Pesticides Pollution and its Toxic Impact on Aquatic Life

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Abstract

Intensification of agriculture in food production for improved quality and modeling of high-yield crop varieties implies the use of pesticides and fertilizers. They fend off pests that threaten crops so as to improve the quality of the produce and also increase production. However, they find extensive use in agriculture and horticulture leading to pollution of water sources through drain off, droplets and leaching. Such contamination is extremely dangerous to the aquatic life. Effects of pesticides include effects on the primary producers accord to different biological organization of life especially, microorganisms, insects and fish. As a result of the above effects, proper monitoring methods should be adopted in order to reduce pesticide runoff during application. For example, utilization of the suspended matter samplers can tidy up the particle bound pesticides from the water hence conserve water ecosystems respectively.

Keywords: High-yield crops, Pesticide runoff, Aquatic contamination, Ecosystem health, Monitoring techniques

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Introduction

Pesticides are chemical compounds used to kill or repel insects, rodents, fungi or weed. Because they protect crops, preserve food and prevent vector borne diseases (Yasmin & D'Souza, 2010), they play a crucial role in agriculture. Insects, herbicides, fungicides, rodenticides are most commonly applied over agricultural fields, homes, schools and communities all over the world (Karr & Rauh, 2024). Pesticide use can be broken down into three phases of history. Before the 1870s pest control relied mainly on natural compounds of animal, plant or mineral origin. Since then, for example, the Sumerians used sulfur compounds over 4,500 years ago and the Chinese used mercury and arsenic based compounds 3,200 years ago (Tudi et al., 2021). Manual weeding was used to control weeds and swimming to reduce insects and plant diseases (strict 1976, 69). *Chrysanthemum cinerariaefolium* has been used for almost 2 thousand years as a natural insecticide (Hodosan et al., 2023). This beginning period also used the use of early synthetic inorganic pesticides including copper and sulfur compounds, such as the Bordeaux mixture which were effective against fungal diseases. It is in the second period from 1870 to 1945 that large scale pesticide applications were introduced followed by a revolutionary period since 1945 in which synthetic pesticides such as DDT, BHC, Aldrin, Dieldrin and 2, 4-D have transformed pest management globally (Zhang et al., 2017).

Pesticides are classified according to the pests to which they are directed. Organophosphates and pyrethroid insecticides are used to keep pest in check while herbicides like glyphosate are used to push out crops plants that are not required (Sood, 2023; Deolikar et al., 2021). For crops, fungicides such as azoles and strobilurins fight off crop fungal infections (Deolikar et al., 2021). Rodenticides composed of anticoagulants keep the numbers of rodent populations down (Karr & Rauh, 2024). On the other hand, these chemicals have enormous benefits such as yielding enhanced agriculture productivity by reducing loss of crops up to 40 percent due to pests, diseases and weed (Mahmood et al, 2015). One of their roles is to control weeds during critical growth stages and hence improve economic efficiency and the other is in public health controlling vectors of diseases such as encephalitis, yellow fever, bubonic plague and typhoid fever (Mahmood et al., 2015).

Pesticides are also major environmental and health risks. Environmental contamination occurs with their indiscriminate use, rising nitrate and ammonium levels to destabilize food webs (AbuQamar et al., 2024). On average, approximately 64% of global agricultural land is at risk from pesticide pollution often in overlap with areas of high biodiversity, intensifying ecological risks (Tang et al., 2021). Long term exposure to pesticide is known to cause severe health problems in human beings (Punia et al., 2023; Huang & Li, 2024). Moreover, pesticides degrade over time and degrade today to increasingly threaten the environment and the food chain (Kaur et al., 2024). To overcome these challenges bioremediation, biological pest control and integrated pest management (IPM) are important sustainable practices. Further, global control of pesticide pollution will require extensive monitoring systems and well developed regulatory frameworks. Pesticides have contributed greatly to agricultural and public health but their potential long-standing environmental and a public health impacts require a conversion towards sustainable practices and greater regulations to achieve a balance between agricultural output and environmental and human welfare (Mitra et al., 2024).

1. Sources and Pathways of Pesticides into Aquatic Ecosystems

These are major ecological and human health concerns and there exist several different pathways for the entry of pesticides into aquatic ecosystems. The degradation of water quality and biodiversity through pesticide pollution is a result, to a certain degree, from agricultural runoff, industrial waste discharge, urban runoff and atmospheric deposition the three principled sources of pesticide pollution.

i. Agricultural Runoff and Drainage

Pesticides are one of the major pathways of entry into aquatic ecosystems from agricultural runoff. During rainfall, these pesticides are deposited into nearby water bodies and have elevated surface water concentrations as revealed in Figure 1. Bioaccumulation of this runoff can produce toxicity and population decline to fish (Chen & Selvinsimpson, 2022).

ii. Industrial Waste Discharge

Direct discharge of pesticide laden waste into water bodies, along with existing elevated pollution levels creates pesticide contamination in industrial activities. These discharges add to a list of poisonous substances that can disturb the environment and pose serious threats to the human health in the food chain (Chen & Selvinsimpson, 2022).

iii. Urban Runoff and Residential Use Fees

But urban areas are also sources of pesticide contamination, most of it from storm water runoff. Residential pesticide uses plus faulty disposal, accidents and spills lead to contamination of local waterways and places around them, resulting in widespread ecological impacts (Chen & Selvinsimpson, 2022).

iv. Leaching

Atmospheric deposition and also the fallout of pesticide particles into water bodies. Moreover, agricultural soils leach pesticides out including those that are applied on a large scale, into groundwater and surface water which endanger both aquatic ecosystems and human health (Chen & Selvinsimpson, 2022). Some other researchers addressed the problems having to do with this problem of pervasive environmental detriment by calling for tougher regulatory measures and utilizing new bioremediation techniques (AbuQamar et al., 2024).

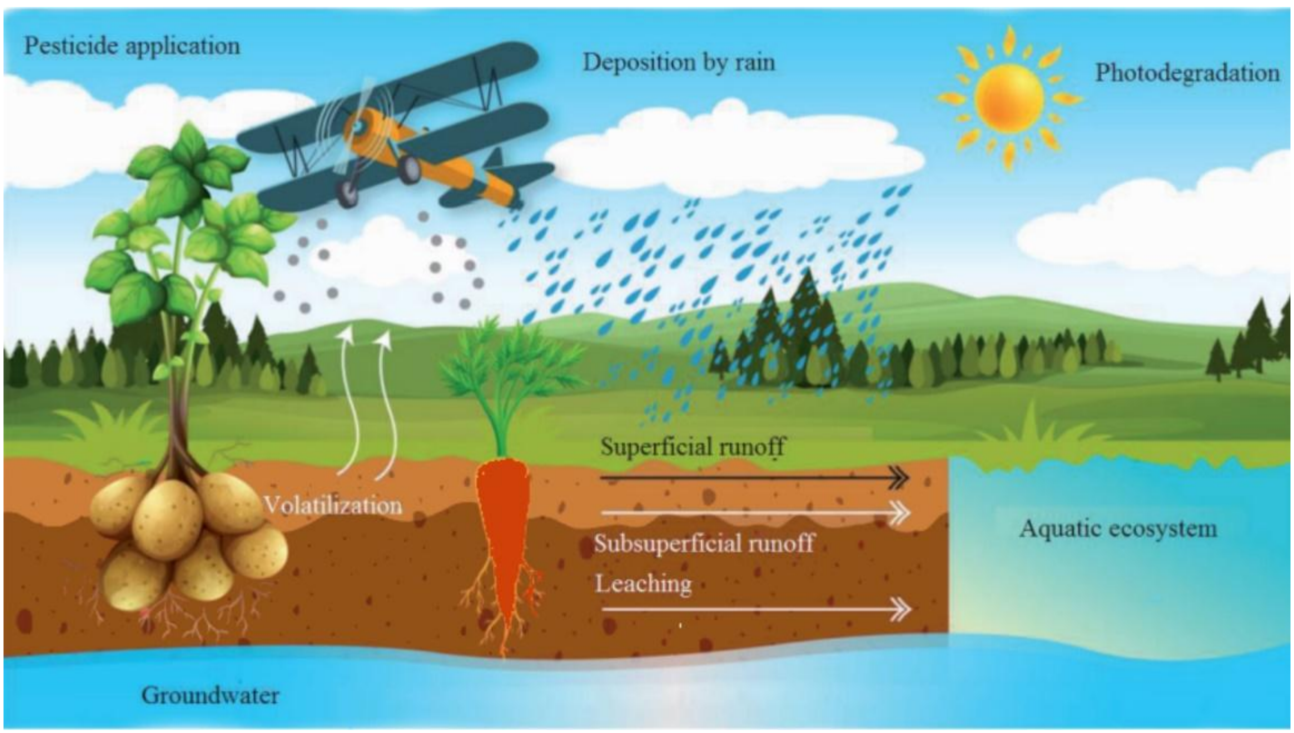

Fig. 1: Pathways of Pesticides to Aquatic Environments.

3. Pesticide Toxicity Mechanisms in Aquatic Life

The major way in which chemicals enter aquatic organisms and pose a threat to them through pesticide use is absorption and ingestion as chemicals enter systems through runoff, spray drift and direct application. Bioaccumulation and biomagnification are shown to occur in food chains as a result. For example, pesticide exposure through skin and gill absorption can be very harmful for fish (Shukla, 2024). Pesticides also enter the aquatic organisms by contaminating water they are in and by consuming prey that also contain pesticide residues (Ghosh & Sarower, 2024). These pesticides accumulate in the tissues of the aquatic organisms over time and end up being above normal environmental concentration (Ray & Shaju, 2023). As organisms increase in trophic level, they become predators, consuming organisms in other levels of the food chain, causing the pesticide concentrations to increase with each new level and eventually leading to the higher level consumers end users such as humans (Ray & Shaju, 2023). Several mechanisms of toxicity of pesticides in aquatic environments have been reported. Exposure of cypermethrin to fish leads to oxidative stress, inducing programmed cell death as one of the main effects (Zhao et al., 2024). Besides disrupting the neurological functions in aquatic organisms, many pesticides cause behavioral changes and mortality in aquatic organisms (Saha & Dutta, 2024). More specifically, herbicides inhibit algal photosynthesis and disrupt community structures and cascading effects up the food web (Narayanan et al., 2024).

Pesticides have different effects on an aquatic ecosystem depending on the class to which they belong. For example, insecticides are known to significantly induce physiological stress and developmental modifications in non-targeted aquatic invertebrates (Brasseur et al., 2023). Reduction of biodiversity and changes in nutrient are herbicides main effects on the primary producers, i.e., algae (Narayanan et al., 2024). Less studied fungicides have been shown to disrupt aquatic ecosystem through the disruption of non-target organisms and alteration of community interactions. Although some studies propose that specific pesticides may have less of an effect on certain non-target species Aquatic ecosystems continue to suffer from the impact of pesticides because in general most pesticides have a negative effect. Being an integral part of the life of agriculture, pesticide use should be more tightly regulated in order to mitigate its adverse effects over aquatic life. However, stronger regulations and more sustainable practices are needed to help the long term health of aquatic ecosystem (Narayanan et al., 2024).

4. Effects of Pesticides on Different Aquatic Organisms

The effects of pesticides on aquatic species are profound: behavior is altered, reproduction affected and mortality increased destabilizing the ecology and posing risks to both aquatic life and human health. However, such impacts show various path in different species and ecosystems. Pesticide exposure in fish has behavioral side effects that can lead to effects of compromised feeding, survival and ecological role. In addition, pesticides bio accumulates in fish tissues, therefore elevating the pesticide levels also elevating mortality particularly in freshwater ecosystems as shown in Table 1 (Hammond et al., 2020).

Table 1: Toxicological Impacts of Organophosphate Pesticides on Aquatic Species.

Species	Pesticide (Class)	Dose	Exposure Time	Toxic Effects	Reference
Hypophthalmichthys molitrix	Sumithion (OPPs)	0.85–1.70 ppm	21 days	Hepatocellular toxicity, necrosis, degeneration, vacuole formation	Hossain et al. (2016)
	Sumithion (OPPs)	0.025–0.1 ppm	6 months	Hepatorenal toxicity, hemorrhage, liver degeneration, necrosis in kidney tissues	Shira et al. (2020)
Danio rerio	Sumithion (OPPs)	0.5–2.0 ppm	1 week	Intestinal villi destruction, sluggish epidermal cells	Ahmed et al. (2015)
Oncorhynchus mykiss	Diazinon (OPPs)	0.1–0.2 mg/L	28 days	Hepatotoxicity, hepatocellular swelling, vacuole formation	Banaee et al. (2013)
	Maneb, Carbaryl (Carbamates)	0.1–3.9 mg/L	4 days	Gill tissue damage, epithelial swelling, necrosis in hepatic and renal tissues	Boran et al. (2010)
Heteropneustes fossilis	Malathion (OPPs)	0.2 ppm	1 month	Hepatocellular apoptosis, hemorrhage, lamellae damage, renal tubule degeneration	Deka & Mahanta (2012)
Cirrhinus mrigala	Cypermethrin (Pyrethroid)	1.026–5.13 µg/L	21 days	Kidney damage, tubular necrosis, pyknosis	Prashanth (2011)
Ctenopharyngodon idella	Lindane (OCPs)	0.25–2 mg/L	4 days	Necrosis, villi destruction, intestinal bleeding	Vajargah et al. (2021)
Channa punctatus	Malathion (OPPs)	$LC50 = 0.4$ mg/L	1–12 days	Liver and kidney injury, increased creatinine and BUN levels	Bharti & Rasool (2021)
	Chlorpyrifos (OPPs)	5 ppm	1 month	Hepatocellular necrosis, gill damage, intestinal villi fusion	Stalin et al. (2019)
Catla catla	Cypermethrin (Pyrethroid)	0.21–0.41 mg/L	45 days	Elevated antioxidant enzyme levels, hepatic cell damage	Sharma & Jindal (2020)

Significant effects on invertebrate populations are also brought about by pesticides. Thus, for example, mortality and reproductive failures of crustaceans can disrupt their populations, as well as the food webs on which they rely. Similarly threats to mollusk growth and survival result in negative consequences for biodiversity. Secondly, a decrease in invertebrate population is related to a decline in system functioning caused by the drop of the phytoplankton population and in general ecosystem stability. Pesticide exposure is particularly hurtful to amphibians because amphibians have skin that is so permeable that they are essentially bathing in pesticides and because they spend large parts of their life cycles in aquatic environments. Pesticides can cause high mortality rates on acute exposure to high pesticide concentrations whereas chronic exposure to pesticides causes reproductive abnormalities, developmental deformities and infertility. Consequently, the contribution of these effects to a decline in amphibian biodiversity is seen in the current threat status of 43% of amphibian species, which includes pesticide induced mortality at levels of 43% (Hammond et al., 2020).

Plankton and primary producers like phytoplankton and algae, which form the foundation of aquatic food webs, are also significantly affected by pesticide contamination. Reduced populations of these primary producers lead to a decrease in oxygen production and nutrient cycling, which in turn negatively affects higher trophic levels. The accumulation of pesticides in sediments poses long-term threats to benthic organisms and alters ecosystem dynamics. Integrated Pest Management (IPM) is a sustainable and cost effective solution to pesticides and these harmful effects. It's an approach that features healthier ecosystems, preserved biodiversity and decreased reliance on chemical pesticides (AbuQamar et al., 2024).

5. Pesticide Pollution: Ecological Consequences

Pesticide pollution causes a great threat to the aquatic ecosystem, such as biodiversity reduction, ecological stability disturbance and food web disturbance. All of this is a complex cause with multiple system impacts. A major result is such disruption of ecosystems when pesticides run off into water bodies and contaminate organic matter and boost such harmful substances as ammonium and nitrate. They destabilize the aquatic environment and even more degradation is more likely to occur (AbuQamar et al., 2024). Pesticide pollution also has another big effect – loss of biodiversity. Particularly vulnerable are primary producers, such as algae, whose growth and function, even a little off of whack, will spell death. This disturbance disrupts energy flow through the ecosystem, changes community structures and finally reduces biodiversity (Narayanan et al., 2024). These effects can have long term consequences for species composition and for ecosystem functionality as the ecosystem weakens in its ability to deal with even small stress (Sobchenko & Fedosova, 2024).

Bioremediation strategies and effective management practice are important to manage and recover from pesticide pollution. Success of recovery efforts depends on how severe the contamination and the resilience of the ecosystem to contamination. To protect both agricultural productivity and aquatic ecosystem health a balance must be achieved between sustainable agricultural practices, such as Integrated Pest Management (IPM), effective monitoring and cleanup strategies. Pesticides have played a critical role in promoting agricultural production, nevertheless their ecological risks need to consistently be monitored, remediated and managed to protect aquatic ecosystems (Farooqi et al., 2022).

6. Regulations Policies and Management Strategies

Pesticide management is carried out within a set of complex and global/regional laws governing pollution and protecting Public Health and the environment. There has been many regulatory frameworks representing approval, use and monitoring of pesticide residues. These frameworks are essential to the responsible and least impactful, use of pesticides. Framework as such as Stockholm Convention for addressing persistent organic pollutants (POPs) and Rotterdam Convention for hazardous chemicals is the bedrock of the pesticide management at global level (Mohapatra et al., 2023). It is these international agreements that all come together to create guidelines and policies for pesticide use, taking steps that are safe. Continued strengthening of pesticide regulation comes from legislative developments at the European Union and United States level, for instance, based on strict pesticide authorization and residue limits and high level monitoring. In developed regions further advanced risk assessment models are applied to estimate pesticides environmental impacts to allow for the approval of new substances (Mohapatra et al., 2023).

At the national level, countries such as India have adopted national policies to minimize the use of pesticide as well as reduce a residue contamination to protect human health and the environment (Reddy et al., 2024). With the challenges of pesticide use still ahead, sustainable pest management strategies are gaining real traction. One group of approaches focuses on environmental impacts with the aim to minimize these impacts and increase agricultural productivity as well as resilience. One of such approach is Sustainable Pest Management (SPM), which uses power of both chemical and biological controls like natural predators to maintain equilibrium of ecosystem and decrease reliance on chemical pesticides. Furthermore, techniques such as crop diversification and ecological farming slow pest outbreaks and increase biodiversity (Dey et al., 2024).

Integrated Pest Management (IPM) is another well-known approach, which is a holistic approach through integration of biological, cultural, chemical and mechanical methods to minimize the application of synthetic pesticides (Samanta et al., 2024). The economic and environmental benefits of this approach extend to higher returns to farmers, lower environmental damage and greater agricultural sustainability in the long run. Along with recent innovations in pest control, the landscape of pesticide management is also changing. New biotechnological advances including CRISPR and RNA interference are bringing about the development of pest resistant crops, attenuating the need for chemical pesticides. Enhanced biological control methods supplemented with genomic tools and nanoparticle delivery systems have also been more efficient, as natural pest control agents (Chaudhary et al., 2024).

7. Future Directions and Research Needs

Threats to aquatic ecosystems from emerging pesticides indicate the need for better detection technologies and more public awareness. Urban and industrial wastewater effluents are one of the major sources of emerging pesticides that lead in disrupting biodiversity and ecosystem functions. Organic matter contaminated with pesticides have elevated nutrient levels and destabilize the aquatic food webs further already strain the ecological imbalances. Chronic exposure to pesticides may also bring about genetic changes in aquatic species, causing them to lose its ability to grow as well as its immune system (AbuQamar et al., 2024).

It is necessary to make advances in detection and monitoring for tackling these emerging pesticides threats. Pesticide detection at low concentrations has been the subject of analytical progress, though the fate of pesticides in wastewater is not yet fully clear. Integrating monitoring schemes is proposed to strengthen ecotoxicological assessments and to improve assessment of exposure to pesticides in aquatic environments (Pelosi et al., 2017). Despite significant research gaps in our understanding of how low pesticide concentrations and mixtures affect wildlife over the longer term, both farmers and regulators often struggle to find ways to reduce pesticide exposures. The effective management strategies require more research in how pesticides interact with environmental factors at different scales. Public awareness and community involvement play a vital role in mitigating the impacts of emerging pesticides. Awareness campaigns can promote sustainable practices and encourage compliance with regulations, helping to reduce pesticide contamination. Local communities also contribute to monitoring efforts, providing valuable data and mobilizing against pesticide-induced pollution. While progress has been made in understanding the impact of pesticides, the complex interactions between pesticides and aquatic ecosystems underscore the need for continued research, technological innovations and active community engagement to protect these critical environments (Pelosi et al., 2017).

Conclusion

In conclusion, the rapid growth of the human population has significantly impacted aquatic ecosystems, primarily through climate change, nutrient enrichment and pollution by toxic substances like pesticides. These environmental disturbances have disrupted the natural balance, leading to harmful effects on various organisms across all biological levels, from invertebrates to mammals. The increasing use of pesticides, while essential for pest control, has had unintended consequences on non-target species, causing developmental abnormalities and contributing to the decline of biodiversity. Therefore, it is crucial to adopt sustainable practices and implement stronger regulations to mitigate the harmful effects of pesticide pollution. These actions will help preserve aquatic ecosystems, safeguard biodiversity and ensure the long-term health of both the environment and human populations.

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