Review Article

Mitigation of Pesticide Runoff in Paddy Agroecosystems Through Endophytic Bacteria: A Pathway Toward Aquatic Biodiversity Restoration

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ABSTRACT

Paddy agroecosystems globally, particularly in regions such as Bangladesh, face critical challenges from the escalating use of agrochemicals. Over the past 20-30 years, pesticide application has surged in Asian rice farming, with residues from banned organochlorine and organophosphorus compounds persisting in the environment. This widespread use leads to significant water contamination, with surface and groundwater often exceeding drinking water standards, and results in food contamination as harmful pesticides aggregate in harvested rice grains. The environmental repercussions are severe, as agrochemical runoff degrades freshwater aquatic environments, leading to bioaccumulation and health risks in fish, and exhibiting toxic effects on freshwater ecosystems. Furthermore, farmers themselves face health hazards due to the overuse of chemicals and insufficient use of personal protective equipment. This review proposes rice-associated endophytic bacteria as a sustainable and multifunctional solution. Our research, supported by complementary studies, highlights that endophytic consortia can effectively degrade persistent pesticide residues directly within the plant, promote plant growth under reduced fertilizer inputs, and enhance plant stress resilience. We advocate for future strategies that rigorously evaluate these pesticide-mineralizing endophytes through field trials, comprehensive environmental monitoring, molecular and omics-level analyses, and advanced bioformulation technologies. Harnessing the power of endophytic bacteria offers a holistic approach to mitigate agrochemical runoff, restore aquatic biodiversity, and safeguard both environmental and human health.

1. INTRODUCTION

Bangladesh's agricultural sector is heavily reliant on its water resources, including freshwater wetlands, which play a vital role in both the national economy and environmental sustainability [1, 2]. The country's geographical and geomorphological conditions make it rich in wetlands, covering around 50% of its area, which are crucial for maintaining ecological balance [2]. Intensive agriculture and a growing population place significant pressure on these aquatic ecosystems [3, 4]. The intensification of crop production, particularly Boro rice, relies heavily on irrigation from rivers, emphasizing the need for sustainable water management [5, 6]. However, these freshwater ecosystems are now under threat due to the excessive use of chemicals, such as pesticides and insecticides, in our agricultural fields [1, 7]. The number of pesticides applied in Bangladesh has significantly increased, reaching over 38,691 metric tons in 2018 alone [8]. When pesticides enter rivers, lakes, and ponds through runoff, leaching, spray drift, or soil erosion, they attempt to alter the chemical composition of water and disrupt the balance of marine life [9]. Studies shown that pesticides like fenitrothion and imidacloprid can significantly affect water quality and various aquatic organisms such as phytoplankton, zooplankton, and macroinvertebrates in freshwater ecosystems. These harmful pesticides not only degrade water quality, destroying the normal growth, reproduction, and survival of non-target organisms [10]. The widespread use of pesticides leads to the deterioration of freshwater ecosystems, resulting in biodiversity decline and impaired ecosystem function [11]. This can lead to ecological imbalance, disturbed food chains, and impaired ecosystem function [12]. For instance, increasing pesticide contamination has been shown to reduce regional aquatic biodiversity, with macroinvertebrate family richness decreasing by approximately 30% at legally accepted regulatory threshold levels [13]

With time, this leads to ecological imbalance, sometimes leading to significant loss in biodiversity, disturbed food chains, [14]impaired ecosystem functions. Beyond toxicity, some pesticide residues are persistent in the environment. They can easily accumulate in sediments, aquatic plants, and animal tissues, which can cause long-term contamination [15]. However, this biomagnification is also a serious threat to human health as people generally rely on freshwater supplies for drinking, agriculture, and fishing. The accumulation of these substances in the food chain threatens higher trophic levels and amplifies the potential for adverse health outcomes, including acute poisoning, cancer, and neurological disorders. On the other hand, the joint effect of pesticides with other environmental disturbances like nutrient pollution, habitat loss, and climate variability can also destabilize aquatic ecosystems, leading to deterioration of water structures, reduced resilience, and damaged ecosystem functions [16]. The ecological imbalance and degradation of water quality resulting from pesticide residues underscore the urgent need for effective management strategies, monitoring programs, and renewable and sustainable agricultural practices [17].

As pesticide contamination increasingly infiltrates freshwater bodies, the search for sustainable, biologically grounded mitigation strategies has become more urgent than ever. Plant-associated endophytic bacterial consortia already isolated and documented across diverse crops have emerged as a promising reservoir of metabolic and enzymatic capacities capable of transforming, detoxifying, or immobilizing persistent pesticides [18, 19]. Their inherent functional diversity, catalytic pathways, and synergistic interactions position them as valuable microbial allies that can intercept pesticide residues before

they escape agricultural soils and enter aquatic systems [20, 21]. Consolidating the growing body of evidence on these hidden microbial partners not only reveals their ecological significance but also highlights their potential as nature-based solutions for safeguarding water quality and preserving biodiversity [22-24]. Despite growing recognition of their potential, a comprehensive synthesis linking endophytic pesticide degradation to aquatic biodiversity restoration in paddy agroecosystems remains limited. This includes cataloguing reported strains, summarizing key metabolic pathways and biodegradation mechanisms examining ecological and agronomic factors that influence their performance, and identifying research gaps and future directions for integrating endophytic consortia into sustainable pesticide management frameworks [24-26].

Therefore, the aim of this review is to (ii) Compile and evaluate documented pesticide-degrading endophytic bacterial taxa and their metabolic mechanisms; (iii) Assess the potential of endophytic consortia to reduce in planta residues and downstream aquatic contamination; and (iv) Identify translational priorities including omics-guided strain selection, bioaugmentation frameworks, and robust bioformulation technologies for integrating endophytes into sustainable pesticide management systems.

2. INCIDENCE OF PESTICIDES RUNOFF IN THE WATER SOURCES

2.1. Pesticides used in rice farming

Rice is one of the staple foods in Bangladesh. The annual rice production in Bangladesh is approximately 40.6 million tons, and around 11.7 million hectares of land are typically used for rice cultivation purposes only [27]. To protect rice plants from insect attacks, weeds, and fungal infections, farmers often rely heavily on synthetic chemicals such as pesticides. However, excessive usage of these chemicals has become a serious threat to the environment [8]. About 77% farmers use pesticides at least once in every crop season[28]. These pesticides often find their way into nearby ponds or lakes or rivers, which is why the water bodies of Bangladesh are severely affected by water pollution. **Table 1** presents a concise overview of the most frequently reported pesticides applied in rice (paddy) cultivation systems across Bangladesh. The list includes ten active ingredients commonly documented in recent field surveys, residue monitoring studies, and risk assessments conducted in rice-based agroecosystems, particularly rice-prawn concurrent systems and intensive paddy farming regions.

Table 1. Common pesticides used in rice farming in Bangladesh, including generic and commercial names and associated toxicity risk.

No.	Generic Name (Active Ingredient)	Commercial/ Trade Names	Pesticide Type	WHO Toxicity Class	Major Toxicity Risk	Ref.
1	Carbofuran	Furadan 5G, Agrifuran 5G, Sunfuran 5G	Insecticide (Carbamate)	Ib (Highly hazardous)	Neurotoxic; acute poisoning risk to humans and wildlife	[27, 28]
2	Chlorpyrifos	Dursban, Pyrifos, Lorsban	Insecticide (Organophosphate)	II (Moderately hazardous)	Neurotoxicity, developmental effects	[12, 26]
3	Lambda-cyhalothrin	Karate 2.5 EC, Fighter 2.5 EC	Insecticide (Pyrethroid)	II (Moderately hazardous)	Toxic to aquatic organisms and beneficial insects	[28]
4	Cypermethrin	Cyperkill, Ripcord, Caught 10 EC	Insecticide (Pyrethroid)	II (Moderately hazardous)	Neurotoxic effects; harmful to aquatic fauna	[12]
5	Diazinon	Diazinon 60 EC, Sudin 10G	Insecticide (Organophosphate)	II (Moderately hazardous)	Cholinesterase inhibition; acute poisoning risk	[27, 28]
6	Imidacloprid	Gain 20 SL, Premier 20 SL, Sunchlorprid 20 SL	Insecticide (Neonicotinoid)	II (Moderately hazardous)	Toxic to pollinators; neurotoxicity	[26]
7	Abamectin	Abamectin 1.8 EC, Avermectin	Insecticide/Acaricide	II (Moderately hazardous)	Neurotoxicity; toxic to aquatic organisms	[26]
8	Glyphosate	Roundup, Brush 200 SL	Herbicide	III (Slightly hazardous)	Potential chronic toxicity and environmental persistence	[14]
9	Paraquat	Gramoxone, Zero Herb 20 SL	Herbicide	II (Moderately hazardous)	Severe poisoning risk; lung toxicity	[13]
10	Carbendazim	Bavistin, Carbendazim 50 WP	Fungicide	II (Moderately hazardous)	Potential endocrine and reproductive toxicity	[26]

2.2. Pathways of pesticide surface runoff into ponds, wetlands, and shallow water bodies

As shown in **Figure 1**, surface runoff remains one of the most significant pathways through which agricultural pesticides enter adjacent ponds, wetlands, and shallow water bodies. During rainfall or heavy irrigation events, residual chemicals applied to crop fields are mobilized and transported into nearby rivers, ponds, and lakes [29]. Agricultural drainage water is a major non-point source of this pollution [30]. This problem becomes particularly pronounced during the rainy or monsoon season, when intense precipitation accelerates the wash-off of pesticides from soil surfaces and can lead to increased contamination of pond water [31]. Studies in Bangladesh indicate a significant concern regarding pesticide residues in water bodies. For instance, monitoring across various upazilas has revealed the presence of different pesticide residues, including carbamates, in pond water and paddy field water [32]. While specific data for Savar and Dhamrai upazilas showing 22% of collected water samples with high levels of pesticide residues, with carbaryl being especially prevalent" were not directly found in the search results, the broader context of widespread pesticide contamination in Bangladeshi water bodies and vegetables is well-documented [33, 34]. Similar contamination patterns with diazinon and fenitrothion have been observed. Several studies have detected diazinon and fenitrothion residues in vegetables like

eggplant, tomato, cauliflower, yard long beans, country beans, and hyacinth beans from various regions of Bangladesh, with some concentrations exceeding established maximum residue limits [35, 36]. While direct evidence of these specific pesticides exceeding limits in rice grains *near industrial zones surrounding Dhaka* wasn't explicitly found, the presence of pesticide residues in food items and the general issue of water pollution near industrial zones in Bangladesh are noted [37, 38]. Together, these findings underscore the persistent threat of pesticide runoff to aquatic ecosystems and food safety in agriculturally intensive regions. Pesticides can have long-lasting effects, contaminating surface water, groundwater, and food products, and can harm aquatic flora and fauna [37, 39]. The ecotoxicological risk posed by these chemicals to aquatic organisms is high, and long-term consumption of contaminated food may pose health risks to humans [40]. The extensive use of pesticides is a significant obstacle to sustainable agriculture, leading to the contamination of essential elements of life: food and water [41].
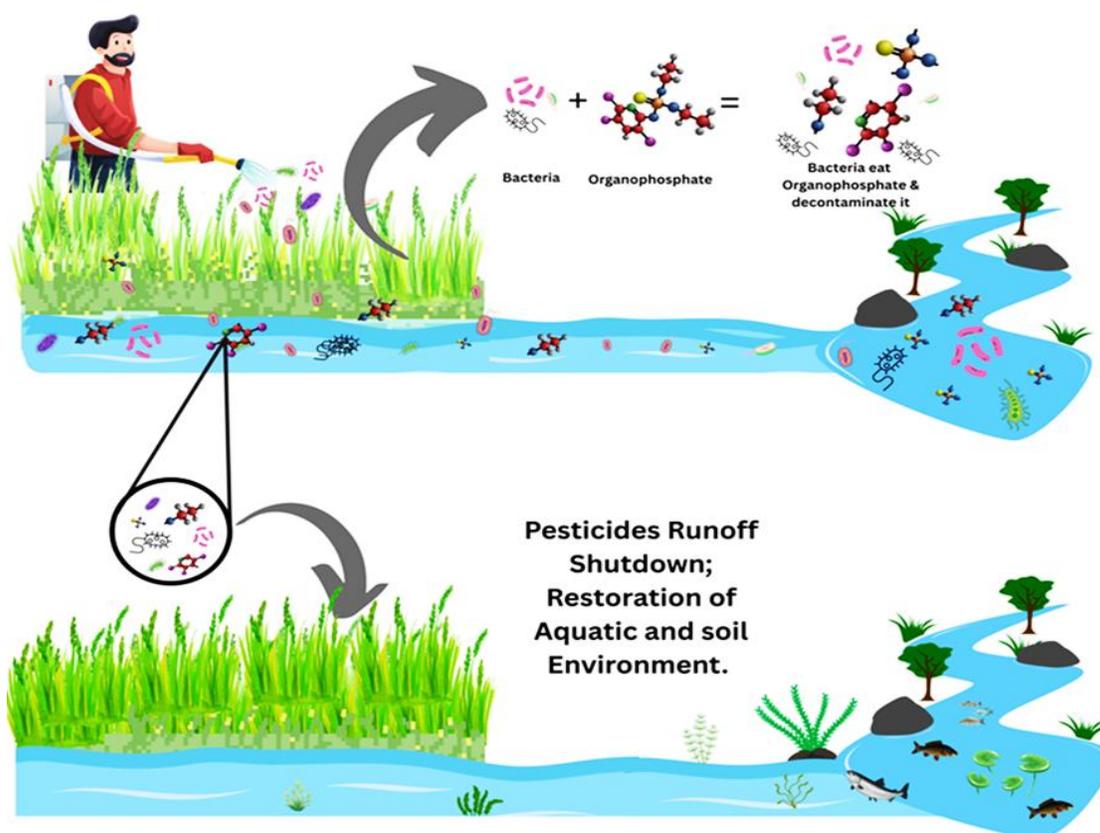

Figure 1. Diagram showing the incidence of pesticide runoff from agricultural fields into freshwater sources and facing challenges with pesticides degrading microbes, ultimately cleaning up the aquatic environment.

2.3. Underlying causes and pathways of pesticide contamination in freshwater ecosystem

Excessive contamination of freshwater ecosystems with pesticide residues results from a complex interaction of agricultural practices, environmental conditions, and management-related factors, including runoff, spray drift, leaching, and improper disposal [15]. To promote sustainable water resource management, it is essential to understand the underlying causes and contributing factors. This will help us develop effective control strategies, such as integrated pest management, bioremediation, and robust monitoring [42-44]. Furthermore, the continuous release of thousands of pesticide residues into

aquatic environments, particularly in regions with intensive agricultural activities, exacerbates contamination risks through mechanisms such as physical-chemical and biological degradation, sorption-desorption, surface runoff, and soil leaching [45]. Some specific underlying causes of pesticides ranoff in sweet water sources is stated below.

i. Intensive agricultural practices

Due to the rapid expansion of agricultural land and as the rice demand increases, farmers have started to depend on chemical pesticides to enhance crop productivity. The chemical synthetics that farmers often apply to the field lead to chemical runoff into nearby rivers, ponds, and irrigation canals [46, 47].

ii. Inadequate pesticide management and application practices

A lack of awareness among farmers about technical guidance on handling toxic chemicals and pesticide application contributes to these problems. Sometimes, using banned or highly persistent pesticides, spraying before rainfall, or disposing of containers near water resources can significantly contribute to contamination [48].

iii. Surface runoff and soil erosion

Surface runoff mainly transports pesticides from the fields into water bodies with the help of irrigation events or rain during the monsoon season. Poor land management, deforestation, and the presence of insufficient protective vegetation around the croplands frequently cause this issue. On the contrary, soil erosion carries both soluble pesticides and contaminated sediments into aquatic systems, which also contributes to degrading the water quality [49].

iv. Lack of wastewater treatment and monitoring systems

Bangladesh is still facing challenges in managing its water pollution. In many developing areas of Bangladesh, agricultural drainage, industrial effluents, and domestic wastewater are discharged into natural water bodies without proper treatment [50]. As a result, pesticide residues remain unmonitored in the environment for longer periods.

3. CONSEQUENCES OF PESTICIDE RESIDUES

Fresh water is essential for the survival and well-being of aquatic plants and animals, as well as for human health and welfare [51-53]. However, when this clean water becomes polluted, particularly by the introduction of unexpected pesticide runoff through agricultural activities, it leading to biodiversity loss and compromised ecosystem services [52, 53]. Such pollution further puts aquatic life at risk by irritating gills, destroying protective mucous, affecting reproduction, and making organisms susceptible to infection [54]. **Figure 2** represent a brief outline of harmful effects of pesticides in our ecosystems and health. The next section of this study will discussion in details.

3.1. Toxicity of pesticides on aquatic life

Figure 2 illustrates the cascading environmental and ecological consequences of pesticide contamination in aquatic systems following entry via agricultural runoff. Key impacts include soil degradation, direct harm to wildlife, toxicity to non-target aquatic organisms, reduced crop yields due to pest resurgence, development of pesticide resistance, and declines in populations of beneficial insects and pollinators.

A key example is chlorpyrifos, a widely used organophosphate insecticide in rice farming. Long-term exposure to chlorpyrifos has been shown to adversely affect reproductive tissues in local freshwater fish, such as the banded gourami (*Trichogaster fasciata*). At sublethal concentrations, it induces histopathological alterations in gonads, including degeneration of ovarian and testicular tissues, while higher exposures (e.g., 500 µg/L) result in complete mortality within 15 days. Low-level chronic exposure also leads to larval malformations and impaired reproductive organ development in adults [55]. Recent assessments of pesticide stress on fish in Bangladesh reveal widespread physiological damage, including gill filament reduction and hemorrhage, liver and kidney necrosis, degeneration of reproductive organs, and developmental anomalies in embryos and larvae [56]. These effects are particularly pronounced in species inhabiting rice-adjacent water bodies exposed to runoff from paddy fields.

Pesticides induce toxicity through diverse biochemical and physiological mechanisms. Organophosphates and carbamates inhibit acetylcholinesterase, disrupting cholinergic neurotransmission in fish, amphibians, and aquatic insects [57, 58]. Pyrethroids target voltage-gated sodium channels, leading to sodium influx, neuroexcitation, and depolarization [59, 60]. Herbicides like glyphosate and atrazine disrupt photosynthetic pathways in algae and aquatic plants, thereby reducing primary productivity and cascading effects through food webs [61, 62]. Such disruptions compromise ecosystem stability by altering trophic interactions [63, 64]. At the organismal level, exposure commonly causes severe histopathological changes: gill hyperplasia, lamellar fusion, and hemorrhage; liver necrosis, vacuolation, and impaired detoxification; and kidney tubular degeneration with osmoregulatory dysfunction [65]. Reproductive toxicity manifests as reduced sperm motility, ovarian atresia, endocrine disruption, and impaired embryogenesis [66, 67]. Chronic exposure is linked to genotoxic outcomes, including DNA fragmentation, chromosomal aberrations, and compromised DNA repair [68, 69].

At population and community scales, planktonic organisms highly sensitive to xenobiotics—exhibit reduced abundance and diversity, disrupting nutrient cycling and prey availability for higher trophic levels [67]. Benthic invertebrates, crucial for decomposition and sediment health, decline under repeated pyrethroid and organophosphate exposure [70]. Pesticide mixtures often exert synergistic toxicity, amplifying mortality, altering predator-prey dynamics, and accelerating biodiversity loss [71, 72].

The multiple pathways of pesticide entry into aquatic environments, combined with their varied modes of action and broad ecological ramifications, emphasize the severity of this contamination and the critical need for sustainable mitigation approaches [73, 74]. A recent investigation of the Feni River in Bangladesh detected multiple pesticide residues including dimethoate, carbofuran, and chlorantraniliprole in surface water, with peak concentrations reaching 14.5 µg/L during the dry season. These findings highlight the escalating threat to Bangladesh's freshwater ecosystems from agricultural runoff [75].

Specific effects on aquatic life and biodiversity Pesticide residues from paddy fields exert profound harm on aquatic organisms, including fish, amphibians, invertebrates, and microorganisms. This frequently results in biodiversity crises, disrupted food webs, altered community structures, and potential local extirpation of sensitive species, leading to long-term ecological imbalance [76, 77]. Ecosystem functions Freshwater ecosystems support essential processes such as nutrient cycling, organic matter decomposition, and natural water purification. Pesticide contamination impairs these functions by

reducing beneficial microbial populations, disrupting microbial interactions, and diminishing overall ecosystem resilience and productivity [78].

Bioaccumulation and biomagnification Persistent, lipophilic pesticides resistant to degradation accumulate in sediments and biota, magnifying concentrations up the food chain. This process heightens toxicity to predators, disrupts trophic balance, threatens wildlife (e.g., birds and mammals), and poses direct human health risks through consumption of contaminated water, fish, or crops [79].
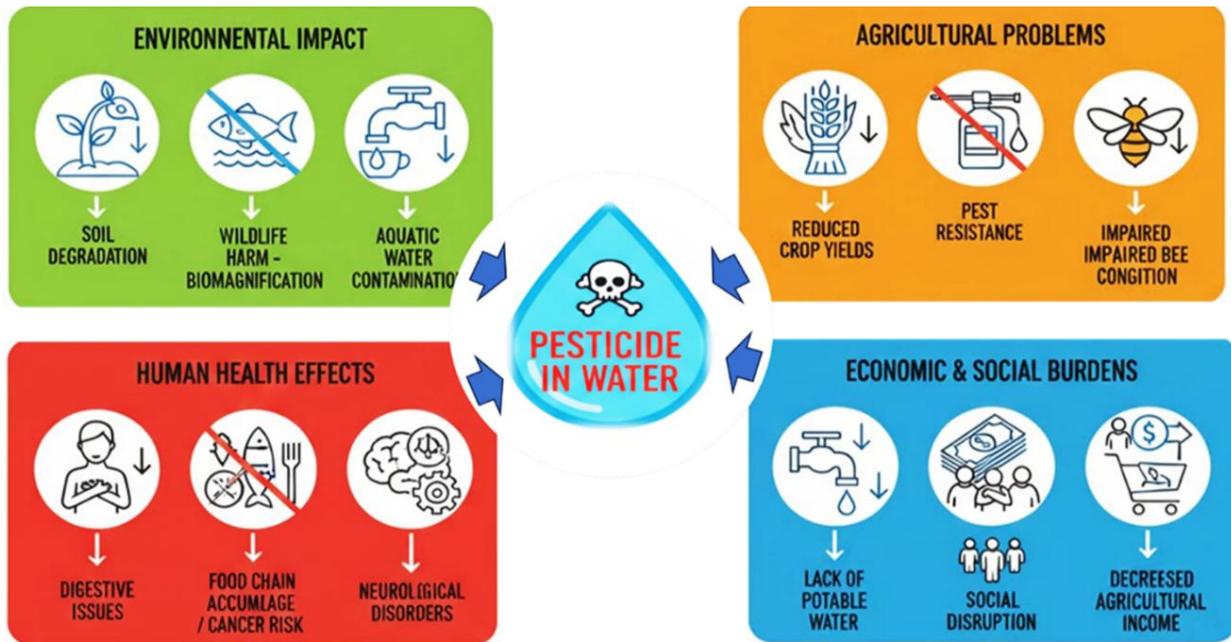

Figure 2. Impacts of pesticide contamination across environmental, agricultural, human health, and socioeconomic sectors.

3.2. Food security and human health implications

As illustrated in **Figure 2,** pesticide contamination of irrigation water and adjacent freshwater bodies not only degrades aquatic ecosystems but also poses direct and indirect risks to human health through the food chain. In Bangladesh, where rice is the primary staple crop and fish constitutes a major protein source (often sourced from rice-field-adjacent ponds, canals, and rivers), pesticide residues can transfer from contaminated water into rice grains and edible fish tissues. Chronic, low-level dietary exposure via frequent consumption of such contaminated rice and fish leads to bioaccumulation in human tissues, potentially resulting in long-term adverse health outcomes, including digestive disorders, neurological impairments, endocrine disruption, reproductive issues, and elevated risks of various cancers [80-82].

Studies in Bangladesh have documented pesticide residues exceeding FAO/WHO maximum residue limits (MRLs) in approximately 25% of rice samples and in fish from rice-paddy ecosystems, amplifying concerns over food safety and chronic toxicity [12, 27]. For instance, organophosphate and carbamate residues in rice and fish have been linked to acetylcholinesterase inhibition, contributing to neurotoxic effects such as dizziness, headaches, memory impairment, and developmental delays in children [56, 81]. Prolonged exposure is also associated with increased carcinogenic potential,

particularly for compounds like certain organochlorines (legacy residues) and organophosphates, with target cancer risk assessments indicating exceedances of acceptable thresholds (e.g., 10^{-6}) in some dietary scenarios [80, 29].

These health risks intersect with broader food security challenges in rice-dependent regions. Excessive pesticide reliance, while aimed at boosting yields to meet national food demands, paradoxically undermines long-term agricultural sustainability through pest resistance, soil degradation, loss of beneficial insects, and reduced ecosystem services (e.g., natural pollination and biological control) [14, 27]. Contaminated irrigation water further compromises rice quality and yield stability, while declining fish catches from polluted water bodies reduce dietary protein diversity and exacerbate malnutrition risks in rural communities [12, 81]. Socioeconomic burdens compound these issues, including elevated healthcare costs from pesticide-related illnesses (acute poisoning in farmers and chronic effects in consumers), reduced agricultural income due to environmental degradation, limited access to safe water, and social disruptions in fishing-dependent households [81, 82].
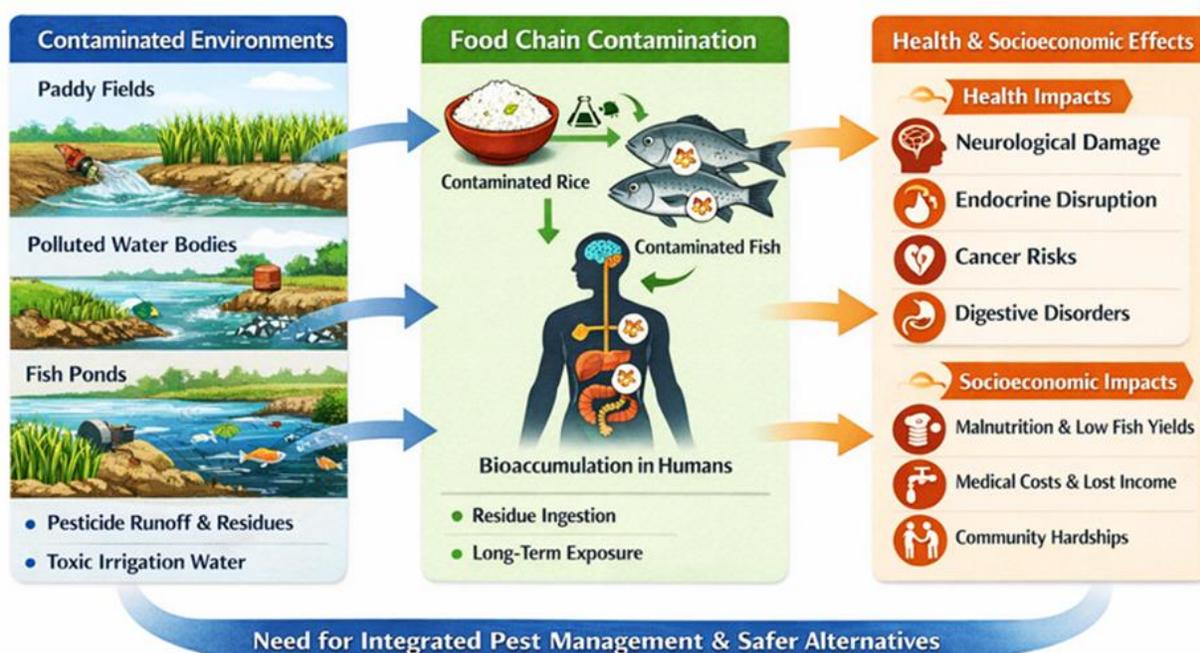

Figure 3. Conceptual diagram illustrating the pathways of pesticide contamination from rice agroecosystems to the food chain and associated implications for food security and human health in Bangladesh. Pesticide runoff from paddy fields contaminates irrigation water and adjacent aquatic systems, leading to residue accumulation in rice and fish.

Overall, the interconnected environmental, health, and socioeconomic consequences of pesticide overuse in rice farming underscore the urgent need for integrated mitigation strategies. These include stricter regulatory enforcement, promotion of integrated pest management (IPM), adoption of safer alternatives, and microbial bioremediation approaches (e.g., endophytic bacteria for in planta pesticide degradation) to reduce residues in rice, drainage water, and aquatic food chains, thereby safeguarding both food security and public health in Bangladesh [26, 73, 74]. **Figure 3** summarizes the pathways linking pesticide use in rice-based agroecosystems to food chain contamination and associated human health and

socioeconomic impacts. Pesticide runoff from paddy fields contaminates surrounding water bodies, facilitating residue accumulation in rice and fish. Subsequent dietary exposure may lead to bioaccumulation in humans and contribute to various health risks, while also affecting fish productivity and rural livelihoods. The diagram highlights the interconnected environmental, food security, and public health implications of pesticide contamination.

4. WATER QUALITY DEGRADATION AND PESTICIDE TRENDS IN ASIA

Frequent use of pesticides, such as rodenticides, bactericides, and fungicides, can severely damage water ecosystems [83, 84]. Pesticides can eradicate beneficial bacteria from the water, Fungicides and bactericides, affect fungi or bacteria and can interfere with the metabolic processes of non-target aquatic microorganisms [85, 86]. This can lead to undesirable effects on microbial communities that are fundamental for biogeochemical cycling [87]. Pesticide residues can also increase levels of ammonium, nitrite, nitrate, and sulfate in aquatic systems, further compromising water quality [88-90]. When pesticides disrupt these microbial communities and their activities, such as denitrification, they directly impair the ecosystem's natural ability to cleanse itself [91, 92]. Inhibited water bodies may suffer from algal blooms, loss of dissolved oxygen, and habitat loss [66]. Pesticide toxicity can decrease dissolved oxygen in water bodies [66], and the nutrient pollution often associated with agricultural runoff can trigger algal blooms and alter species composition, leading to anoxic conditions [93]. The overall impact of pesticides on water quality and aquatic species can also contribute to the loss of aquatic habitats [66, 79]. **Table 2** summarizes the incidence of pesticide use, their environmental persistence, and associated ecological and human health impacts across Asia over the past 20–30 years. Data compiled from FAO databases and national statistics indicate that pesticide consumption in several Asian countries has risen by up to 400%, reflecting growing chemical dependence in modern farming systems [93]. Vietnam, for example, has shown a continuous increase in pesticide use since the late 1980s as part of its agricultural intensification strategy [93]. A similar trend is evident in Bangladesh, where pesticide imports escalated sharply from approximately 3,000 metric tons in 1990 to more than 45,000 metric tons by 2021, paralleling the rapid expansion of rice and vegetable cultivation [94]. Residue surveillance studies further reveal that a substantial proportion of agricultural produce exceeds FAO/WHO maximum residue limits, highlighting emerging food safety concerns [94]. Despite the introduction of regulatory frameworks, the continued use and circulation of highly hazardous pesticides (HHPs), including WHO Class Ia and Ib compounds, remain widespread in many Asian countries. Regulatory reviews and field surveys indicate that weak enforcement mechanisms and policy gaps allow banned or restricted pesticides to persist in local markets, posing long-term environmental and public health risks [95]. The ecological consequences of such practices are well documented [96]. Environmental persistence of pesticides represents another major concern. Monitoring studies from Thailand and China demonstrate that residues of organochlorine and organophosphorus pesticides banned between 1994 and 2000 are still detectable in agricultural soils and rice grains decades later [97]. In Bangladesh, although 21 hazardous pesticides were officially banned between 1996 and 2007, residues continue to be reported in soils, water bodies, and crop samples, reflecting the high stability and slow degradation rates of these compounds [98]. Aquatic contamination has emerged as a dominant pathway of pesticide dissemination. Surface and groundwater monitoring in Japan, Vietnam,

and parts of Europe consistently report pesticide concentrations exceeding drinking water standards, including the European threshold of 0.1 mg/L [99,100]. Field-scale studies in paddy ecosystems indicate that approximately 8–22% of applied herbicides and insecticides are lost through surface runoff, with comparable trends observed across Malaysia and Southeast Asia, underscoring the vulnerability of freshwater ecosystems to agricultural pollution [101, 102].

Table 2. Current trends in pesticide use, environmental persistence, and ecological impacts across Asian agricultural systems.

Study focus	Methodological approach	Key findings	Implications for aquatic environments	Ref.
1.Regional trends in pesticide use in Asia	Historical surveys, FAO statistics, national datasets	Pesticide use increased up to 400% across several Asian countries due to intensified agriculture and export-oriented crop production	Demonstrates rapid chemical intensification and growing environmental pressure on agroecosystems	[29]
2.Pesticide consumption trends in Bangladesh	National agricultural statistics and import records	Imports increased from ~3,000 metric tons (1990) to >50,000 metric tons (2022); residues exceeding FAO/WHO limits detected in ~25% of rice and ~40% of vegetables	Indicates rising chemical dependency and potential food safety concerns	[30]
3.Continued use of highly hazardous pesticides (HHPs)	Regulatory reviews and field surveys	WHO Class Ia/Ib pesticides remain in circulation in several Asian countries despite regulatory bans	Weak enforcement contributes to environmental persistence and human exposure risks	[94]
4.Pest resurgence associated with pesticide overuse	Long-term field observations and ecological studies	Intensive insecticide use linked to outbreaks of brown planthopper (BPH) in rice systems	Disruption of natural predators undermines ecological pest regulation	[95]
5.Environmental persistence of banned pesticides	Residue monitoring and chemical analyses	Organochlorine and organophosphorus pesticides banned in the 1990s remain detectable in soils and rice grains decades later	Legacy contaminants pose long-term threats to soil health and food safety	[96]
6.National pesticide bans in Bangladesh	Policy and regulatory analysis	Bangladesh banned 21 highly hazardous pesticides (1996–2007)	Continued environmental detection indicates slow degradation and persistent contamination	[97]
7.Pesticide contamination of surface and groundwater	Environmental monitoring studies	Residues frequently exceed drinking-water safety thresholds (e.g., 0.1 mg/L standard in Europe)	Demonstrates extensive transport via runoff and leaching into freshwater ecosystems	[98,99]
8.Runoff losses from paddy fields	Field-scale pesticide transport measurements	Approximately 8–22% of applied pesticides lost via runoff in paddy systems	Paddy agriculture is a significant contributor to freshwater pesticide pollution	[100,101]
9.Food contamination and dietary exposure	Crop residue analyses	Organophosphate and carbamate residues detected in harvested rice grains	Indicates transfer of pesticide residues from soil and water into the human food chain	[99,103]
10. Occupational exposure among farmers	Farmer surveys and PPE assessments	Pesticide application rates 1.2-11x higher than recommended with low PPE usage	Occupational health risks and need for training and safer pest management strategies	[100, 104]

5. BIOREMEDIATION OF PESTICIDE CONTAMINATION

5.1. Effectiveness and mechanisms

Bioremediation offers a sustainable, cost-effective, and environmentally benign strategy for mitigating pesticide residues leaching from rice paddies into freshwater systems [105]. Microorganisms including bacteria, fungi, cyanobacteria, and algae naturally abundant in paddy soils and floodwater can metabolize a wide range of xenobiotics, transforming highly toxic parent compounds into less harmful or non-toxic metabolites through enzymatic pathways such as hydrolysis, oxidation, dechlorination, and conjugation [106, 107]. The following section and **Figure 4**, illustrated overall mechanism of bioremediation of pesticide residues by endophytic, rhizospheric bacteria and others microorganisms.

5.1.1. Bioaugmentation

Bioaugmentation involves the deliberate introduction of selected pesticide-degrading microbial strains or consortia into contaminated paddy soils, floodwater, or engineered systems (e.g., biobeds) to enhance degradation rates [106, 108]. Indigenous or enriched isolates, particularly from genera *Acinetobacter*, *Pseudomonas*, *Bacillus*, and *Klebsiella*, have demonstrated high efficacy against organophosphates (e.g., chlorpyrifos, methyl parathion, diazinon) and carbamates (e.g., carbofuran) under flooded conditions [109-112]. These consortia utilize organophosphorus hydrolases (OPH/Opd), carboxylesterases, and cytochrome P450-mediated oxidation to cleave P–O, C–O, or C–S bonds, often achieving >80–90% degradation within days to weeks [113-115]. Field-relevant applications include direct inoculation into paddy water, seed coating, or integration into constructed wetlands and biobed systems, which intercept drainage and reduce downstream aquatic exposure [108].

5.1.2. Biostimulation

Biostimulation enhances the activity of native pesticide-degrading populations by amending soils or floodwater with low-cost organic substrates (e.g., compost, biochar, manure) or adjusting nutrient ratios (C:N:P) to favor degraders [116, 117]. In rice fields, this approach exploits naturally tolerant microbial biofilms and consortia that proliferate under alternating redox conditions [118]. Organic amendments stimulate cometabolic degradation and increase the abundance of key taxa (*Pseudomonas*, *Bacillus*, *Enterobacter*), leading to accelerated breakdown of residual organophosphates and pyrethroids without external strain introduction [117, 119].

5.1.3. Role of specific microbial groups in pesticide degradation

Paddy ecosystems, characterized by periodic flooding and redox fluctuations, support diverse microbial communities adapted to anaerobic and aerobic niches [118].

Bacteria: Aerobic genera (*Pseudomonas nitroreducens*, *Bacillus subtilis*, *Acinetobacter*, *Klebsiella*) dominate organophosphate and carbamate degradation via phosphotriesterases, esterases, and oxidative pathways [110, 113]. Anaerobic conditions favor reductive dechlorination and sulfur metabolism by taxa such as *Enterobacter* and *Alcaligenes faecalis* [112, 115].

Fungi and Actinomycetes: Ligninolytic fungi (*Phanerochaete chrysosporium*) and actinomycetes (*Rhodococcus*, *Streptomyces*) utilize extracellular peroxidases, laccases, and monooxygenases to transform recalcitrant organochlorines, triazines, and pyrethroids into degradable intermediates [107, 120, 121].

Cyanobacteria and Algae: Phototrophic organisms (*Anabaena oryzae*, *Nostoc muscorum*) contribute to pesticide uptake, adsorption, and metabolic detoxification in floodwater, although many are sensitive to herbicides that inhibit photosynthesis [122, 123].
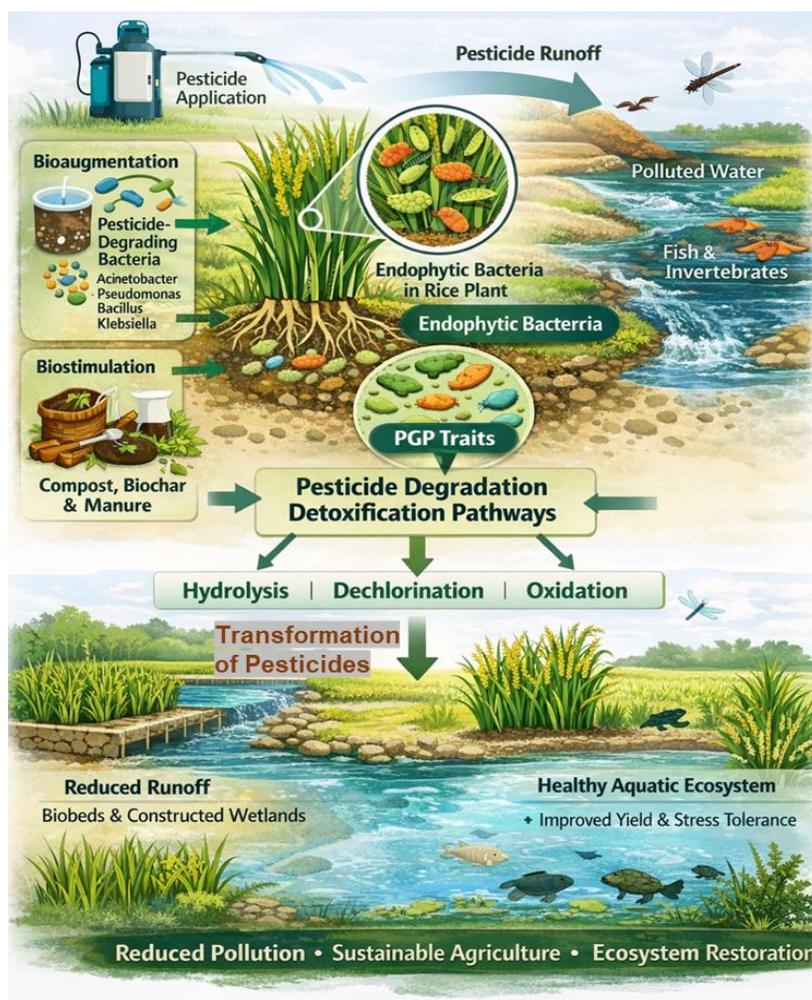

Figure 4. Bioremediation of pesticide runoff by endophytic bacteria in rice agroecosystems. Endophytic and rhizospheric bacteria colonizing rice roots and tissues contribute to bioremediation. These microorganisms produce key degradative enzymes such as organophosphorus hydrolases (OPH), carboxylesterases, and cytochrome P450 monooxygenases that catalyze hydrolysis, oxidation, and dechlorination reactions, transforming toxic pesticide molecules into less harmful or non-toxic metabolites. In addition to detoxification, many endophytic bacteria exhibit plant growth–promoting (PGP) traits, including nitrogen fixation and indole-3-acetic acid (IAA) production, which enhance rice growth, stress tolerance, lower aquatic toxicity, and support ecosystem restoration.

5.2. Prospects for Sustainable Agroecosystems and Biodiversity Restoration Using Pesticide-Degrading Bacteria

Recent isolation and characterization of chlorpyrifos-mineralizing endophytic consortia from rice tissues (roots, stems, leaves) have revealed strains with dual functionality: efficient pesticide degradation and plant growth promotion (PGP) traits, including nitrogen fixation, phosphate solubilization, indole-3-acetic acid production, and ACC deaminase activity [109,124]. These consortia significantly reduce in planta residues and support rice growth under reduced fertilizer regimes [115]. Complementary studies confirm that rice endophytes (*Pseudomonas*, *Bacillus*, *Klebsiella sp.* HSTU-F2D4R, *Alcaligenes faecalis*, *Metabacillus indicus*) mineralize organophosphates while enhancing yield and stress tolerance (e.g., salinity) via hormone modulation, antioxidant upregulation, and ion homeostasis [109, 125].

Table 3. Bacterial genera involved in pesticide biodegradation in agricultural ecosystems, their target pesticides, degradation mechanisms, and contributions to agroecosystem sustainability and biodiversity restoration.

Bacterial genus /species	Major pesticide(s) degraded	Crop / agroecosystem relevance	Degradation mechanisms	Role in sustainability & biodiversity restoration	Ref.
Pseudomonas putida	Parathion, chlorpyrifos, carbofuran	Vegetables, cereals	Organophosphorus hydrolase, esterases	Reduces residue toxicity; improves microbial diversity	[109,115, 124]
Pseudomonas fluorescens	Endosulfan, chlorpyrifos	Rice, vegetables	Oxidation, hydrolysis	Enhances rhizosphere stability; biocontrol synergy	[110]
Bacillus subtilis	Chlorpyrifos, diazinon, endosulfan, λ-cyhalothrin	Field crops, horticulture	Phosphotriesterase, hydrolases	Improves soil fertility and plant vigor	[111,126, 129]
Bacillus cereus	Carbofuran, malathion, β Cypermethrin, deltamethrin, imidacloprid, fipronil, sulfosulfuron, chlorpyrifos	Vegetable crops	Carbamate hydrolase	Detoxification of soil and groundwater	[127,128]
Acinetobacter sp.	Diazinon, carbaryl, profenofos	Rice-based systems	Carboxylesterase, oxidoreductases	Rhizosphere restoration; reduced ecotoxicity	[123]
Enterobacter cloacae	Chlorpyrifos, cypermethrin	Cereals, vegetables	Esterase, hydrolase	Improves rhizosphere resilience	[26,123, 131]
Sphingobium japonicum	Hexachlorocyclohexane (HCH)	Legacy-polluted farmlands	Lin pathway enzymes	Reclaims historically polluted soils	[132]
Enterobacter asburiae	Imidacloprid, chlorpyrifos	Vegetable ecosystems	Oxidative degradation	Supports beneficial insect recovery	[26]
Cupriavidus necator	2,4-D, organophosphates	Cropping systems	Oxygenase-mediated degradation	Improves ecosystem resilience	[133]
Rhodococcus erythropolis	Pyrethroids, triazines, Cypermethrin, pretilachlor	Broad agroecosystems	Monooxygenases, hydrolases	Detoxifies persistent residues	[134]
Stenotrophomonas maltophilia	Chlorpyrifos, endosulfan	Rice ecosystems	Esterase, dechlorination	Supports aquatic biodiversity recovery	[130]
Paenibacillus polymyxa	Chlorpyrifos (co-metabolism)	Integrated farming systems	Co-metabolic degradation	Plant growth promotion remediation	[135]
Azospirillum brasilense	Organophosphate residues (low-level)	Stress-prone soils	Co-metabolism, PGPR traits	Enhances crop tolerance and biodiversity	[112]

Table 3 describing the phylogenetic and functional diversity of pesticide-degrading bacteria relevant to paddy agroecosystems. Dominant genera (*Pseudomonas*, *Bacillus*, *Acinetobacter*, *Sphingomonas*, *Enterobacter*, *Klebsiella*,

Alcaligenes faecalis) exhibit broad-spectrum activity against organophosphates (chlorpyrifos, diazinon), carbamates (carbofuran), pyrethroids (cypermethrin), and neonicotinoids (imidacloprid) through hydrolytic enzymes (Opd, OPH, carboxylesterases), oxidative pathways (monooxygenases, P450s), and dechlorination [126-141]. Many also display PGP traits and salinity tolerance, enabling synergistic remediation and productivity benefits [139, 140, 142]. By facilitating in planta detoxification, these endophytes intercept residues before runoff, substantially reducing ecotoxicological pressure on downstream aquatic communities (fish, invertebrates, plankton) and promoting biodiversity recovery in rice-wetland interfaces [143, 144].

6. CONCLUSION

Pesticide residues from rice paddies posed a great threat to the adjacent aquatic ecosystems. Sometimes the effect is so severe that it's escalating environmental concern. While these toxic chemicals are the leading cause of immediate mortality and environmental issues in non-target aquatic life (like fish and invertebrates), they are also persistent pollutants that are destroying the food chain, jeopardizing the ecosystems, and compromising food safety. To mitigate this lethal environmental contamination, an optimal mechanism would be bioremediation. This biologically driven solution represents the most effective, economical, and sustainable approach by utilizing the advanced catabolic machinery of environmental microbes (bacteria and fungi). This technique can surely accelerate the mineralization of persistent residues by implementing enhanced strategies like bio stimulation (boosting native microbe activity) and bioaugmentation (introducing highly efficient degrader strains). In conclusion, the large-scale strategic adoption of bioremediation is not just an option but a vital step for saving the environment. It offers the best pathways to successfully degrade these toxic residues, thus securing the long-term health, biodiversity, and ecological productivity of freshwater resources interwoven with rice cultivation.

Future Directions

In the context of restoration ecology and sustainable agriculture, several key research and development priorities are recommended:

i. Field trials of endophytic bacterial formulations should be conducted to rigorously evaluate their real-world efficacy in reducing pesticide residues in soil, plant tissues, and drainage water—an essential step in translating laboratory findings into agricultural practice [145].

ii. In this regard, formulations of endophytic strains possessing both PGP traits and biodegradation capacities for pesticides (e.g., chlorpyrifos, diazinon) have been developed using newly designed growth chambers capable of producing biofertilizer formulations within two days, suitable for efficient rice field application.

iii. Monitoring downstream aquatic ecosystems (e.g., canals, ditches) is crucial for assessing pesticide load reduction and tracking biodiversity recovery following bioinoculant application, as pesticide runoff has been shown to significantly affect aquatic ecosystems [146].

iv. Molecular and omics-level analyses, including metagenomics and transcriptomics, are needed to elucidate interactions between introduced endophytes, native microbial communities, and plant metabolism, ultimately providing insights into long-term ecosystem resilience and functional stability.

v. Development of robust bioformulation technologies is essential to ensure the stable colonization and persistence of beneficial endophytes across various growth stages and environmental conditions. Such technologies will help protect endophytes from environmental stressors and enable sustained biodegradative and growth-promoting activity in the field. By amplifying and translating our research findings into an ecosystem-level remediation strategy, the potential of endophytic bacteria can be effectively harnessed not only for enhancing crop productivity and soil health but also for achieving comprehensive environmental protection and biodiversity restoration in rice-based agroecosystems.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ETHICS STATEMENT

This study did not involve any experiments on human participants or animals; therefore, formal written informed consent was not required by the Institutional Review Board. All figures in this study were created; therefore, no permission for reuse is required for any figure presented herein.

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