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Investigation and comprehensive study on environmental ecosystem and human health impacts of chemical pesticide usage in India

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Abstract
This manuscript critically examines the multifaceted impacts of chemical pesticides on environmental ecosystems and human health, highlighting the urgent need for sustainable pest management practices in India. The widespread use of pesticides, such as organochlorine compounds (DDT, endrin) known for their persistence and bioaccumulation, poses significant risks to biodiversity, water quality, and food safety. By accumulating in the food chain, these substances threaten higher trophic levels and amplify the potential for adverse health outcomes, including acute poisoning, cancer and neurological disorders. Specific examples such as glyphosate and atrazine illustrate the pervasive nature of pesticide contamination in various environments. Key findings include the association of pesticide exposure with increased risks of lymphoma and Parkinson's disease, and the development of antibiotic resistance in microbial communities. The investigation mainly discusses potential remediation methods, including physicochemical techniques like photodegradation and advanced oxidation processes, as well as bioremediation strategies involving microbial degradation. Photodegradation rates are influenced by environmental factors such as sunlight intensity, soil properties, and organic matter content. Bioremediation using specific microbial consortia has shown promise in degrading persistent pesticides, enhancing soil recovery. Emphasizing the importance of integrated pest management (IPM), enhanced regulatory frameworks and user education, this paper advocates for a strategic shift towards practices that minimize environmental harm and safeguard human health. Implementing these measures can significantly contribute to the advancement of sustainable agriculture by reducing pesticide reliance and promoting ecological balance.

Keywords: Environmental, ecosystem, human health, chemical pesticides India

Introduction

The deployment of pesticides in modern agriculture is a doubleedged sword, enhancing agricultural productivity and food security while posing significant risks to environmental and human health. Pesticides are defined as chemical compounds used to manage and deter the population of pests, which are any plants, animals, or microorganisms that affect food, health, or comfort. The Environmental Protection Agency (EPA) further defines pesticides as substances that are applied to manage or eliminate harmful pests such as weeds, diseases that affect plants, and other species. Pesticides are also used to control other living things, such as nematodes, arthropods such as insects and vertebrates, which can ruin our food sources and lead to various health problems. In sum, pesticides are chemicals that are applied to a wide variety of crops to protect them from insects, weeds, and pests, thereby nourishing and improving agricultural productivity and efficiency.

Pesticides are pivotal in curtailing significant agricultural losses dover 45 % annually due to pest infestations [1], and in safeguarding against vector borne diseases. Utilized in various domains beyond agriculture, such as in consumer products, pesticides are classified based on application and chemical properties, targeting specific pests to enhance productivity and ensure food security effectively and affordably [2]. Pesticides, integral to modern agriculture and pest management, are typically classified into four main categories based on their chemical composition and mode of action: organochlorines, organophosphates, carbamates, and pyrethroids [3]. Organochlorines are recognized for their environmental persistence and include potent chemicals like lindane, aldrin, dieldrin, hexachlorobenzene, chlorinated derivatives of DDT and other chlorinated hydrocarbons. These compounds are highly stable, leading to accumulation in the environment and biological magnification through food chains, raising concerns about their long term ecological and health impacts. On the other hand, organophosphates form a broad and significant portion of the global pesticide market, accounting for about 36 % of sales [3]. They function by inhibiting acetylcholinesterase, causing over accumulation of acetylcholine and disrupting the nervous system of pests. Although0 they are favoured for their effectiveness and relatively lower environmental persiste compared to organo chlorines, the acute toxicity of organophosphates to non-target species, including humans, necessitates cautious application. Car bamates, which also inhibit acetylcholinesterase but with a diverse range of chemical structures, offer versatility in pest control applications but share similar toxicity concerns. Meanwhile, pyrethroids, synthetic versions of natural pyrethrins, are used for their insecticidal efficiency and lower mammalian toxicity, making them a preferred choice in various settings. Together, these categories encompass the spectrum of pesticide chemistry, each with distinct properties, applications, and implications for environmental health and safety. More importantly, despite their undeniable benefits in reducing crop loss and disease vectors, the extensive application of pesticides raises concerns over environmental harm, highlighting the urgent need for balancing agricultural efficiency with ecological and health considerations.

Materials and method

The utilization of chemical pesticides has been pivotal in advancing crop quality and yield, significantly bolstering food security amidst a burgeoning global population. The use of pesticides dates back to ancient civilizations, where natural substances such as sulfur and mercury were employed to control pests. The modern era of pesticide use began in the 20th century with the development of synthetic chemicals like DDT, which was extensively used during World War II to combat malaria and typhus [4]. For instance, the evolution from the first synthetic pesticide, Paris Green, to the widespread adoption of DDT post-1945, illustrates the technological strides in pest management [5]. The publication of Rachel Carson's Silent Spring in 1962 marked a pivotal moment, highlighting the adverse effects of pesticide use and leading to increased regulation and the eventual banning of DDT in many countries. Since then, pesticide development has continued to evolve, with a growing emphasis on safer and more sustainable alternatives [6].

Global pesticide usage has continued to rise over recent years, driven by the intensification of agricultural practices to meet the growing food demand. According to the Food and Agriculture Organization (FAO), pesticide use worldwide reached approximately 4.1 million tons in 2019, reflecting a steady increase over the past decade. This trend is particularly pronounced in developing countries where agricultural expansion and increased pest pressures necessitate higher pesticide applications. In Africa however, despite a reliance on agriculture, pesticide consumption remains the lowest globally, a scenario exacerbated by reduced Government oversight and the emergence of unofficial pesticide routes, leading to a significant spike in imports between 2000 and 2010[7]. Asia experiences rapid growth in pesticide usage, with countries like India becoming major producers and consumers, although India has recently sought to stabilize usage rates [8]. India's pesticide consumption has been substantial, with around 1.8 million tons used in 2018, although recent policies aim to reduce reliance on chemical pesticides through Integrated Pest Management (IPM) practices [9]. The United States is a significant user of pesticides, primarily herbicides like glyphosate, due to its extensive cultivation of genetically modified (GM) crops. The Environmental Protection Agency (EPA) reported that U.S. agricultural pesticide use was approximately 408 million kilograms in 2016, with herbicides accounting for the majority. The European Union has implemented stringent regulations to control pesticide use, focusing on reducing risks to human health and the environment. Despite these regulations, pesticide usage remains high in certain countries, such as Spain and Italy, due to intensive farming practices. Brazil is one of the largest consumers of pesticides in Latin America, driven by its extensive agricultural sector, particularly soybean and sugarcane cultivation. Pesticide use in Brazil reached around 550,000 tonnes in 2018, raising concerns about environmental contamination and health risks [10]. The increasing global pesticide usage has significant implications for both environmental sustainability and human health. The widespread application of pesticides leads to contamination of soil, water, and air, impacting biodiversity and ecosystem services. Additionally, the persistence of pesticide residues in food and the environment poses chronic health risks, including cancer, endocrine disruption, and neurological disorders. In contrast, Australia's battle against invasive weeds has heightened reliance on herbicides, while Europe's increase in pesticide use has raised environmental concerns, prompting varied regulatory responses across countries [11, 12]. The United States, grappling with high labor costs and disease vectors, employs herbicides and insecticides extensively, with regulatory efforts aimed at minimizing environmental impact [13]. Globally, pesticide application continues to rise, driven by the imperative to feed an expanding population. The distribution of pesticide use reflects regional disparities in agricultural practices, economic conditions, and environmental policies, with Asia and the Americas leading in consumption. Efforts to optimize pesticide use while mitigating adverse effects underscore the complex interplay between agricultural productivity and sustainable practices [14]. The extensive use of pesticides in the United States, particularly in the Midwest agricultural regions, has had profound impacts on both agriculture and the environment. The widespread application of herbicides like glyphosate has led to the emergence of herbicide-resistant weeds, which pose significant challenges to crop production. Additionally, the runoff of pesticides into water bodies has contaminated drinking water sources and affected aquatic ecosystems. A study found that atrazine and its metabolites were frequently detected in streams and rivers, leading to ecological risks for aquatic organisms [15]. A comprehensive review of the impacts of agricultural pesticides in the United States found that pesticides pose a serious threat to soil invertebrates and the essential ecosystem services that they provide [16].

In India, the intensive use of pesticides in agricultural practices has led to significant environmental contamination and health concerns. Pesticides such as organophosphates and pyrethroids including fenpropidin, cypermethrin, deltamethrin and cyhalothrin have been found in high concentrations in water and soil samples, posing risks to both human health and biodiversity. Moreover, the persistence of these chemicals in the environment has resulted in long-term soil degradation and reduced soil fertility, impacting agricultural productivity. Another report from four coastal cities of Shandong Province analyzing 192 seafood samples detected fenpropathrin, cypermethrin and deltamethrin in seafood [17]. The results indicated the monitoring of pyrethroid residues in seafood is worthy of continuous attention to ensure food safety. Every year, India intensifies its activity in agriculture and, as a result, it has become one of the biggest consumers of pesticides in the world. In Brazil, the use of pesticides has significantly impacted the Amazon rainforest and surrounding agricultural areas. The widespread application of pesticides in soybean and sugarcane plantations has led to the contamination of soil and water resources, threatening the biodiversity of the Amazon basin. Pesticides such as glyphosate and paraquat have been detected in significant concentrations, contributing to the decline of aquatic species and impacting indigenous communities who rely on these ecosystems [18]. Furthermore, the drift of pesticides from agricultural areas into protected forest regions poses additional threats to the delicate balance of these ecosystems. Key findings include high concentrations of malathion, carbendazim, and chlorpyrifos, particularly in particulate forms, posing ecotoxicological risks to freshwater invertebrates. The study emphasizes the need for continued monitoring of these pesticides, especially during the rainy season and after heavy rainfall, to assess their environmental impact in Northern India [19] showed that the use of pesticides in rural catchments leads to the contamination of surrounding water resources. They described that 17 out of 18 water samples from the South region were contaminated with at least one pesticide like atrazine, simazine, propoxur, imidacloprid, carbendazim, azoxystrobin, thiamethoxam, fipronil, propiconazole, tebuconazole, and carbofuran, the water that irrigate soybean, corn, and winter cereals crops and grassland forage production region.

Results and discussion

Effect of chemical pesticide on environmental and human health: The extensive use of chemical pesticides in agriculture and other sectors poses significant environmental and human health risks, primarily due to their persistent nature and bioaccumulative potential. These substances, designed to eliminate pests, inadvertently harm nontarget species, contaminate ecosystems, and degrade the quality of air, water, and soil, leading to adverse effects on wildlife, humans, and food safety.

Effect of pesticides on soil: Pesticides significantly accumulate in soil, disrupting its physicochemical and biological characteristics, which in turn, harms flora and fauna and undermines soil health crucial for crop quality and ecosystem services. The contamination extends to water bodies, with agricultural runoff and industrial effluent introducing these chemicals into rivers and groundwater, thus impairing water quality and posing risks to human health through exposure and the food chain [20]. The ecological toxicity of chemical pesticides, measured by indices like the Environmental Impact Quotient and the Environmental Risk Index, underscores the need for cautious use, as compounds such as Carbofuran and Chlorpyrifos exhibit high environmental risk indices. Furthermore, the detrimental impacts on soil ecosystems and biodiversity, including the inhibition of natural nitrogen fixation processes and the harm to beneficial insects like bees, highlight the broader ecological imbalances caused by pesticide use [21]. Pesticides have significant longterm effects on soil health, impacting its microbial diversity, fertility and overall ecosystem functions. Continuous pesticide use leads to a reduction in soil microbial diversity and biomass, which are crucial for nutrient cycling and organic matter decomposition. For instance, persistent organochlorine pesticides (OCPs) can remain in the soil for decades, continually affecting soil biota and potentially leading to the development of pesticide resistant microbial populations [22]. However, research indicates that soil can recover from pesticide contamination once the use of these chemicals is reduced or stopped. It has been found that after the cessation of pesticide. The diverse effects of chemical pesticides on different environmental components pesticides influence water quality by leaving residues in drinking water and reducing dissolved oxygen levels, affect land by disturbing natural flora and soil fertility, impact the atmosphere through volatile aerosols contributing to climate change, and disrupt entire ecosystems by affecting the survival and health of fauna and flora, ultimately leading to ecological imbalance and degradation. Application, the microbial community structure began to show signs of recovery within a few months, with a noticeable increase in microbial biomass and diversity [23]. Additionally, the natural degradation processes, such as photolysis and microbial degradation, can gradually reduce pesticide residues in the soil over time. The implementation of organic farming practices and the use of bioremediation techniques can further enhance soil recovery, promoting a more rapid return to a healthy balanced ecosystem. Pesticides impact soil health and microbial communities through several mechanisms, including direct toxicity, alterations in microbial community composition and disruption of essential soil processes. The longterm application of pesticides can lead to a decline in microbial diversity and biomass, affecting the soil's ecological balance and its ability to perform critical functions. Furthermore, adopting organic farming practices and utilizing bioremediation techniques can enhance soil recovery. Organic amendments, such as compost and biochar, can improve soil structure, increase microbial activity and accelerate the degradation of pesticide residues. Additionally, introducing specific microbial consortia that degrade pesticides can further support the detoxification and rehabilitation of contaminated soils. Overall, soil contamination with pesticides disrupts microbial populations, enzyme activities and nitrogen transformation processes, adversely affecting soil health and agricultural productivity [24]. The persistence of pesticides in soil can lead to longterm ecological and health risks, emphasizing the need for strategies to mitigate their impact and promote sustainable agricultural practices [25].

Effect of pesticides on water: Pesticides, essential for controlling pests and bacteria, pose risks to water bodies when mismanaged or overused, contaminating ecosystems and entering the food chain [26]. Events like flooding and excessive irrigation facilitate the mixing of chemical residues with river water, introducing toxic compounds into environments and the food supply [27]. Pesticides not absorbed by plants persist in the soil into other compounds, with soluble forms being transported to groundwater during precipitation and insoluble forms accumulating in the topsoil, leading to contamination of surface waters. This contamination adversely affects aquatic life and drinking water sources. The disruption of aquatic ecosystems, particularly the impact on open water fish species and primary producers like phytoplanktons, highlights the need for careful pesticide management to protect water quality [28]. Ensuring the safety of drinking water is a critical public health priority and various regulatory organizations have established acceptable limits for pesticide residues to protect human health. The United States Environmental Protection Agency (EPA) sets Maximum Contaminant Levels (MCLs) for various pesticides, such as atrazine, which has an MCL of 0.003 mg/L (3 mg/L) to prevent cardiovascular and reproductive effects. Similarly, the European Union's Drinking Water Directive mandates a limit of 0.1 mg/L for any single pesticide and 0.5 mg/L for the total concentration of all pesticides detected, reflecting stringent precautionary measures. The World Health Organization (WHO) provides guideline values, such as 0.9 mg/L (900 mg/L) for glyphosate, based on healthbased targets to ensure safe drinking water. In Australia, the National Health and Medical Research Council (NHMRC) sets limits like 0.02 mg/L (20 mg/L) for simazine, addressing risks such as endocrine disruption. Health Canada specifies Maximum

Acceptable Concentrations (MACs) for pesticides, with 0.1 mg/L (100 mg/L) for 2,4-dichlorophenoxyacetic acid to protect against longterm health risks. These standards underscore the global commitment to safeguarding drinking water quality and highlight the need for continuous monitoring and updates as new scientific evidence and pesticide usage patterns evolve.

Effect of pesticides on the microbial community: The influence of pesticides on microorganisms is multifaceted, affecting microbial communities in both soil and water. These organisms play a crucial role in degrading pesticides, but their effectiveness can be hindered by the chemicals' toxicity [29]. Pesticides can drastically alter the physical, chemical, and biological properties of habitats, proving hazardous to soil dwelling organ-isms and affecting microbial growth and enzymatic activities. The presence of pesticides, even in low concentrations, disrupts soil microbial communities, impacts key nitrogen cycle processes, and can reduce soil fertility by killing beneficial microbes [30]. Research has shown varied effects on microbial quantity, biomass, diversity and enzyme activity, with certain pesticides decreasing bacterial numbers and microbial biomass, thereby potentially affecting biogeochemical processes [31]. The impact on soil biological processes such as nitrification, denitrification, and ammonification furtherillustrates the complex interactions between pesticides and soil health, emphasizing the importance of understanding and mitigating these effects for sustainable agricultural practices. Pesticides can be toxic to a broad range of soil microorganisms, including bacteria, fungi and actinomycetes. Continuous pesticide application can select for resistant microbial strains while reducing the abundance of sensitive species. This leads to an imbalanced microbial community structure, where beneficial microbes, such as nitrogen fixing bacteria and mycorrhizal fungi, are often suppressed [32]. A study highlighted that glyphosate application altered the soil bacterial community by reducing the relative abundance of beneficial genera, such as Pseudomonas and Bacillus. Further, pesticides can interfere with essential soil processes like nitrogen fixation, organic matter decomposition, and nutrient cycling. For instance, atrazine, a commonly used herbicide, has been shown to inhibit nitrification by affecting ammoniaoxidizing bacteria and archaea, leading to reduced nitrogen availability for plants [33]. Once pesticide use is reduced or stopped, the soil ecosystem has the potential to recover. The resilience of soil microbial communities depends on various factors, including the soil type, the history of pesticide application, and the environmental conditions. These changes are likely due to the reduction of chemical stressors, allowing microbial communities to recover and thrive, enhancing soil's natural functions and fertility. Further, pesticides are known to contribute to the development and spread of antibiotic resistance in microbial communities through several mechanisms. This emerging concern has significant implications for public health and environmental sustainability. Recent research has provided substantial evidence linking pesticide use to the proliferation of antibiotic resistance. Study demonstrated that exposure to common agricultural pesticides, such as carbendazim, azoxystrobin, and chlorothalonil, increased the abundance of ARGs in greenhouse soils. Another study [34] found that application of pesticides such as atrazine, carbaryl and 2,4-D in agricultural soils led to a significant increase in the diversity and abundance of ARGs, suggesting that pesticides can act as a selective agent for antibiotic resistance. Pesticides can coselect for antibiotic resistant bacteria by applying selective pressure that promotes the survival of resistant strains. Coselection occurs when genes conferring resistance to both pesticides and antibiotics are located on the same genetic elements, such as plasmids or transposons. Rivers and streams adjacent to agricultural fields with heavy pesticide use showed elevated concentrations of ARGs compared to areas with minimal pesticide application. These findings highlight the potential for pesticides to contribute to the environmental reservoir of antibiotic resistance. Cross resistance occurs when a single resistance mechanism provides protection against both pesticides and antibiotics. For instance, efflux pumps, which bacteria use to expel toxic substances, can be upregulated in response to pesticide exposure, providing resistance to both pesticides and antibiotics [35]. Further, pesticides can disrupt the balance of microbial communities, leading to a reduction in susceptible populations and an increase in resistant strains. This shift in community structure can create ecological niches that favor the proliferation of antibiotic resistant bacteria. The role of pesticides in promoting antibiotic resistance is an emerging environmental and public health issue. Through mechanisms such as coselection, horizontal gene transfer, and alteration of microbial community structures, pesticides can enhance the spread and persistence of antibiotic resistant bacteria. Addressing this issue requires integrated management practices that consider the ecological impacts of both pesticide and antibiotic use.

Effect of pesticides on human health: The widespread use of pesticides has led to significant human health concerns. Infants and children are especially vulnerable to their adverse effects due to their developing bodies and the potential for both acute and chronic exposure consequences. It has been estimated that about 385 million cases of unintentional, acute pesticide poisoning occur annually worldwide including around 11,000 fatalities, and based on a worldwide farming population, about 44 % of farmers are poisoned by pesticides every year [36]. Organochlorines (OCs) and organophosphates (OPs), known for their high toxicity, affect the nervous system and can lead to severe health issues, including cancer and damage to multiple organs. Exposure routes include dietary intake and environmental contact, posing risks of cytotoxic effects and various organ damages [37]. Carbamates, considered less hazardous, are linked to respiratory conditions and developmental issues, while pyrethrins and pyrethroids, though less persistent, can lead to systemic and even fatal effects [38].

Cancer: A strong correlation exists between pesticide exposure and an increased risk of various cancers, supported by numerous studies indicating heightened risks of leukemia, multiple myeloma, and other cancers among those exposed to pesticides [39].

Diabetes: An alarming increase in diabetes prevalence has been linked to pesticide exposure, with epidemiological studies pointing to a higher risk associated with organochlorine and organophosphate pesticides [40].

Respiratory disorders: Pesticide exposure is linked to various respiratory issues among farm workers, including asthma and chronic lung diseases, with several studies indicating an increased risk from regular pesticide interaction [41].

Neurological disorders: Exposure to pesticides has been implicated in the development of neurological disorders like Parkinson's and Alzheimer's disease. Research shows a clear association between pesticide exposure and an increased risk of these conditions [42].

Reproductive syndromes: Exposure to pesticides can adversely affect fertility in both men and women, disrupting hormonal signaling and leading to reduced semen quality, increased risk of neural tube defects, and other reproductive issues [43]. These findings underscore the need for stringent regulatory measures and greater awareness to mitigate the health risks associated with pesticide exposure, ensuring safer use practices and reducing the overall burden of disease attributable to these chemicals. Further, the environmental and health impacts of chemical pesticides necessitate a more sustainable pest control methods to protect human health and preserve environmental integrity.

Impacts of Pesticide Toxicity and its environmental and human health: The pervasive use of pesticides poses significant risks to aquatic systems, terrestrial habitats, and atmospheric quality. Due to the interconnected nature of these ecosystems, contamination in one area often precipitates widespread ecological disturbances. Pesticides are primarily dispersed through water runoff, soil leaching, and atmospheric transport. These pathways facilitate not only local distribution but also contribute to the global spread and deposition of these chemicals. Such dynamics underscore the urgent need to understand and mitigate the environmental impacts of pesticide use. In Ganga River, located within the Haridwar District prominent rice cultivation area usage is extensive to increase crop yields and minimize damage [44]. This extensive application has led to significant environmental repercussions, particularly for the Yamuna River, a critical source of drinking and irrigation water. According to a recent study, eleven pesticides were detected in the river with concentrations ranging from 2.7 ng/L to 4493.1 ng/L. At the Water Treatment Plant, four pesticides were found in the treated water, with concentrations between 5.2 ng/L and 56.6 ng/L. Notably, imidacloprid and tebuconazole were frequently detected, reaching highest levels of 57.7 ng/L downstream and 512.1 ng/L midstream, respectively. The Ganga River basin, traversing Guangdongdone of China's most developed provincesdexemplifies the environmental impact of mixed land uses, including agriculture. Out of three tested pesticides, isoprothiolane showed the highest concentration at 279.51 ng/L. Approximately 35,320 kg of isoprothiolane was used in the area, highlighting its prevalent application to combat diseases in paddy rice [45]. The Ganga River's water quality has deteriorated significantly due to combined pressures from agricultural runoff and urban sewage, which denotes compromised ecological functions and services. A comprehensive analysis identified 18 pesticides in every water sample, with concentrations ranging from below the limit of quantification (LOQ) for buprofezin, up to 607.30 ng/L for carbendazimda broad-spectrum fungicide extensively used across various crops [46]. Spatial and temporal studies conducted across five zones of the Ganga River in India identified significant residues of banned pesticides, influenced by agricultural and industrial activities. The post-monsoon period showed particularly high concentrations, with g-HCH peaking at 1722 ng/L. Other detected pesticides included a-HCH (432 ng/L), b-HCH (24 ng/L), d-HCH (88 ng/L), and various forms of DDT and endosulfan, reflecting persistent environmental contamination despite their banned status. In one of recent studied conducted and they found in the freshwater ecosystems of Lake concentrations of organochlorine pesticides (OCPs) varied significantly, with ranges from 10.11 to 125.65 mg/kg and 10.96e45.17 mg/kg, respectively. There was a statistically significant difference in mean OCP concentrations across different sampling sites within Lake. Among the OCPs analyzed, deltamethrin and lindane were found in lower concentrations, while endrin, DDT, and their metabolites were predominant and exceeded WHO and USEPA residue limits, except for endosulfan. The Risk Quotient values indicated potential ecological risks ranging from low to high for aquatic organisms, with values between 0.006 and 865.4 in Lake and 0.005 to 729.9 in Lake. In the marine environments of coastal water, Total OCP concentrations in seawater and sediments exhibited variations from 10 to 120 ng/L and 1.5e17 ng/g dry weight, respectively [47]. Various studies in recent years have documented pesticide concentrations in aquatic environments worldwide reported nearshore pesticide concentrations near the Great Barrier Reef ranging from 2.2 to 6.4 ng/L during the wet season and 3.8 ng/L in the dry season, while offshore concentrations were below detection limits; however, river discharges nearby recorded levels up to 350 ng/L. More recent findings by [48] in the Sea and South India Sea showed pesticide concentrations varying from 9.5 to 267 ng/L, consistent with historical data. In a comprehensive study [49] along a transect from the western Pacific to the Southern Ocean detected 27 frequently occurring pesticides among 221 tested, underscoring the pervasive presence of these contaminants across diverse marine ecosystems. Recent studies have highlighted the significant accumulation of pesticides in the bodies of animals, humans, and fish, demonstrating the toxicity and long-term impacts of these chemicals. For instance [50] studied the concentrations of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) in seven species of freshwater food products, including fish and crayfish, from aquaculture farms around India. They analyzed the muscle tissue of these species to assess health risks from dietary intake. The mean concentrations of OCPs ranged from 6.38 to 15.90 ng/g wet weight, and PCBs ranged from 3.18 to 5.12 ng/g wet weight. Heptachlor and d-HCH were the predominant OCPs, accounting for over 74 % of total OCPs. Cancer risk and hazard ratios calculated at the 50th and 95th percentile exposures indicated that SHCHs, heptachlor, and PCBs could pose a cancer risk to consumers based on average consumption rates. This bioaccumulation poses serious health risks and such findings under score the pervasive nature of pesticide contamination and its ability to biomagnify up the food chain, resulting in significant health implications for both wildlife and humans. The quantitative data on the Health and Environmental Impacts of Pesticide Toxicity are summarized in Table-1 [51].

Remediation methods and future prospective: The challenge of eliminating pesticides from various matrices has prompted extensive research into diverse remediation techniques. Methods integrating physical and chemical treatments have been widely adopted, each offering unique benefits and constraints influenced by factors like pH, temperature, pesticide characteristics, and cost considerations. Notable techniques for pesticide removal include adsorption, activated carbon filtration, reverse osmosis, membrane filtration, nanofiltration, advanced oxidation processes, photolysis, and enzymatic biodegradation.

Physical treatment method: Physical treatments, crucial for pretreating pesticideladen wastewater, utilize methods like nanofiltration and reverse osmosis to efficiently remove pesticides, such as glyphosate, atrazine, and diuron, from effluents. Nanofiltration is a pressure driven purification process that uses membranes with nanometresized pores to remove dissolved solutes and organic molecules, including pesticides. It is particularly effective against small molecular weight contaminants like herbicides, which can pass through largerpore membranes used in other filtration methods. This method is advantageous due to its lower energy requirements compared to reverse osmosis and its ability to operate at lower pressures, which reduces operational costs. On other hand, reverse osmosis (RO) involves forcing water through a semipermeable membrane that blocks the passage of dissolved pesticides and other contaminants. RO is highly effective for removing a broad range of pesticides, including those with complex structures, from water. It is often used when a high level of purity is required, although it is energy intensive and generates a significant volume of brine as a byproduct, which must be handled appropriately. Adsorption, employing materials like natural clays and activated carbon, leverages their selective binding properties for pesticide retention, influenced by their chemical and structural characteristics [52]. Adsorption is a widely used method for pesticide removal, utilizing adsorbents such as activated carbon, biochar, or natural clays. These materials attract and hold pesticide molecules on their surface, primarily through physical forces, although chemical interactions can also occur depending on the material and the pesticide. The effectiveness of adsorption is influenced by the surface area, pore size distribution, and the chemical nature of the adsorbent. It is particularly beneficial for removing non-polar, hydrophobic compounds. Other advanced physical filtration techniques, like ultrafiltration and microfiltration, can also be employed, though they are generally less effective at removing small molecular weight pesticides compared to nanofiltration and RO. These methods are better suited for larger particles and are often used in combination with other treatment processes to enhance overall efficiency. More recently, advanced materials such as metalorganic frameworks are reported to possess the highest porosity of all adsorbents and have proven excellent for the adsorption of pesticides [53].

Chemical treatment method: Chemical treatment methods for pesticide remediation involve reactions that alter the chemical structure of the contaminants, rendering them less harmful or easier to remove. These methods are critical when dealing with persistent organic pollutants that are resistant to physical methods alone. Chemical treatments utilize oxidation technologies to decompose pollutants, with Advanced Oxidation Processes (AOPs) being notable for generating hydroxyl radicals for the mineralization of organic contaminants [54]. Advanced Oxidation Processes (AOPs) are a group of chemical treatment procedures that create highly reactive species, predominantly hydroxyl radicals. These radicals are extremely effective in breaking down complex organic molecules into simpler, nontoxic forms, often achieving complete mineralization. AOPs include several technologies such as ozone oxidation, hydrogen peroxide oxidation, and photocatalytic oxidation. The choice of technology depends on the specific pesticides involved, as well as the costs and practicality of implementing these systems. Photodegradation plays a crucial role in pesticide breakdown, with variables like soil properties and environmental conditions affecting the degradation rates [55]. Photodegradation is a vital chemical process for breaking down pesticides, heavily influenced by environmental and chemical factors. The rate and efficiency of photodegradation are contingent on the pesticide's chemical structure, sunlight exposure, soil properties, and climatic conditions. Ultraviolet (UV) light, in particular, plays a crucial role in driving photochemical reactions, transforming complex pesticide molecules into simpler, less harmful compounds. The intensity and duration of sunlight are critical variables; regions with high sunlight exposure experience faster degradation rates, whereas areas with limited sunlight due to geographical or seasonal factors show slower degradation [56]. Soil properties significantly impact the photodegradation process. Soil texture, organic matter content, and moisture levels can alter the rate at which pesticides degrade. Organic matter in the soil can absorb and retain pesticides, reducing their exposure to light and thus slowing the degradation process. For instance, soils rich in organic matter may trap pesticides, making them less available for photodegradation. Conversely, sandy soils with low organic content may facilitate faster photodegradation due to less retention of the chemicals [57]. Environmental conditions such as temperature and humidity also play a role. Higher temperatures generally increase the rate of photodegradation by enhancing the photochemical reactions. Similarly, humidity levels can influence the process; higher moisture content in the soil can either promote or inhibit photo-degradation depending on the specific pesticide and environmental context. Some pesticides may degrade faster in moist conditions due to increased microbial activity, while others might persist longer if moisture protects them from UV exposure [58]. Additionally, the presence of other substances in the environment, such as pollutants or naturally occurring chemicals, can interact with pesticides and influence their degradation. These interactions can either accelerate the breakdown process through synergistic effects or hinder it if the substances form complexes that are more resistant to degradation. Understanding these complex interactions is essential for accurately predicting the environmental fate of pesticides and implementing effective management practices to mitigate their impact [59].

Table 1: Quantitative data on the health and environmental impacts of pesticide toxicity.

Impact Category	Specific Impact	Quantitative Data	Citation
Human Health	Acute Poisoning Fatalities	Approximately 385 million cases of acute pesticide poisoning annually, with around 11,000 fatalities worldwide	106
	Parkinson's Disease Risk	70% higher incidence in exposed individuals	107
	Non- Hodgkin Lymphoma Risk	Increased risk of 41% among exposed individuals	108
Environment - Water	Stream Contamination	Pesticides found in 50% of global water samples	109
Environment - Soil	Microbial diversity reduction	Decrease in soil microbial diversity by up to 30%	110
Environment - Biodiversity	Bee population Decline	Up to 30% decline i bee populations in some areas	111
Environment - Bioaccumulation	Pesticides levels in marine mammals	Polychlorinated biphenyls and DDts levels up to 466 ng/g and 3819 ng/g lipid weights, respectively.	112
Environment - Air	Atmospheric Pesticicde Transport	Pesticide detected up to 100 km from application sites	113

Biological treatment method

Biological treatments capitalize on microbial metabolism to degrade organic pollutants, with processes like activated sludge, biofilms, and bioremediation being costeffective alternatives to physical and chemical methods. The activated sludge process is a type of aerobic treatment where microorganisms are mixed with wastewater in an aeration tank. This allows the microbes to consume organic pollutants, including pesticides, as food. The mixture is then settled in a secondary clarifier where the clean water is separated from the biomass. This method is widely used in municipal and industrial wastewater treatment facilities due to its effectiveness and scalability. In the context of pesticide remediation, biofilms can degrade persistent substances as water passes over them. The stability and resilience of biofilms make them particularly useful in continuous flow systems, where they can provide sustained treatment over long periods. Techniques such as the membrane bioreactor (MBR) combine biological and filtration methods for high efficiency pollutant removal. A Membrane Bioreactor combines biological degradation and membrane filtration in a single process. In MBR systems, microorganisms degrade organic pollutants in the wastewater, while the membrane filters separate the treated water from the microbial biomass. This technology enhances the efficiency of pollutant removal, provides excellent treated water quality and reduces the footprint of the treatment plant. MBRs are particularly effective for complex industrial wastewaters containing high levels of pesticides.

Future prospective

Evolving trends in sustainable pest management

As global agricultural practices evolve, the imperative to integrate sustainable pest management solutions becomes increasingly critical. The environmental and health impacts delineated in earlier sections of this article underline the urgent need to harmonize agricultural productivity with ecological health. This calls for a concerted effort to pioneer innovative, low impact pesticides, particularly focusing on biopesticides derived from natural sources. These biopesticides, characterized by reduced toxicity to non-target organisms and lower environmental persistence, represent a promising avenue toward mitigating the adverse ecological effects currently observed. Concurrently, the exploration and broader application of genetically engineered crops that possess innate resistance to pests and diseases offer a potent strategy to minimize reliance on synthetic chemical inputs. This approach not only addresses the immediate reductions in synthetic pesticide usage but also aligns with long term sustainability goals by promoting ecological balance and enhancing soil health. The resultant ecological connectivity from these endeavors could lead to diminished environmental pollution, preservation of biodiversity, and the restoration of natural pest predators, thereby fostering a balanced ecosystem where agricultural lands coexist harmoniously with surrounding natural habitats.

Advancements in remediation technologies

The extensive and increasing use of pesticides globally has far reaching implications for environmental sustainability and public health. The documented impacts, such as the reduction in soil microbial diversity, contamination of water bodies, and the development of antibiotic resistance in microbial communities, underscore the need for immediate and concerted action. The persistence of organochlorine pesticides (OCPs) in agricultural soils highlights the long-term ecological risks and potential health hazards associated with these chemicals [60]. While significant strides have been made in understanding the environmental and health impacts of pesticide use, there remain critical gaps in our knowledge. Comprehensive risk assessments that encompass the synergistic effects of multiple pesticide residues, long term exposure, and the impacts on non-target species are urgently needed. The current literature often focuses on individual pesticides, but in reality, agricultural practices involve the use of complex pesticide mixtures. Studies should also consider the cumulative impacts of pesticides in conjunction with other agricultural chemicals, such as fertilizers and antibiotics. More research is needed to understand how pesticides affect non-target species, including beneficial insects and soil fauna, which play crucial roles in ecosystem functioning [61]. The role of pesticides in contributing to antibiotic resistance in microbial communities represents a significant emerging concern. Recent studies have shown that pesticide exposure can significantly enhance the horizontal gene transfer (HGT) of antibiotic resistance genes (ARGs), exacerbating the public health crisis of antibiotic resistance. The exposure to chlorothalonil in-creases intracellular reactive oxygen species, stimulates the SOS response, and increases cell membrane permeability, while azoxystrobin and carbendazim enhance the expression of conjugation-related genes on plasmids, facilitating HGT. Fungicides like triadimefon, chlorothalonil, azoxystrobin and carbendazim have been shown to increase the abundance of ARGs in agricultural soils by about twofold, a process mediated by mobile genetic elements such as conjugative plasmids. Future research should focus on elucidating the molecular mechanisms underlying this phenomenon and developing strategies to mitigate its impacts. Therefore, parallel to advancements in pesticide application, the development of efficient remediation technologies capable of extracting pesticide residues from environmental matrices stands as a critical research domain. Future innovations could include the development of novel adsorbents with enhanced specificity and capacity for pesticide capture and the exploration of enzymatic degradation pathways tailored to decompose persistent pesticides into harmless byproducts. The integration of advanced bioremediation techniques, leveraging genetically modified microorganisms or specialized microbial consortia, could offer targeted and effective degradation of pesticide compounds, thus cleansing soils and water bodies of toxic residues.

Regulatory and educational advances

To support these technological and biological advancements, strengthening regulations to limit pesticide use and promote safer alternatives is essential. Looking ahead, it is plausible to speculate that advancements in biotechnology and precision agriculture could offer novel solutions to reduce pesticide dependence. For instance, the development of genetically engineered crops with enhanced pest resistance or the use of biopesticides derived from natural sources could significantly mitigate the negative impacts associated with synthetic pesticides. Additionally, the adoption of Integrated Pest Management (IPM) practices and organic farming can promote ecological balance and soil health, potentially reversing some of the adverse effects of conventional pesticide use. Strengthening regulations to limit pesticide use and promote safer alternatives is critical. As per their report, respondents were most likely to rate developing new cultivation technologies as the most effective strategy for achieving target reductions in pesticide use (27 %), followed by limiting the use of the most dangerous pesticides and incentives for farmers to reduce the use of pesticides (21 % for both). Pesticide taxation (18 %) and adoption of organic farming (12 %) were rated as less effective. Regardless of which measure was chosen, Limiting the use of the most dangerous pesticides, Taxation of pesticides, Adoption of organic farming, Developingnew cultivation technologies, that can reduce the need for pesticides, Incentives for farmers to reduce the use of pesticides, Other, the majority of respondents (67 %) believed such measures should be introduced at the EU level. Furthermore, education plays a crucial role in this transition. By increasing awareness of the safe use of pesticides and the benefits of environmentally friendly remediation technologies, we can ensure both public health and environmental safety. Efforts to mitigate pesticide use and pollution must also encompass enhancements in production, management, and capacity building processes across the agricultural sector. The development of bio pesticides and the widespread implementation of integrated pest management strategies can significantly reduce reliance on chemical pesticides, thereby conserving biodiversity and main taining environmental balance.

Research gaps and future directions

Despite significant progress in understanding the environmental and health impacts of pesticide use, critical gaps remain in our knowledge. Comprehensive risk assessments are required to address the synergistic effects of multiple pesticide residues, long-term exposure, and impacts on non-target species. Moreover, the role of pesticides in contributing to antibiotic resistance in microbial communities represents a significant emerging concern, with recent studies showing that pesticides can enhance the horizontal gene transfer of antibiotic resistance genes (ARGs), potentially exacerbating public health crises related to antibiotic resistance. The development of new cultivation technologies and practices that reduce the need for pesticides is crucial. As per recent surveys, such technologies are viewed as the most effective strategy for achieving significant reductions in pesticide use. Additionally, legislative measures that ban highly toxic pesticides and promote precision in pesticide application must be globally adopted to ensure sustainable practices. The journey towards reducing pesticide use and enhancing ecological sustainability is complex and multifaceted, requiring a concerted effort from scientists, policymakers, and farmers alike. By embracing biotechnology, precision agriculture, and regulatory reforms, we can tackle the challenges posed by conventional pesticide use and pave the way for a sustainable agricultural future that safeguards both ecological integrity and public health.

Conclusion

The employment of chemical pesticides in agronomic systems presents a nuanced challenge, the necessity of pest management against environmental and health concerns. The persistence and bioaccumulation of compounds like organochlorine pesticides exemplify the enduring impact of these substances on ecosystems and food chains, where their slow degradation and long half lives pose significant risks, particularly to higher trophic levels. This scenario underscores the critical need for a paradigm shift in pest management strategies. Advancing towards sustainable agriculture necessitates a reevaluation of pesticide use, emphasizing the development and implementation of new methodologies and technologies to assess and mitigate the environmental impacts of pesticides. A pivotal component of this shift involves the promotion and development of biological pesticides characterized by their efficacy and minimal toxicity. This approach not only aligns with environmental protection goals but also sup-ports the health of ecosystems and human populations. In parallel, enhancing user knowledge and fostering practices that prioritize efficiency and safety are imperative. Education and training programs that highlight the advantages of biological over chemical pesticides could play a crucial role in this transition. Additionally, regulatory frameworks and incentives that encourage the adoption of safer, ecofriendly alternatives can further catalyze the move towards reduced reliance on hazardous chemicals. In conclusion, addressing the complex issue of pesticide use demands a multifaceted approach that balances agronomic needs with ecological integrity and public health. There is a pressing need for longitudinal studies that monitor the long-term effects of reduced pesticide usage on soil health and ecosystem recovery. Such studies should investigate the time frames required for the restoration of microbial diversity and soil fertility once pesticide application is halted. Moreover, research should focus on developing and validating sustainable agricultural practices that can be implemented at scale, particularly in regions heavily reliant on pesticides. While the facts presented in this article provide a comprehensive overview of the current state of pesticide use and its impacts, the field must now move towards addressing these complex challenges through interdisciplinary research and innovative solutions. The potential benefits of reducing pesticide use are clear, but achieving this goal requires a concerted effort from scientists, policymakers, and farmers alike.

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