Molecular Soil Biology 2024, Vol.15, No.3, 118-128
http://bioscipublisher.com/index.php/msb

Research Insight Open Access

Pesticide Usage in Rice Cultivation: Consequences for Soil and Water Health

Ruchun Chen, Qifu Zhang
Hier Rice Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China
Corresponding email: qifu.zhang@hitar.org
Molecular Soil Biology, 2024, Vol.15, No.3 doi: 10.5376/msb.2024.15.0013
Received: 07 Apr., 2024
Accepted: 14 May, 2024
Published: 28 May, 2024

Preferred citation for this article:
Chen R.C., and Zhang Q.F.., 2024, Pesticide usage in rice cultivation: consequences for soil and water health, Molecular Soil Biology, 15(3): 118-128 (doi: 10.5376/msb.2024.15.0013)

Abstract As global food demand continues to grow, the use of pesticides in rice cultivation has become a common practice to ensure high yields. However, the widespread application of these chemicals has significantly impacted soil and water health. This study provides an overview of the history and evolution of pesticide use in rice cultivation, explores the functions and application patterns of different types of pesticides, and further analyzes their effects on soil health. Through case studies, the study highlights the long-term impacts of pesticide use on soil in certain rice-producing regions. Pesticides entering water bodies through runoff and leaching can have significant negative effects on water quality. These chemicals, once in rivers, lakes, and groundwater, can lead to water pollution, degrade water quality, and consequently threaten the health of aquatic ecosystems. This study aims to systematically assess the environmental consequences of pesticide use in rice cultivation, particularly its impact on soil and water health, to fill the existing knowledge gaps and provide scientific evidence for the development of more sustainable agricultural practices.
Keywords Pesticide use; Rice cultivation; Soil health; Water quality; Environmental impact

1 Introduction

Pesticides play a crucial role in modern agriculture, particularly in rice cultivation, where they are extensively used to combat various pests and diseases that threaten crop yields. Despite their benefits in enhancing productivity, the persistent and excessive use of pesticides has led to significant environmental concerns. Pesticides often contaminate soil and water ecosystems, posing risks to non-target organisms and human health (Sharma et al., 2019; Tiwari et al., 2019). For instance, studies have shown that pesticides can disrupt soil biodiversity, affect microbial communities, and lead to the bioaccumulation of toxic residues in the environment (Tang and Maggi, 2021; Onorati et al., 2022). The continuous application of pesticides such as chlorpyrifos has been observed to impact soil microbes and nematodes adversely, highlighting the need for safer pesticide practices.

Rice is a fundamental staple food for a significant portion of the global population, particularly in Asia and developing countries. It is not only a primary source of nutrition but also a critical component of food security and economic stability for millions of rural households (Selvaraj et al., 2014; Wong and Brown, 2020). The crop's importance is underscored by its extensive cultivation across diverse agro-climatic zones, making it a vital agricultural commodity. The phrase "rice is life" aptly captures its significance in countries like India, where it supports the livelihoods of millions and plays a pivotal role in the national food security strategy.

This study reviews the extent and pattern of pesticide application in rice fields, assesses the environmental impacts of pesticide residues on soil and aquatic ecosystems and the potential risks of pesticide contamination to non-target organisms and human health, and proposes sustainable practices and policy recommendations to mitigate the adverse effects of pesticide use in rice cultivation. By addressing these objectives, this study aims to contribute to the broader discussion on sustainable agriculture and environmental protection, providing insights that can inform better rice cultivation management practices and policy frameworks.

2 Historical Context of Pesticide Usage in Rice Cultivation

2.1 Evolution of pesticide use in agriculture

The use of pesticides in agriculture has evolved significantly over the past century. Initially, pesticides were introduced to combat pests and increase crop yields, which was crucial for food security. Early pesticides included natural substances like sulfur and arsenic compounds. However, the development of synthetic pesticides in the mid-20th century, such as DDT and organophosphates, marked a significant shift. These chemicals were highly effective but also brought about environmental and health concerns due to their persistence and toxicity (Parsons et al., 2010). Over time, the adverse effects of these chemicals led to stricter regulations and the development of more targeted and less persistent pesticides (Tiwari et al., 2019; Onorati et al., 2022).

2.2 Specifics of pesticide application in rice fields

Rice cultivation, being a water-intensive crop, presents unique challenges and practices for pesticide application. Pesticides are often applied directly to the water in paddy fields, which can lead to widespread contamination of water bodies and affect non-target organisms. Commonly used pesticides in rice fields include herbicides, insecticides, and fungicides. For instance, chlorpyrifos, a widely used insecticide, has been shown to persist in soil and affect soil microbes and nematodes adversely (Kumar et al., 2017). The overapplication of pesticides, sometimes exceeding recommended rates by up to 11 times, has been documented, leading to significant environmental risks. The use of pesticides in rice fields is also influenced by the type of rice cultivation system, with lowland rice fields showing higher impacts on human health and freshwater ecotoxicity compared to upland and terraced systems (Toolkiattiwong et al., 2023) (Figure 1).

Lowland rice fields, due to their intensive farming practices, often use more fertilizers, herbicides, and pesticides, leading to a higher carbon footprint and gray water footprint, as well as more significant risks to human health and freshwater ecosystems. Studies have shown that the types and quantities of pesticides used in lowland rice fields are greater, primarily for commercial purposes, aiming for higher yields. These pesticides tend to persist in the soil, and their residues can cause long-term impacts on ecosystems through soil and water migration. In contrast, upland and terraced systems typically rely on natural conditions for cultivation and are mainly used for household consumption, resulting in lower pesticide usage and reduced environmental and health impacts.

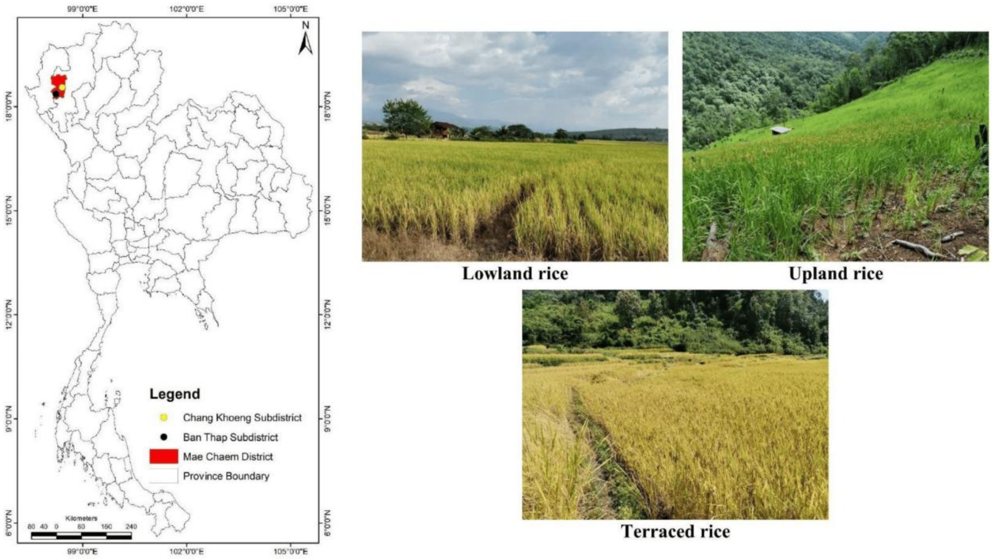

Figure 1 Environmental, human and ecotoxicological impacts of different rice cultivation systems (Adopted from Toolkiattiwong et al., 2023)

2.3 Case studies of historical pesticide impacts

Several case studies highlight the historical impacts of pesticide use in rice cultivation. In Sri Lanka, a study assessing pesticide residues in water from rice paddies found that overapplication of pesticides led to high environmental risks and adverse effects on local fauna, including fish, amphibians, and insects (Gamaralalage et al., 2021). In Northern Italy, the presence of oxadiazon in water from both conventional and organic rice paddies was identified as a major cause of toxicity, demonstrating the widespread impact of pesticide use even in organic farming systems. Another study in Pakistan revealed significant health issues among rice farmers due to pesticide exposure, including skin and eye irritation, cough, dizziness, and even cases of serious illness and death (Elahi et al., 2019). These case studies underscore the need for better management practices and stricter regulations to mitigate the adverse effects of pesticide use in rice cultivation.

3 Types of Pesticides Used in Rice Cultivation

3.1 Insecticides, herbicides, fungicides

Rice cultivation employs a variety of pesticides to manage pests, weeds, and diseases. The primary categories of pesticides used include insecticides, herbicides, and fungicides. Insecticides target insect pests, herbicides control weed growth, and fungicides prevent fungal diseases.

3.2 Common active ingredients and their functions

Several active ingredients are commonly used in rice cultivation for their effectiveness. Common active ingredients in insecticides include imidacloprid and chlorpyrifos. Imidacloprid is widely detected in rice fields and is known for its effectiveness against a broad spectrum of insect pests. Chlorpyrifos, although effective, has significant non-target effects on soil microbes and nematodes (Kumar et al., 2017). Penoxsulam and profoxydim are newer generation herbicides used in rice paddies. Penoxsulam is particularly persistent in water, while profoxydim dissipates quickly. Butachlor is another widely used herbicide, known for its effectiveness in controlling weeds. Tricyclazole and carbendazim are common fungicides. Tricyclazole is highly persistent in soil, making it effective for long-term fungal control (Tsochatzis et al., 2013; Wandscheer et al., 2017). Carbendazim is frequently detected in rice-vegetable rotation systems and poses a risk of water contamination.

3.3 Usage patterns and application methods

The application of pesticides in rice cultivation varies based on the type of pest, weed, or disease being targeted, as well as the environmental conditions. Insecticides like imidacloprid are often applied during specific crop stages to maximize effectiveness against pests. Chlorpyrifos is applied regularly but has a short half-life, necessitating frequent applications. Herbicides such as penoxsulam and profoxydim are applied under submerged conditions typical of rice paddies. The dissipation rates of these herbicides vary, with penoxsulam persisting longer in water. Butachlor is applied more frequently in regions with direct seeding methods (Dash et al., 2018). Fungicides like tricyclazole are applied to manage fungal diseases, with application rates and timing adjusted to ensure persistence in the soil. Carbendazim is applied in rotation systems, with its residues frequently detected in both soil and water (Tan et al., 2020; 2021). These usage patterns and application methods are critical for managing the environmental impact of pesticide use in rice cultivation, ensuring effective pest control while minimizing risks to soil and water health.

4 Impact of Pesticides on Soil Health

4.1 Soil contamination and residue persistence

Pesticide residues in soil are a significant concern due to their persistence and potential to cause long-term contamination. Studies have shown that continuous application of pesticides like chlorpyrifos can lead to residue accumulation, although the persistence may vary. For instance, chlorpyrifos residues in rice field soil were found to dissipate significantly within 15 days, with a half-life of approximately 4.02 days, indicating that while residues are present, they may not be highly persistent in certain conditions. However, other studies have highlighted the presence of multiple pesticide residues in agricultural soils, with some compounds like glyphosate and DDTs being found at high concentrations and persisting in the environment (Silva et al., 2019).

4.2 Effects on soil microbial diversity and function

Pesticides can have profound effects on soil microbial communities, which are crucial for maintaining soil health and fertility. Long-term pesticide application has been shown to reduce the abundance and diversity of key microbial groups. For example, continuous use of chlorpyrifos significantly reduced populations of nitrogen-fixing bacteria, nitrifiers, and denitrifiers, which are essential for nutrient cycling. Similarly, the application of various pesticides and chemical fertilizers in rice fields led to a significant decrease in the abundance of microbial communities, including anammox and denitrifying bacteria, which are vital for nitrogen cycling (Rahman et al., 2020). Additionally, pesticides like propiconazole have been observed to initially stimulate microbial growth and enzyme activities at lower concentrations, but higher concentrations and prolonged exposure resulted in detrimental effects on microbial populations and soil enzyme activities (Satapute et al., 2019).

4.3 Alterations in soil chemistry and nutrient cycling

Pesticides can alter soil chemistry and disrupt nutrient cycling processes. The use of herbicides in direct-seeded rice fields, for instance, has been shown to impact soil nutrient status and microbial populations, which in turn affects soil health and productivity (Dubey et al., 2023). The reduction in microbial diversity and function due to pesticide exposure can lead to decreased soil organic carbon and nitrogen content, further impairing soil fertility. The interaction between tillage management and pesticide application can influence the dissipation of agrochemicals and the functioning of soil microbiomes, highlighting the complex dynamics between agricultural practices and soil health (Liu et al., 2020).

4.4 Case study: long-term pesticide effects on soil health in a rice-producing region

A long-term study conducted at the National Rice Research Institute in Cuttack, India, investigated the effects of continuous chlorpyrifos application on soil health over seven seasons. The study found that while chlorpyrifos residues dissipated relatively quickly, the repeated application had significant impacts on non-target soil microbes and nematodes. Populations of beneficial microbes such as nitrogen fixers and nitrifiers were significantly reduced, while certain plant parasitic nematodes showed varying trends in population dynamics (Kumar et al., 2017). This case study underscores the importance of monitoring and managing pesticide use to mitigate adverse effects on soil health in rice-producing regions. By understanding the multifaceted impacts of pesticides on soil health, we can develop more sustainable agricultural practices that protect and enhance soil ecosystems.

5 Impact of Pesticides on Water Quality

5.1 Pesticide runoff and leaching into water bodies

Pesticides applied in rice cultivation often find their way into nearby water bodies through various pathways such as surface runoff, leaching, and drainage. Studies have shown that pesticides like Alphamethrin, MCPA, Oxadiazon, and Pretilachlor can be detected in runoff water shortly after application, with concentrations decreasing over time (Comoretto et al., 2008). The runoff from rice paddies can carry significant loads of dissolved pesticides to adjacent wetlands, posing a risk to water quality. Additionally, models like RICEWQ-VADOFT have been developed to predict the environmental concentration of pesticides in soil, runoff, and groundwater, highlighting the importance of soil permeability and water management practices in influencing pesticide fate (Ogura et al., 2021).

5.2 Effects on aquatic ecosystems and biodiversity

The presence of pesticides in aquatic environments can have detrimental effects on non-target organisms, including fish, mollusks, and other benthic organisms. These compounds can cause physiological changes, genetic injuries, and even bioaccumulation in aquatic species. For instance, fish exposed to pesticides in rice-fish farming systems have shown bioaccumulation of harmful chemicals, leading to oxidative stress and adverse biochemical responses (Liu et al., 2020). The impact on aquatic ecosystems is profound, as pesticides can disrupt the balance of these habitats and reduce biodiversity (Araújo et al., 2020).

5.3 Bioaccumulation and biomagnification in aquatic food chains

Pesticides in water bodies can bioaccumulate in aquatic organisms, leading to biomagnification through the food chain. This process can result in higher concentrations of pesticides in top predators, posing risks to both wildlife and human health. For example, fish in rice-fish farming systems have been found to bioaccumulate pesticides like lambda-cyhalothrin and tebuconazole, which can then be transferred to humans through consumption (Clasen et al., 2018). The bioaccumulation of pesticides in aquatic food chains underscores the need for stringent regulations and monitoring to protect ecosystem health and food safety.

5.4 Case study: water contamination and ecosystem disruption in a rice-growing area

A case study conducted in the Deduru Oya River Basin, Sri Lanka, assessed the concentration of pesticide residues in water associated with rice ecosystems and their potential impacts on environmental health. The study found that several pesticides were overapplied, leading to high environmental risks, particularly from 2-methyl-4-chlorophenoxyacetic acid and diazinon. These chemicals posed significant threats to fish, amphibians, insects, and beetles, with adverse outcomes ranging from physiological stress to mortality (Figure 2) (Gamaralalage et al., 2021). The findings highlight the need for adopting environmental health indicators and regulating pesticide use to balance food security with ecosystem sustainability. By understanding the pathways and impacts of pesticide runoff, leaching, and bioaccumulation, we can develop better management practices to mitigate the adverse effects on water quality and aquatic ecosystems.

The assessment using the Environmental Impact Quotient (EIQ) method shows that the variation in pesticide use across different plots leads to significant changes in ecosystem impacts. For example, MCPA has the highest Environmental Impact Quotient among all the pesticides studied, indicating a very high potential hazard to ecosystems. At the plot level, the environmental impact is greater in upstream areas, while it is relatively smaller in midstream areas. Overall, the excessive use of these pesticides poses a significant threat to local biodiversity, particularly to the growth, behavior, and survival of fish, insects, and amphibians. To reduce the adverse effects on ecosystems, the use of highly harmful pesticides should be restricted, and farmers' awareness of the rational application of pesticides should be increased.

6 Consequences for Human Health

6.1 Direct and indirect exposure to pesticides

Direct exposure to pesticides primarily occurs through dermal contact and inhalation during pesticide application. Farmers often use knapsack sprayers, which can lead to significant dermal exposure, especially when protective measures are not adequately adopted (Wong and Brown, 2020). Indirect exposure can occur through contaminated water sources and residues in soil and crops. For instance, in the Babol Roud River in Northern Iran, high concentrations of diazinon, carbaryl, and butachlor were detected in water samples, posing risks to both human health and the environment (Jolodar et al., 2021).

6.2 Health risks for farmers and nearby communities

Farmers and nearby communities face various health risks due to pesticide exposure. Common symptoms reported include skin irritation, eye irritation, cough, dizziness, nausea, and diarrhea (Vieira et al., 2016). In severe cases, there have been instances of death and serious illness due to intentional or unintentional ingestion of pesticides. The lack of education and awareness about safe pesticide use exacerbates these health risks. Protective measures such as wearing protective clothing, goggles, masks, gloves, and boots can significantly reduce these risks.

6.3 Pesticide residues in rice and implications for consumers

Pesticide residues in rice can pose significant health hazards to consumers. Studies have shown that pesticides like chlorpyrifos, butachlor, and fipronil remain in the soil and can be absorbed by rice plants, leading to residues in the harvested grains (Selvaraj et al., 2014). The presence of excessive pesticide residues above tolerance levels can lead to chronic health issues for consumers, including potential carcinogenic effects. Monitoring and regulating pesticide use are crucial to ensure food safety and protect consumer health.

6.4 Case study: human health impacts in regions with intensive rice cultivation

In regions with intensive rice cultivation, such as the Mae Chaem District in Northern Thailand, the use of pesticides has led to significant human health impacts. The study found that lowland rice fields, which use more agricultural inputs, had the highest impact on human health and freshwater ecotoxicity (Toolkiattiwong et al., 2023). Similarly, in Punjab, Pakistan, a study reported various health issues among rice growers due to pesticide exposure, including skin and eye irritation, cough, dizziness, and nausea (Elahi et al., 2019). These findings highlight the urgent need for sustainable farming practices and effective pesticide management to mitigate health risks in such regions.

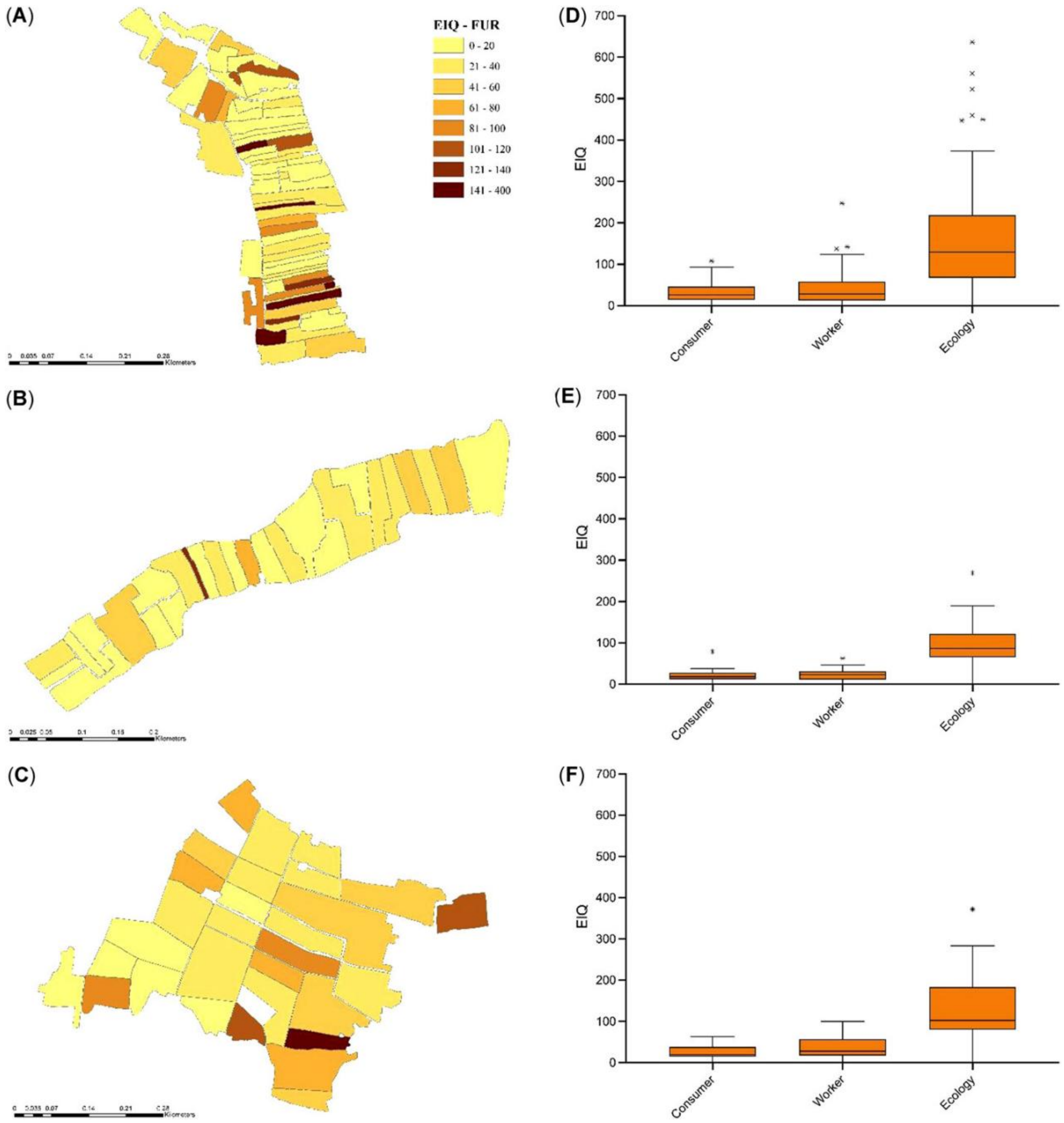

Figure 2 The role of rice fields in pesticide-related environmental risks (Adapted from Gamaralalage et al., 2021)

Imagine caption: (A) Total EIQ-FUR of site 1. (B) Total EIQ-FUR of site 2. (C) Total EIQ-FUR of site 3. (D-F) Distribution of EIQ values for consumer, worker, and ecology components for the three sites in the Deduru Oya irrigation scheme (Adapted from Gamaralalage et al., 2021)

7 Sustainable Alternatives to Pesticides

7.1 Integrated pest management (IPM) strategies

Integrated Pest Management (IPM) is a holistic approach that combines various pest control methods to minimize the use of synthetic pesticides and reduce their environmental impact. IPM strategies in rice cultivation include cultural practices, use of resistant varieties, biological control, and chemical methods as a last resort. The implementation of IPM has shown to be effective in reducing pesticide use while maintaining or even increasing crop yields. For instance, in Indonesia, the adoption of IPM technology led to a significant reduction in pesticide use, demonstrating its potential for sustainable agriculture (Veres et al., 2020). IPM has been successfully implemented in various Asian countries, resulting in reduced pesticide imports and stable rice production (Dhakal and Poudel, 2020).

7.2 Biological control methods and natural predators

Biological control involves the use of natural predators, parasites, or pathogens to manage pest populations. This method is environmentally friendly and can be integrated into IPM strategies. For example, the use of

Trichogramma egg-cards as a biological control agent in the Greater Mekong Subregion led to a substantial reduction in pesticide use and slightly higher yields in rice and maize (Babendreier et al., 2019). The abundance of natural enemies in tropical Asian irrigated rice systems helps prevent significant pest problems, highlighting the importance of preserving these natural predators through IPM education and training.

7.3 Use of biopesticides and organic farming practices

Biopesticides, derived from natural materials such as plants, bacteria, and certain minerals, offer a sustainable alternative to synthetic pesticides. They are often used in organic farming practices, which emphasize the use of natural inputs and processes. The integration of biopesticides into IPM strategies can enhance pest control while minimizing environmental and health risks. For instance, bio-based IPM practices in rice cultivation have been shown to be effective, environmentally benign, and economically viable (Fahad et al., 2021). The increased implementation of biological approaches, including biopesticides, is crucial for sustainable agriculture, as highlighted by the need for greater adoption and education on these methods (Baker et al., 2020).

7.4 Case study: successful implementation of sustainable practices in rice cultivation

A notable case study of successful implementation of sustainable practices in rice cultivation is the IPM program in Indonesia. Since its introduction in 1989, the program has significantly reduced pesticide use by improving rice production processes and promoting efficient pesticide application. The success of this program is evidenced by the widespread adoption of IPM technology among farmers, leading to more sustainable and cost-effective rice cultivation (Mariyono, 2008). Another example is the FAO's inter-country program on rice IPM, which has contributed to promoting IPM practices across several Asian countries, resulting in reduced pesticide imports and stable rice yields.

Sustainable alternatives to pesticides, such as IPM strategies, biological control methods, and the use of biopesticides, offer promising solutions for maintaining soil and water health in rice cultivation. Successful case studies demonstrate the potential of these practices to reduce pesticide use, enhance crop yields, and promote environmental sustainability. Continued research, education, and policy support are essential for the widespread adoption and success of these sustainable practices.

8 Policy and Regulation

8.1 Current regulations on pesticide usage in rice farming

Current regulations on pesticide usage in rice farming vary significantly across different countries. In Thailand, for instance, the use of certain pesticides like glyphosate and chlorpyrifos is restricted due to their long-term health effects, although their application in rice cultivation still needs close monitoring. In Sri Lanka, despite the presence of regulations, overapplication of pesticides is common, with some being used at rates 1.2 to 11 times higher than recommended (Gamaralalage et al., 2021). In Italy, laws and directives exist to regulate and restrict pesticide use, but contamination still occurs due to the free circulation of water through irrigation canals (Onorati et al., 2022). In Iran, the use of pesticides in rice production is monitored, but the concentrations of pesticides like diazinon, carbaryl, and butachlor in water bodies still pose significant health risks.

8.2 International standards and guidelines

International standards and guidelines for pesticide usage in agriculture are established by organizations such as the Food and Agriculture Organization (FAO) and the World Health Organization (WHO). These guidelines aim to minimize the environmental and health impacts of pesticide use. For example, the European Union has set acceptable daily intake levels for various pesticides to protect human health (Jolodar et al., 2021). The Cornell University Environmental Impact Quotient (EIQ) calculator is used to assess the environmental risks associated with pesticide application, providing a standardized method to evaluate the impact of different pesticides.

8.3 Role of government and NGOs in promoting sustainable practices

Governments and non-governmental organizations (NGOs) play a crucial role in promoting sustainable agricultural practices. In Bangladesh, government extension workers and NGOs are involved in educating farmers about integrated pest management (IPM) practices to reduce pesticide use and minimize environmental hazards

(Rahaman et al., 2018). In Rwanda, the government has initiated projects like the Muvumba rice project to promote rice as a staple crop, but there is a need for stricter regulation and training on safe pesticide use to protect human and ecosystem health (Ndayambaje et al., 2019). In Pakistan, the use of protective measures during pesticide application is highly recommended to reduce occupational health risks, and there is a push towards using bio-chemicals for agricultural sustainability.

8.4 Case study: regulatory impacts on pesticide usage and environmental health

A case study from Northern Thailand highlights the impact of regulations on pesticide usage and environmental health. In the Mae Chaem District, the use of pesticides like chlorpyrifos and glyphosate is restricted, yet these chemicals are still found in significant quantities in soil and water samples. The study found that lowland rice fields had the highest impact on human health and freshwater ecotoxicity, followed by terraced and upland rice cultivation systems. Despite the restrictions, the presence of these pesticides indicates a need for more effective monitoring and enforcement of regulations to protect environmental and human health (Toolkiattiwong et al., 2023).

While regulations and guidelines exist to control pesticide usage in rice farming, their effectiveness varies across regions. Governments and NGOs play a vital role in promoting sustainable practices, but there is a need for stricter enforcement and better education to minimize the adverse impacts of pesticides on soil and water health.

9 Future Directions and Research Needs

9.1 Emerging technologies for pest control

Emerging technologies in pest control are crucial for reducing the environmental impact of pesticides in rice cultivation. Integrated Pest Management (IPM) techniques, which combine biological, cultural, and chemical methods, have shown promise in minimizing pesticide use while maintaining crop yields. For instance, research has demonstrated that IPM can significantly reduce the need for chemical insecticides by promoting natural pest predators and using pest-resistant rice varieties (Hajjar et al., 2023). Additionally, innovative practices such as the use of rice fields for phytoremediation of pesticide-contaminated water have been explored, showing significant reductions in pesticide loads in water systems (Moore et al., 2018). These technologies not only help in controlling pests but also contribute to the overall health of the ecosystem.

9.2 Long-term monitoring and impact assessment

Long-term monitoring and impact assessment are essential to understand the cumulative effects of pesticide use on soil and water health. Studies have highlighted the need for systematic and continuous monitoring to capture the long-term impacts of pesticides on non-target organisms and soil health. For example, continuous application of chlorpyrifos in rice fields has been shown to affect soil microbial populations and nematode species over multiple growing seasons, indicating the importance of long-term studies to assess ecological impacts (Kumar et al., 2017). Monitoring pesticide residues in water bodies associated with rice paddies can help in evaluating the environmental risks and guiding policy decisions (Gamaralalage et al., 2021).

9.3 Need for interdisciplinary research and collaboration

Interdisciplinary research and collaboration are vital for developing sustainable pest management strategies in rice cultivation. The complexity of pesticide impacts on the environment and human health necessitates a collaborative approach involving agronomists, ecologists, toxicologists, and social scientists. For instance, research in Bangladesh has shown that increasing farmers' awareness and knowledge through extension services and educational programs can significantly reduce pesticide misuse and its associated risks (Rahaman et al., 2018). Collaborative efforts can also lead to the development of more effective and sustainable pest management practices, as demonstrated by the successful implementation of IPM techniques through farmer participatory research and community-based approaches.

9.4 Case study: innovative research initiatives in sustainable rice farming

Innovative research initiatives in sustainable rice farming have shown promising results in reducing pesticide use and improving environmental health. One notable example is the collaborative research conducted with smallholder farmers to test various pest management practices. This study found that reducing insecticide application and promoting natural pest predators can maintain crop yields while significantly decreasing pesticide use (Ali et al., 2017). Another initiative involved the use of rice fields for phytoremediation, which effectively reduced pesticide concentrations in water, demonstrating the potential of rice paddies to mitigate agricultural runoff. These case studies highlight the importance of integrating scientific research with practical farming solutions to achieve sustainable rice cultivation.

10 Concluding Remarks

These studies collectively emphasize the significant impact of pesticide use in rice cultivation on the environment and health. Different rice cultivation systems exhibit varying carbon and water footprints. Terraced fields have the highest carbon footprint, while lowland paddies have the highest water footprint. Commonly used pesticides such as chlorpyrifos, butachlor, and fipronil persist in the soil, while acephate, glyphosate, and metaldehyde are prevalent in freshwater. Excessive use of pesticides like MCPA and diazinon poses high environmental risks. Pesticides such as diazinon, carbaryl, and butachlor present significant non-carcinogenic health risks, especially to children. Pesticide exposure is associated with various health issues, including skin and eye irritation, coughing, dizziness, and nausea. Pesticides have adverse effects on aquatic ecosystems, posing significant risks to fish, amphibians, insects, and beetles. Pesticides also affect soil and water microbial communities and mesofauna, which are crucial for soil fertility and ecosystem health.

The findings underscore the need for sustainable rice cultivation practices to mitigate the adverse effects of pesticide use. Implementing Integrated Pest Management (IPM) measures can reduce reliance on chemical pesticides, thereby lowering environmental and health risks. Adopting organic farming practices and isolating water cycles in organic areas can minimize pesticide contamination. Utilizing rice fields for phytoremediation can effectively reduce pesticide loads in agricultural runoff, thereby protecting aquatic ecosystems. Educating farmers on safe pesticide use and encouraging the use of protective gear can significantly reduce health risks.

To address the challenges posed by pesticide use in rice cultivation, the following recommendations are proposed. Policymakers should enforce stricter regulations on pesticide use and promote Integrated Pest Management and organic farming practices. National policies that include quantifiable environmental health indicators should be developed and implemented to regulate pesticide use. Support research and development of alternative pest control methods and sustainable agricultural practices. Farmers should adopt IPM and organic farming practices to reduce dependence on pesticides and minimize environmental impact. Protective measures such as gloves, masks, and protective clothing should be used when applying pesticides to minimize health risks. Participate in training programs to increase knowledge and awareness of safe pesticide use and sustainable agricultural practices. Researchers should further investigate the long-term impacts of pesticide residues on soil and water health, especially in different rice cultivation systems. Study the effectiveness of phytoremediation and other innovative practices in mitigating pesticide pollution. Develop and promote biopesticides and other environmentally friendly pest control methods to reduce reliance on chemical pesticides. By implementing these recommendations, a balance can be achieved between rice production and environmental sustainability, ensuring the health and well-being of ecosystems and humans.

Acknowledgments

The BioSci Publisher would like to thank two anonymous peer reviewers for their careful review and feedback.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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