Insecticide Toxicity in Paddy Agroecosystems, Impacts on Soil Health, and Microbial Bioremediation Strategies: A Review

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Received:- 08 August 2023/ Revised:- 13 August 2023/ Accepted:- 21 August 2023/ Published: 31-08-2023

Abstract— *Paddy (Oryza sativa) rice cultivation in India extensively employs chemical insecticides to manage insect pests such as stem borers, leaf folders, and planthoppers. While effective in controlling pests, several commonly used active ingredients, including fipronil, chlorantraniliprole, lambda-cyhalothrin, and thiamethoxam, exhibit persistence in soil ecosystems and pose toxicity risks. This review synthesizes current knowledge on the types of insecticides used, their persistence and toxicological profiles, effects on soil microbial communities critical for fertility, and potential risks to human health. Furthermore, it evaluates microbial bioremediation as a promising strategy to mitigate pesticide residues and restore soil health. In view of the above, sustainable pesticide management practices integrated with bioremediation approaches are needed to balance crop protection and ecosystem health.*

Keywords— Oryza sativa, chemical insecticides, toxicity, soil fertility, microbial bioremediation, integrated pest management.

I. INTRODUCTION

Rice (Oryza sativa), a staple for over half the world's population, is predominantly grown in flooded paddy fields, covering approximately 167 million hectares globally. In India, rice serves as a cornerstone staple crop, playing a pivotal role in national food security and rural livelihoods. Persistent threats from pests, including the rice stem borer, leaf folder, brown plant hopper (BPH), and green leaf hopper (GLH), undermine yields and necessitate robust control measures (Litsinger et al., 2009). Farmers apply an estimated 2–3.5 million tonnes of pesticides annually, with insecticides comprising 61%, herbicides 22%, and fungicides 11% of usage (Aktar et al., 2009). Common contaminants in paddy fields include organophosphates (e.g., chlorpyrifos, malathion), carbamates (e.g., carbofuran), organochlorines (e.g., endosulfan, DDT), triazines (e.g., atrazine), and pyrethroids. These persist due to high organic matter and anaerobic conditions in flooded soils, leading to bioaccumulation in rice grains and runoff into waterways (John & Prakash, 2002).

Chemical insecticides, featuring active ingredients such as fipronil, chlorantraniliprole, lambda-cyhalothrin, and thiamethoxam, have become integral to pest management protocols. Despite their efficacy, evidence highlights their environmental persistence and ecological toxicity, particularly disrupting soil health and non-target biota (DeLorenzo et al., 2001). Risks to human health arise from occupational exposure and dietary residues in harvested rice, with impacts ranging from neurotoxicity and endocrine disruption to millions of pesticide-related deaths since 1960, disproportionately affecting rural Asia (Kumar, 2017). Environmental degradation includes reduced soil microbial diversity and biodiversity loss, as pesticides inhibit bacterial abundance in irrigated rice fields (Gupta et al., 2022). Traditional remediation methods (e.g., incineration, chemical oxidation) are costly and generate secondary pollutants, whereas microbial bioremediation—using indigenous or augmented microbes—degrades xenobiotics via enzymatic pathways, offering substantial cost savings and eco-compatibility (Bhagawati et al., 2020).

1.1 Objectives and Scope of this Review:

This narrative review aims to: (1) synthesize contemporary evidence on the persistence and toxicity profiles of major insecticides used in Indian paddy fields; (2) critically analyze their cascading effects on soil microbial communities and related fertility functions; and (3) evaluate the current state, practical challenges, and future potential of microbial bioremediation as a restorative strategy within this specific agroecosystem.

II. COMMON INSECTICIDES IN INDIAN RICE FIELDS

Major insecticidal active ingredients include fipronil (a phenylpyrazole), chlorantraniliprole (an anthranilic diamide), lambda-cyhalothrin (a synthetic pyrethroid), and thiamethoxam (a neonicotinoid). These compounds target various pests through systemic or contact action and are marketed under brands such as Monil GR (fipronil), Vesticor (chlorantraniliprole), Xylo 5 (lambda-cyhalothrin), and Spora (thiamethoxam). Their widespread use reflects efficacy but necessitates careful management to avoid adverse effects (Prakash et al., 2014).

The common chemical pesticides and herbicides used in rice/paddy fields across India, including active compounds and popular brand names are listed as below (Table 1-3). A notable trend is the reliance on systemic neonicotinoids (e.g., thiamethoxam) for sap-sucking pests like BPH and GLH, while newer chemistry like diamides (chlorantraniliprole) and phenylpyrazoles (fipronil) target lepidopteran borers. The market is served by both multinational and domestic agrochemical companies.

TABLE 1
INSECTICIDES FOR CONTROLLING MAJOR PESTS LIKE STEM BORER, LEAF FOLDER, BROWN PLANT HOPPER

Pest	Active Compound(s)	Brand Name (Trade Name)	Company
Stem borer	Fipronil 0.3% GR	Monil GR	Atul Crop Care
	Flubendiamide 480SC	Fame	Bayer Crop Science
	Chlorantraniliprol 18.5% SC	Vesticor	BASF India Ltd
Leaf folder	Thiamethoxam 25% WG	Spora	Atul Crop Care
	Lambda Cyhalothrin 5% EC	Xylo 5	Atul Crop Care
Brown Plant Hopper	Thiamethoxam 30% FS	Spora Super	Atul Crop Care
	Dinotefuran 20% SG	Token	Indofil India Ltd
	Pymetrozine 50% WG	Chess	Syngenta
	Triflumezopyrim 10% SC	Pexalon	Corteva/DuPont
Green Leaf Hopper	Thiamethoxam 30% FS	Spora Super	Atul Crop Care
Thrips, Gall midge	Spinetoram 11.7% SC	Summit (Delegate)	Dow Agrosciences
	Buprofezin 25% SC	Applaud	Tata Rallis, Orion
	Acetamiprid 20% SP	Manik	Tata

TABLE 2
FUNGICIDES FOR DISEASES LIKE BLAST, SHEATH BLIGHT, FALSE SMUT

Disease	Active Compound(s)	Brand Name (Trade Name)	Company
Blast	Isoprothiolane 40% EC	Rhizo, Fujione	Atul Crop Care, Rallis
	Tebuconazole 50% + Trifloxystrobin 25% WG	Nativo	Bayer Crop Science
	Zineb 68% + Hexaconazole 4% WP	Avtar	Indofil Industries Ltd
Sheath blight	Picoxystrobin 7% + Propiconazole 12% SC	Galileo Way	Corteva Agriscience
False Smut	Copper Hydroxide 77% WP	Blue Shield	Bayer

TABLE 3
HERBICIDES FOR CONTROLLING WEEDS INCLUDING GRASSES, SEDGES, BROADLEAF WEEDS

Weed Type	Active Compound(s)	Brand Name (Trade Name)	Company
Grasses, broadleaf weeds	Bispyribac Sodium 10% SC	Nominee Gold	PI Industries
Annual grasses, broadleaf	Pendimethalin 30% EC	Panida	Tata Rallis India
Various weeds	Pretilachlor 50% EC	Rifit	Syngenta
Grassy weeds	Pyrazosulfuron 0.15% + Pretilachlor 6% GR	Eros Gold	UPL
Target grassy weeds	Cyhalofop-Butyl 5.1% + Penoxsulam 1.02% OD	Vivaya	Corteva

III. PERSISTENCE AND TOXICITY IN SOIL ECOSYSTEMS

Fipronil is highly persistent, with a soil half-life ranging from weeks to months, leading to accumulation risks that threaten soil microbial communities responsible for nutrient cycling and organic matter breakdown (Sundaram & Sundaram, 1996). Its toxicity to beneficial soil microbes and arthropods disrupts soil biological activity, potentially diminishing soil fertility (Meena & Meena, 2021). Lambda-cyhalothrin, another persistent insecticide, is highly toxic to non-target soil organisms, including earthworms and microbial populations, impairing soil structure and function (Cycoń et al., 2022). Chlorantraniliprole and thiamethoxam, though moderately persistent, affect soil microbial diversity and functionality, raising concerns for long-term sustainability (John et al., 2001). Declining microbial biodiversity slows nitrogen fixation and organic matter decomposition, both essential for maintaining soil fertility and crop productivity (Johnsen et al., 2001).

Chemical insecticides and herbicides exert significant negative effects on soil microbial ecology, disrupting community structure, diversity, and functions such as nutrient cycling and organic matter decomposition (Gupta et al., 2022). Herbicides like glyphosate and 2,4-D inhibit nitrogen-fixing bacteria (e.g., Azotobacter and Rhizobium) and nitrifying microbes (Nitrosomonas, Nitrobacter), reducing biological nitrogen fixation, ammonification, and nitrification rates, which impairs soil fertility and nutrient availability (Aktar et al., 2009). Insecticides, such as chlorpyrifos and carbofuran, exhibit variable effects; some show no significant broad impacts on microbial abundance or diversity, while others suppress bacterial and fungal populations at high doses, altering dehydrogenase and phosphatase activities critical for carbon and phosphorus cycling (Kadyan & Chawla, 2020). This variability is often mediated by soil properties like texture, pH, and organic matter content (Gani, 2022). Overall, these pesticides reduce microbial biomass and biodiversity, with persistence influenced by soil properties, potentially exacerbating ecosystem imbalances and long-term soil degradation. Herbicide-induced microbiome shifts can cascade to affect plant health and trophic interactions, underscoring the need for sustainable alternatives to mitigate these ecological consequences (Ruuskanen et al., 2023; Boudh & Singh, 2016).

3.1 Effects on Microbiota and Plant Growth:

At recommended dosages, most insecticides are safe for crops; however, overdose or improper application of persistent insecticides such as fipronil and lambda-cyhalothrin may cause phytotoxic symptoms, including stunted growth, leaf yellowing, and reduced tillering (DeLorenzo et al., 2001). Chemical insecticides and herbicides exert significant and often detrimental effects on soil microbial ecology, impacting community structure, diversity, and crucial ecosystem functions. Soil microorganisms, including bacteria and fungi, are fundamental to soil health, playing vital roles in nutrient cycling (e.g., nitrogen fixation, phosphorus solubilization), organic matter decomposition, and maintaining soil fertility (Jaiswal et al., 2022). The application of various pesticides can lead to reductions in microbial biodiversity, hindering essential ecosystem services (Sharma & Sharma, 2021). For instance, persistent insecticides like fipronil and lambda-cyhalothrin pose accumulation risks detrimental to beneficial soil microbes and arthropods, disrupting biological activities and potentially diminishing soil fertility (Pathak et al., 2020). Such insecticides can reduce soil macro-organism activity, growth, and reproduction, ultimately increasing mortality (Srivastav, 2021). Even moderately persistent insecticides like chlorantraniliprole and thiamethoxam affect soil microbial diversity and functionality, raising concerns for long-term sustainability in agricultural fields (Bhagawati et al., 2020).

Herbicides, while targeting unwanted plants, can inadvertently harm non-target soil microorganisms, altering community composition and metabolic functions, including carbon cycling-related enzymatic activities such as α-1,4-glucosidase, β-1,4-glucosidase, and β-D-cellobiohydrolase (Drigo et al., 2022). Impacts vary depending on the pesticide, concentration, soil type, and existing microbial communities (John & Shah, 2018). For example, studies comparing commercial pesticides have found variable effects on soil carbon microbial functions and community composition, with some showing impacts even at recommended doses (Drigo et al., 2022).

Furthermore, fertilization practices can modify the non-target effects of pesticides on soil microbial communities (Muñoz-Leoz et al., 2012). Combined applications of pesticides and fertilizers lead to complex interactions that influence microbial responses, sometimes exacerbating or mitigating negative impacts.

In conclusion, the widespread use of chemical insecticides and herbicides in intensive farming necessitates a deeper understanding of their interactions with soil microbial communities, with profound implications for soil fertility, plant health, and ecosystem stability. Sustainable pesticide management is essential to mitigate adverse ecological impacts (Ewere et al., 2024).

3.2 Human Health Concerns:

Exposure to these insecticides occurs primarily through occupational contact during application and food residues (Bhoi et al., 2022). Fipronil exposure can induce acute symptoms such as headaches, dizziness, nausea, and, in severe cases, seizures, as it acts on insect and mammalian nervous systems (Jolodar et al., 2016). Lambda-cyhalothrin can cause skin irritation, respiratory distress, and neurotoxic effects due to its action on sodium channels in nerve cells (Upadhayay et al., 2015). Thiamethoxam and chlorantraniliprole exhibit moderate acute toxicity but pose risks of chronic neurotoxicity and reproductive effects with prolonged exposure (Kumar, 2017). Proper personal protective equipment (PPE) use and adherence to residue limits in food products are essential to reduce health risks (Balasangu, 2021).

IV. SUSTAINABLE PEST MANAGEMENT AND RECOMMENDATIONS

Given the environmental and health risks associated with persistent and toxic insecticides, integrated pest management (IPM) practices emphasizing minimal chemical use, biological control agents, and crop rotation are imperative (Prakash et al., 2014; Singh & Gupta, 2016). Adoption of safer alternatives and precise application techniques can reduce pesticide loads in soil and minimize exposure risks (Sehgal et al., 2021). Continuous monitoring of soil health and pesticide residues supports sustainable rice production and protects ecosystem integrity (Singh & Jasrotia, 2021; Elakkiya & Sujeetha, 2017).

4.1 Microbial Bioremediation:

Microbial bioremediation harnesses the metabolic properties of microbes and their catabolic enzymes to mineralize xenobiotics into CO_2, H_2O, and non-toxic byproducts via mineralization, co-metabolism, or cometabolism with carbon sources such as glucose (Pathak et al., 2020). Core pathways include hydrolysis by organophosphorus hydrolase (OPH), which cleaves P-O bonds in chlorpyrifos to yield 3,5,6-trichloro-2-pyridinol (TCP) subsequently oxidized by dioxygenases; oxidation through cytochrome P450 monooxygenases hydroxylating imidacloprid to olefin and 5-hydroxy metabolites; reductive dehalogenation of endosulfan to dieldrin mediated by glutathione S-transferases; and fungal conjugation via lignin peroxidases in species like Phanerochaete chrysosporium for pyrethroid ring cleavage (Sharma & Sharma, 2021). In anaerobic paddy soils, sulfate-reducing bacteria drive organochlorine reduction, while flooding induces desorption to improve bioavailability (Jaiswal et al., 2022). Remediation strategies encompass bioaugmentation (e.g., inoculating 10^4 cells g^{-1} soil with degraders), biostimulation using amendments like biochar to enhance native populations, and rhizoremediation leveraging rice root exudates to activate consortia, collectively reducing pesticide half-lives by 50–80% (Bhagawati et al., 2020).

Bacteria predominate due to rapid proliferation, with consortia surpassing monocultures by 20–30% through synergistic interactions (Srivastav, 2021). Notable examples are summarized in Table 4. Fungi such as Phanerochaete chrysosporium degrade 91% of endosulfan-chlorpyrifos mixtures without peroxidase induction and synergize with mycorrhizae (Glomus spp.) for phoxim remediation in rice-analogous systems, whereas Trametes versicolor eliminates cypermethrin using laccases in herbicide-insecticide blends (Bharadwaj et al., 2019; Sharma et al., 2016). Algal contributors like Chlorella vulgaris and Scenedesmus quadricauda, sourced from paddy effluents, biosorb propanil and degrade dimethomorph at 40 $\mu g\ L^{-1}$; cyanobacteria such as Anabaena sequester up to 6779 ppm chlorpyrifos in bioreactors (Gomes et al., 2022).

TABLE 4
EXAMPLES OF MICROORGANISMS DEMONSTRATED TO DEGRADE PESTICIDES IN PADDY-RELEVANT CONTEXTS

Microorganism	Pesticide Degraded	Key Mechanism/Enzyme	Efficiency / Notable Finding	Reference
Ochrobactrum sp. JAS2	Chlorpyrifos	Organophosphorus hydrolase (OPH)	Degraded 300 mg L^{-1} in 12h; reduced soil half-life from 40.8 to 18.7 days. Also promotes plant growth via IAA production.	Jaiswal et al., 2016
Burkholderia cepacia PCL3	Carbofuran	Carbofuran hydrolase	Shortened half-life to 3.62 days (alone) or 1.60 days (in consortia) in flooded soils.	Odukkathil & Vasudevan, 2012
Phanerochaete chrysosporium (Fungus)	Endosulfan, Chlorpyrifos	Lignin peroxidases, non-specific oxidation	Degraded 91% of pesticide mixtures without enzyme induction.	Bharadwaj et al., 2019
Consortium of native soil microbes	Various	Synergistic metabolic pathways	Performance exceeds monocultures by 20-30% in degradation rates.	Srivastav, 2021

V. CHALLENGES AND LIMITATIONS

Despite these efficacies, challenges include sorption-induced low bioavailability (elevated K_d for chlorpyrifos), ageing residues retaining 10% persistence, and abiotic optima (pH 6–8, 15–35°C) beyond which degradation ceases (<5°C) (Boudh & Singh, 2016). Paddy-specific issues include flooding-imposed oxygen deficits impeding aerobes, competitive exclusion of inocula by natives, toxic byproducts like TCP, and GMO regulatory impediments, exacerbated by herbicides curbing rice field microbial diversity by 20–50%. A significant challenge remains scaling successful lab and pot trials to consistent field-level efficacy under variable environmental conditions. Pesticide applications further disrupt community structures, diminishing eco-multifunctionality (Padmavathi, 2015).

VI. SUMMARY & CONCLUSIONS

Chemical insecticides play a critical role in safeguarding Indian rice crops; however, their persistence and toxicity challenge soil microbial health, plant growth, and human safety (Bhoi et al., 2022). Balancing effective pest control with environmental stewardship requires informed pesticide use, promotion of IPM, and enhanced regulatory oversight (Dhandapani, 2018). Future research to understand long-term impacts and develop safer practices is key to sustainable rice agriculture (Pathak & Shakywar, 2015).

VII. RECOMMENDATIONS

To harmonize pest control with sustainability in Indian rice cultivation, a multi-stakeholder approach is recommended:

- **For Researchers:** Prioritize development of efficient microbial consortia over single strains, conduct long-term field validations of bioremediation strategies, and investigate the combined effects of pesticide mixtures on soil microbiomes under realistic paddy conditions.
- **For Farmers, Agronomists, and Extension Services:** Actively adopt IPM frameworks incorporating biological control agents (e.g., *Trichogramma japonicum*), cultural practices like crop rotation, and promote the use of biofertilizers (e.g., *Azolla*) to reduce chemical reliance. Training must emphasize safe handling, precise dosing, and proper PPE use.
- **For Policymakers and Regulators:** Strengthen enforcement of Maximum Residue Limits (MRLs) in food and promote routine environmental monitoring. Support policies that incentivize soil health initiatives (e.g., organic

amendments, cover cropping) and fund farmer education programs. Public awareness campaigns can drive consumer demand for sustainably produced rice.

Microbial bioremediation, integrated within a robust IPM strategy, offers a promising pathway to detoxify contaminated paddy soils, restore microbial balance, and ensure the long-term productivity and ecological health of this vital agroecosystem.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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