C., Szentiványi, O., Xu, X., Jeffries, P., 2004. Biology and biocontrol potential of *Ampelomyces* mycoparasites, natural antagonists of powdery mildew fungi. *Biocontrol Science and Technology* 14(7), 635-651. DOI: https://doi.org/10.1080/09583150410001683600.

Kogan, M., 1998. Integrated pest management: Historical perspectives and contemporary developments. *Annual Review of Entomology* 43(1), 243-270. DOI: https://doi.org/10.1146/annurev.ento.43.1.243.

Kopparthi, A.V.S., 2020. Compatibility of biopesticides with insecticides in ipm. *Indian Journal of Entomology* 82(3), 588-592. DOI: https://doi.org/10.5958/0974-8172.2020.00146.7.

Kumar, G., Ramya, V., 2014. Compatibility of agrochemical with entomopathogenic fungi (*Paecilomyces lilacinus*) - A biological nematicide. *Journal of Global Biosciences* 3(2), 406-410.

Kumari, N., Yadav, D.L., Bochalya, R.K., Sharma, S., Meena, C.B., Gautam, C., 2025. Compatibility of *Trichoderma asperellum* with different fungicides. *Journal of Advances in Microbiology* 25(8), 1-7. DOI: https://doi.org/10.9734/jamb/2025/v25i8970.

Lin, N., Lin, J., Dan-Tzu Lin-Tan, R. N., Yu, C., 2003. Combined initial cyclophosphamide with repeated methylprednisolone pulse therapy for severe paraquat poisoning from dermal exposure. *Journal of Toxicology:*

Clinical Toxicology 41(6), 877-881. DOI: https://doi.org/10.1081/CLT-120025356.

Martinez-Balerdi, M., Caballero, J., Aguirre, E., Caballero, P., Beperet, I., 2025. *Baculoviruses* as microbial pesticides: Potential, challenges and market overview. *Viruses* 17(7), 917-953. DOI: https://doi.org/10.3390/v17070917.

Matthews, G.A., 2018. A history of pesticides. CAB International (CABI). p. 287.

Mawcha, K.T., Malinga, L., Muir, D., Ge, J., Ndolo, D., 2025. Recent advances in biopesticide research and development with a focus on microbials. *F1000Research* 13, 1071. DOI: https://doi.org/10.12688/f1000research.154392.5.

Mejia, C., Espinel, C., 2022. *In vitro* versus in planta: Comparing the compatibility of *Akanthomyces lecanii* with pesticides against *Trialeurodes vaporariorum*. *Journal of Applied Entomology* 146(10), 1272-1280. DOI: https://doi.org/10.1111/jen.13064.

Mohiddin, F.A., Khan, M.R., 2013. Tolerance of fungal and bacterial biocontrol agents to six pesticides commonly used in the control of soil borne plant pathogens. *African Journal of Agricultural Research* 8(43), 5272-5275. DOI: https://doi.org/10.5897/AJAR11.677.

Moosavi, M.R., Zare, R., 2011. Fungi as biological control agents of plant-parasitic nematodes. In: *Plant Defence: Biological Control (Progress in Biological Control)*. (Eds.) Mérillon, J.M. and Ramawat, K.G. Springer, Dordrecht. pp. 67-107. DOI: https://doi.org/10.1007/978-94-007-1933-0_4.

Morris, O.N., 1977. Compatibility of 27 chemical insecticides with *Bacillus thuringiensis* var. *kurstaki*. *Canadian Entomologist* 109(6), 855-864. DOI: https://doi.org/10.4039/Ent109855-6.

Niassy, S., Maniania, N.K., Subramanian, S., Gitonga, M.L., Maranga, R., Obonyo, A.B., Ekesi, S., 2012. Compatibility of *Metarhizium anisopliae* isolate ICIPE 69 with agrochemicals used in French bean production. *International Journal of Pest Management* 58(2), 131-137. DOI: https://doi.org/10.1080/09670874.2012.669078.

Oerke, E.C., 2006. Crop losses to pests. *The Journal of Agricultural Science* 144(1), 31-43. DOI: https://doi.org/10.1017/S0021859605005708.

Patil, D.B., Karmarkar, M.S., Gondhalekar, S.B., Borkar, P.G., Mehendale, S.K., Kasture, M.C., 2022. Evaluating *In vitro* compatibility of pesticides with *Metarhizium anisopliae* (Metchnikoff) Sorokin and its pathogenicity against *Aphis craccivora* Koch. *Asian Journal of Agricultural Extension, Economics and Sociology* 40(1), 1-13. DOI: https://doi.org/10.9734/AJAEES/2022/v40i230840.

Patyal, S.K., Sharma, I.D., Chandel, R.S., Dubey, J.K., 2013. Dissipation kinetics of trifloxystrobin and tebuconazole on apple (*Malus domestica*) and soil - A multi location study from North Western Himalayan Region. *Chemosphere* 92(8), 949-954. DOI: https://doi.org/10.1016/j.chemosphere.2013.02.069.

Puzari, K.C., Hazarika, L.K., Dutta, P., Das, P., 2006. *In vitro* inhibition of *Beauveria bassiana* (Bals.) Vuill. growth by different commonly used insecticides in rice. *Journal of Biological Control* 20(1), 51-56.

Roberti, R., Veronesi, A., Finestrelli, A., Brunelli, A., 2010. Compatibility of *Ampelomyces quisqualis* with fungicides for the control of downy and powdery mildew and grey mould. In: *Giornate Fitopatologiche 2010*, Cervia (RA), Italia. 9-12 marzo 2010. Atti, Volume Second. pp. 345-348.

Roberti, R., Righini, H., Masetti, A., Maini, S., 2017. Compatibility of *Beauveria bassiana* with fungicides *in vitro* and on zucchini plants infested with *Trialeurodes vaporariorum*. *Biological Control* 113(1), 39-44. DOI: 10.1016/j.biocontrol.2017.06.006.

Saha, S., Sawant, I.S., Pawar, S.B., Yadav, D.S., Ranade, Y., 2020. Compatibility of polyoxin D zinc salt 5% SC against various biocontrol agents used in grapes. *Journal of Mycopathoogical Research* 58(1-2), 33-38.

Samal, I., Bhoi, T.K., Vyas, V., Majhi, P.K., Mahanta, D.K., Komal, J., Singh, S., Kumar, P.V.D., Acharya, L.K., 2024. Resistance to fungicides in entomopathogenic fungi: Underlying mechanisms, consequences and opportunities for progress. *Tropical Plant Pathology* 49(1), 5-17. DOI: https://doi.org/10.1007/s40858-023-00585-6.

Sanchez-Bayo, F., Wyckhuys, K.A.G., 2019. Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation* 232, 8-27. DOI: https://doi.org/10.1016/j.biocon.2019.01.020.

Sarwar, G., Maan, N.A., Ayub, M.A., Shahid, M.R., Malik, M.A., Farooq, M., 2021. Evaluation of indigenous the nucleopolyhedrovirus (NPV) of *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) in combination with chlorantraniliprole against *Spodoptera* species. *Egyptian Journal of Biological Pest Control* 31(1), 58. DOI: https://doi.org/10.1186/s41938-021-00403-8.

Sharma, A.K., Sharma, D., Chopra, A.K., 2020. An overview of pesticides in the development of agriculture crops. *Journal of Applied and Natural Science* 12(2), 101-109. DOI: https://doi.org/10.31018/jans.vi.2254.

Shejale, B.T., Parjane, N.V., Mahale, A.S., 2026. Compatibility of *Lecanicillium lecanii* with pesticides. *Journal of Biological Control* 40(2), 287-294. DOI: https://doi.org/10.18311/jbc/2026/54963.

Shishkoff, N., McGrath, M.T., 2002. AQ10 biofungicide combined with chemical fungicides or AddQ spray adjuvant for control of cucurbit powdery mildew in detached leaf culture. *Plant Disease* 86(8), 915-918. DOI: https://doi.org/10.1094/PDIS.2002.86.8.915.

Shiva, V., 1991. *The Violence of the Green Revolution: Third World Agriculture, Ecology and Politics*. Zed Books, Malaysia. p. 264.

Sunkad, G., Joshi, R., Patil, M., 2023. Compatibility of indigenous *Trichoderma asperellum* with chemical fungicides for the management of chickpea wilt. *Journal of Biological Control* 37(1), 06-12. DOI: https://doi.org/10.18311/jbc/2023/32435.

Suntres, Z.E., 2002. Role of antioxidants in paraquat toxicity. *Toxicology* 180(1), 65-77. DOI: https://doi.org/10.1016/S0300-483X(02)00382-7.

Timmi., Joshi, N., 2024. *In vitro* interactions of *Bacillus thuringiensis* with biorationals and synthetic insecticides. *Indian Journal of Ecology* 51(6), 1337-1340. DOI: https://doi.org/10.55362/IJE/2024/4405.

Ummer, N., Kurien, S., 2021. *In vitro* evaluation on compatibility of *Lecanicillium lecanii* with selected pesticides. *Pesticide Research Journal* 33(1), 105-108. DOI: https://doi.org/10.5958/2249-524X.2021.00026.1

Vijaykrishna, K.K., Reddy, M.S., Kloepper, J.W., Yellareddygari, S.K.R., Lawrence, K.S., Zhou, X.G., Sudini, H., Miller, M.E., Appa, R.P., Surendranatha, R.E.C., Niranjana, S.R., Chandra, N.S., 2011. Plant growth-promoting activities of *Bacillus subtilis* mbi 600 (integral®) and its compatibility with commonly used fungicides in rice sheath blight management. *International journal of Microbiological Research* 3(2), 120-130. DOI: https://doi.org/10.9735/0975-5276.3.2.120-130.

Xie, T., Jing, L., Zhang, X., Zhang, Y., Yue, M.A., Jiang, L., Wang, X., Jia, Y.X., 2020. Compatibility of 8 common pesticides with *Lecanicillium lecanii* JMC-01 and the toxicity of different pesticide - *L. lecanii* combinations toxicity to *Bemisia tabaci* nymphs. *Chinese Journal of Applied Entomology* 57(3), 682. DOI: https://doi.org/10.7679/j.issn.2095-1353.2020.069.

Zandalinas, S.I., Mittler, R., Balfagón, D., Arbona, V., Gómez-Cadenas, A., 2018. Plant adaptations to the combination of drought and high temperatures. *Physiologia plantarum* 162(1), 2-12. DOI: https://doi.org/10.1111/ppl.12540.