



## POTENTIAL TOXICITY OF PESTICIDES AND ITS TRANSFORMATION PRODUCTS TO AQUATIC ORGANISMS

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### Abstract

The escalation of agricultural productivity in recent decades has compelled a swift upsurge in the utilization of pesticides, ultimately leading to their presence in the aquatic ecosystem. Pesticides and their transformed products have adverse impact on the growth, reproduction, physiology, immunity, and histopathology of multiple tissues of fish. Pesticides have emerged as a significant global problem because to their potential to bioaccumulate inside various fish tissues, hence posing substantial health risks for consumers. Within this particular context, the present review aims to illustrate the potential adverse impact of pesticides and their transformed products on aquatic species, with a specific focus on fish. Research has revealed that the introduction of pesticides into aquatic environments might have detrimental effects on the mangroves and immunological response of fish, ultimately exacerbating the ecological impact by increasing their vulnerability to diseases. Hence, it is imperative to explore environmentally friendly, efficient, and appropriate pesticide alternatives in order to safeguard the aquatic ecosystems and the overall health of various aquatic life, particularly fish.

**Keywords:** Pesticides, Fish, Bioaccumulation, Transformed products

### Introduction

Aquatic contamination is widely recognized as a significant global hazard. The introduction of various pollutants into aquatic ecosystems, originating from a multitude of human activities, has led to significant pollution. This contamination poses a substantial threat to the aquatic habitat and the animals inhabiting it, resulting in potentially severe negative consequences (Rohani, 2023). Pesticides represent a significant category of hazardous substances that have been associated with human exposure and have been found to have significant effects on aquatic ecosystems (Helfrich et al., 2009; Islam et al., 2022). The global utilization of pesticides is experiencing a gradual rise due to the persistent development of the global population, which necessitates higher food production. Approximately 33% of agricultural commodities on a global scale undergo pesticide treatment (Liu et al., 2002; Islam et al., 2022). In instances of incorrect application, the majority of pesticides exhibit significant toxicity to the human beings and environment. The widespread utilization and release of pesticides are well recognized as significant contributors to the occurrence of pesticide metabolites in rivers, sediment, and air that poses a considerable risk to both ecosystems and human well-being (Sitaramaraju et al., 2014). Multiple research investigations have illustrated the detrimental impacts of pesticides on aquatic life. The observed consequences encompass stunted growth and hindered maturation of larvae and embryos, modifications to the hemato-biochemical indicators, and disruptions to the functionality of vital organs (gill, kidney, liver and gonad) in many fish species (Aktar et al., 2009; Mostakim et al., 2015; Uddin et al., 2016; Rohani, 2023). The degree of toxicity exhibited by pesticides in fish is subject to significant variation based on factors such as their types, forms, and species. The direct impact of pesticide intoxication on aquatic creatures manifests through significant mortality rates or the destruction of their food sources. The potential indirect consequences of these factors could be associated with their adverse impact on the growth and survival rates of fish (Helfrich et al., 2009; Sabra and Mehana, 2015; Rohani, 2023). The observation of significant changes in histology, hematological, biochemical parameters, and

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immunological profile of fish serves as crucial indicators in toxicological investigations, specifically in relation to the toxicity of pesticides (Vali et al., 2022).

The majority of pesticides utilized in agricultural practices undergo various processes (physical, chemical, biological) resulting in the development of one or more transformation products (TPs). Typically, more than 50% of the transformation products derived from triazines, carbamates, and phenoxypropionic acids exhibit a theoretical risk level that is either similar to or higher than that of the main pesticide. Conversely, more than half of the transformation compounds originating from synthetic pyrethroids, organophosphorus pesticides, and dithiocarbamates are expected to have a reduced level of risk (Belfroid et al., 1996). The detrimental impacts of pesticides and their products (transformed) on the well-being of fish have been widely documented in many scientific studies (Shelley et al., 2009; Clasen et al., 2018; Xie et al., 2022; Slaby et al., 2022). This brief review aims to offer valuable insights into the impacts of pesticides and their transformation products on the environment, health of fish and their immunological reaction using the keywords such as "pesticides," "transformation products," "fish," and "immune response."

### **Application of pesticides worldwide**

Pest control has long been recognized as a highly effective method for significantly increasing crop output, a critical requirement that aligns with the concurrent growth of the global population. According to estimates, global agricultural losses resulting from pest infestations range from approximately 50% to over 80% (Alexandratos and Bruinsma, 2012; Sabzevari and Hofman, 2022). However, during the latter portion of the 19<sup>th</sup> century, there was a significant rise in global economic growth, encompassing both the industrial and agricultural sectors. This growth resulted in a gradual rise in the production and application of chemicals derived from agriculture, which frequently caused detrimental impacts on the environment. The imprudent utilization of pesticides along with other persistent organic contaminants in agricultural soils has resulted in severe long-term consequences. The bioaccumulative qualities and high toxicity of agriculture-based pesticides together with other organic pollutants have had detrimental effects on human populations, given their persistent and widespread presence (Sharma et al., 2019). Under these conditions, the global pesticide market has become lucrative and cannot be ignored. The total pesticide trade in 2018 reached a volume of 5.9 million tons, equivalent to a value of 37.6 billion USD. In 2010, the quantity of pesticide transported between nations was three times greater than in 1990 (FAOSTAT, 2020). Nevertheless, when subjected to the examination of the Rotterdam Convention, such quantity had a more slow and steady increase from 2007 to 2018. Asia has become the largest exporter of pesticides in recent years, with exports increasing from 2.0 million to 2.5 million tons (from 2015 to 2018), and China accounting for two-thirds of this total at 1.6 million tons in 2018. In 2018, Germany, India, and the USA emerged as significant contributors to pesticide exports, with respective quantities of 0.47, 0.44, and 0.43 million tons (FAOSTAT, 2020; Sabzevari and Hofman, 2022). The utilization of pesticides in Bangladesh remained at a relatively low level till the year 1970. The global utilization of pesticides experienced a significant surge, rising from 1.69 million tonnes in the year of 1990 to 2.7 million tonnes in 2017 followed by South America, Asia, USA, China and India (Figure 1) (Ritchie et al., 2021). The degradation of aquatic habitats has significantly occurred as a result of the buildup of hazardous inorganic and organic pollutants, which have the ability to inflict widespread and harmful impacts on human health. Organochlorine pesticides, like hexachlorobenzene, heptachlor, dieldrin, endrin, aldrin, and dichlorodiphenyltrichloroethane (DDT's), are notably accountable for instances of acute contamination (Islam et al., 2022). Residues of organochlorine pesticides (OCPs) have the potential to enter aquatic habitats by many pathways, including wet and dry degradation, non-point source runoff, industrial wastewater, and drainage water outflows. In aquatic ecosystems, OCPs can infiltrate food chains and accumulate in plankton and other aquatic organisms (Guzzella et al., 2011; Islam et al., 2022). In a study conducted in the early part of 1986, Pimental and Lavitan discovered that an only 0.1% of pesticides successfully reach their intended targets, while a significant proportion of these substances result in environmental contamination (Pimentel, 1995).

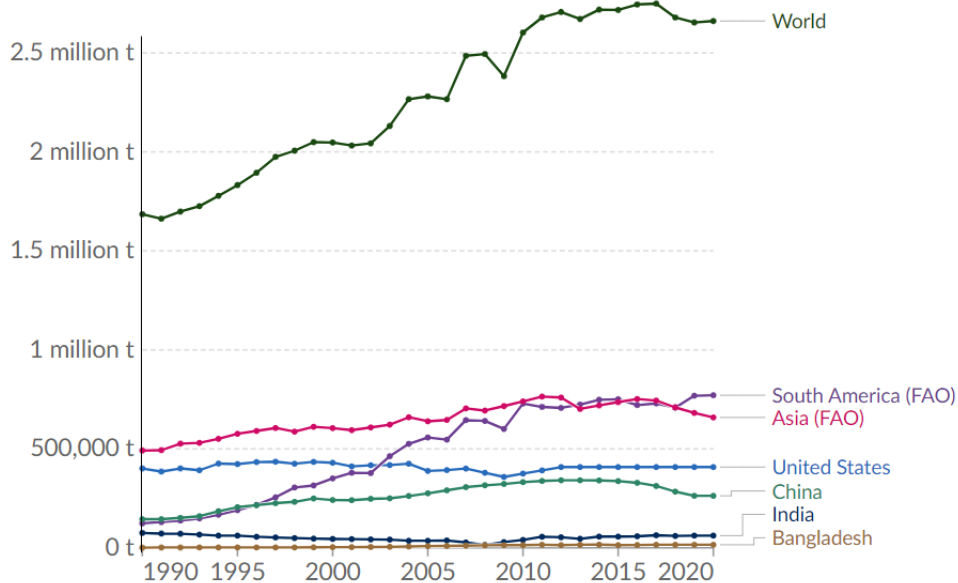


Figure 1. Total pesticide use measured in tonnes of pesticide consumption per year (Ritchie et al., 2021).

### Bioaccumulation and biomagnification of pesticides in fish

Synthetic organic pesticides may be broadly divided into three primary classes, namely organochlorines, organophosphates, and carbamates. Among these, organochlorines (OCs) are the initial group to be developed and are characterized by their non-polar nature, lipophilicity, and high persistence. They are introduced into the aquatic system by processes such as soil diffusion, surface water runoff, leakage, or the dumping of unused containers. Once present, they exhibit long-term stability, persisting in the surroundings for prolonged durations. The majority of these substances have been prohibited for agricultural use, however their remnants persist in numerous biological and non-biological constituents (Dhananjayan and Muralidharan, 2010; Mudiam et al., 2012). They undergo bioaccumulation and biomagnification processes as they progress through food chains, resulting in detrimental impacts at each level (Muralidharan et al., 2009). Bioaccumulation is associated with the logarithmic octanol-water partition coefficient ( $\log K_{ow}$ ), which indirectly measures lipid solubility, as well as the environmental persistence of chemicals. If the  $\log K_{ow}$  of pesticides exceeds 3 and their half-life in soil exceeds 30 days, there is a significant likelihood for these pesticides to accumulate on aquatic organisms (Ernst et al., 2018; Rossi et al., 2020). While the initial levels of Organochlorine pesticides (OCPs) in water might be very modest, they have a tendency to preferentially associate with particulate matter and subsequently deposit into sediment (Khuman et al., 2020). OCPs have a tendency to form associations with lipids and exhibit biomagnification as they progress through the food chain. Organisms inhabiting upper trophic levels, such as humans, have the potential to encounter elevated concentrations of certain substances, with levels in their bodies reaching magnitudes that are approximately 10 million times superior to those present in the surrounding water (Osuala et al., 2020; Xie et al., 2022). According to Rossi et al. (2020), the pesticides used in rice fields, such as glyphosate, bifenthrin, azoxystrobin, and cyproconazole, are indeed accumulating in fish and having an effect on their physiology, biochemistry, and therefore their health. Additionally, it was noted that the combination of pesticides could potentially pose a threat to human health via the food chain due to the bioaccumulation of these substances in fish. In a separate study, Clasen et al. (2018) conducted an observation wherein they found that the pesticides, lambda-cyhalothrin and tebuconazole exhibited bioaccumulation in the muscles of carp (*Cyprinus carpio*) over a 100-day period of exposure in an integrated rice-fish farming systems. Additionally, the researchers highlighted the significant negative impacts of these pesticides on fish populations, as well as their potential to pose a threat to human health through the process of bioaccumulation in farmed fish. Bioaccumulation is a phenomenon that can also be observed in the fish species that reside in open water environments (Figure 2) (Gerber et al., 2016). For instance, the accumulation and identification of organochlorine pesticides were observed in the fish species, namely *Oreochromis mossambicus* and *Clarias gariepinus*, inhabiting an estuarine zone. The recorded amounts of these pesticides surpassed the highest residue limits

established by the European Commission, hence posing a potential health concern (Buah-Kwofie et al., 2018). Additionally, it was observed that there was a buildup of pyrethroid insecticides in the wild fish specimens obtained from the river. Moreover, the levels of pyrethroids detected in carnivorous fish were significantly greater compared to those discovered in omnivorous and phytophagous fish (Xie et al., 2022). The findings presented in these studies offer empirical support for the potential risks associated with pesticide pollution in aquatic ecosystems, hence posing a significant hazard to human health.

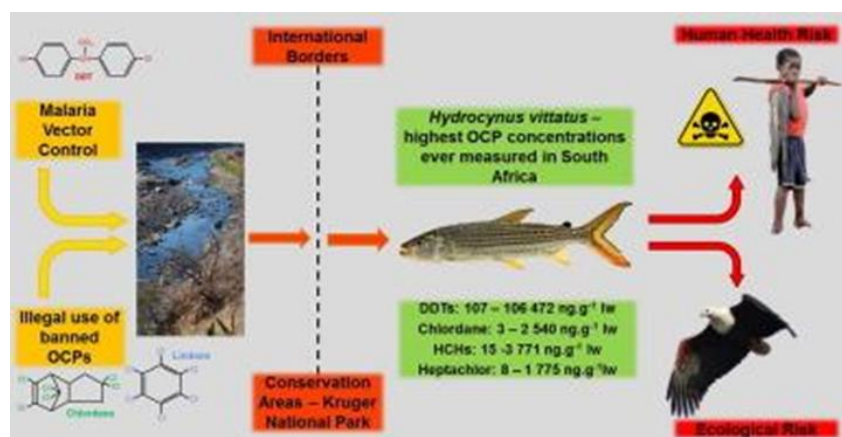


Figure 2. Bioaccumulation of pesticides that threaten human health (Gerber et al., 2016)

### Pesticides toxicity in mangrove and estuary

Mangroves are a distinctive assemblage of plant species that thrive in tropical and sub-tropical coastal regions. They possess the remarkable capacity to mitigate various forms of pollution, including heavy metals and permanent organic compounds, inside coastal waterways (Ivorra et al., 2021). Mangroves have emerged as a highly imperilled and susceptible environment, facing escalating ecological stress due to intensified human activities. Mangrove forests have a crucial role in mitigating the impact of anthropogenic pollutants because to their elevated primary productivity, copious organic matter debris, fine-grained soil composition, and oxygen-deprived conditions (Chen et al., 2020). Mangrove ecosystems have robust flushing and intermittent flooding cycles that are driven by tidal patterns. The hydrological conditions present in areas with robust flushing and tidal effects, can potentially contribute to the observation of lower concentrations of organochlorine pesticides (OCPs). The vigorous flushing currents characteristic of these areas generates an upwelling force that acts between the sediments at the surface and the water that has the potential to enhance the presence of suspended particles within the water column (Wong et al., 2006; Ivorra et al., 2021). Given the moderate to high lipophilicity of the target compounds, with logP values ranging from 1.7 to 6.2, it is reasonable to hypothesize that these compounds will exhibit a preference for adsorption onto suspended particles. This phenomenon would eventually lead to their accumulation in the sediments of mangrove ecosystems, as previously noted by Tam et al. (2001). A scientific research was undertaken to examine the bioaccumulation patterns of OCPs and PCBs within three mangrove reserves located in southern China. The research uncovered the existence of bioaccumulation of OCPs and PCBs in these mangrove ecosystems. Furthermore, it was observed that lower chlorinated PCB congeners exhibited higher levels of bioaccumulation within the mangroves (Qiu et al., 2019). In another investigation, Shete et al. (2009) examined the presence of organochlorine pesticides (OCPs), specifically hexachlorocyclohexane (HCH), Aldrin, Endosulfan, DDE, DDD, and DDT, in different components of *Avicennia marina*, including the leaf, root, and sediment. The findings indicated that the leaf and root samples exhibited higher levels of OCP uptake, while the sediment samples displayed comparatively lower concentrations of these pesticides. Furthermore, Borrell et al. (2019) performed a study to evaluate the levels of polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDT) in fish and crustaceans inhabiting the Sundarbans mangroves in Bangladesh. The researchers found that the median values for tDDT and PCBs were determined to be under the limits of detection at 176.3 ng/g lipid weight and 275.9 ng/g, respectively. In general, the reported concentrations in these regions were comparatively lower when compared to those typically observed in other global regions.

Estuaries, coastal lagoons, and other transitional habitats have a propensity to serve as primary repositories for contaminants that are carried by continental runoff. Of particular concern within this category are pesticides. The presence of elevated levels of dissolved and particulate organic matter significantly facilitates the deposition of pesticides, which then become sequestered in sediment or are transferred through various trophic levels in ecosystems. It is not unexpected to observe heightened concentrations of pesticides in estuary sediments even several decades following their prohibition (Matthews, 2015; Cuevas et al., 2018). The broad spectrum of organisms targeted by pesticides, ranging from plants and fungus to molluscs and insects, renders them capable of impacting all components of the intricate estuarine food web, including people. This is attributed to the distinct mode-of-action exhibited by these chemical agents (Cuevas et al., 2018). Pesticides, even when present in residual amounts, can have a variety of impacts including endocrine disruption, nervous system damage, immunotoxicity, and obstruction of photosynthesis (Casida, 2009; Cuevas et al., 2018). Various estuaries across the globe have been shown to contain a diverse range of pesticides. For instance, a study investigated the levels of isomers of hexachlorocyclohexane (HCHs), dichlorodiphenyl trichloroethane and its metabolites (DDTs) in sediment samples obtained from the entrance of the Hugli estuary in India. The findings revealed that the concentrations of these compounds were found to be relatively low. Furthermore, among the isomers and metabolites of HCH and DDT,  $\beta$ -HCH, pp'-DDT and pp'-DDE were established to be prevailing (Bhattacharya et al., 2003). In a distinct study, the presence of 17 OCPs was assessed in surface sediments obtained from the Zhang River Estuary located in the southeastern region of China. It is worth noting that the usage of  $\gamma$ -HCH (commonly known as lindane) and endosulfan in the vicinity of this particular mangrove forest has been infrequent in recent times. However, the ratios of (DDD+DDE)/DDT indicated that the usage of DDTs was yet being conducted in violation of regulations (Chen et al., 2020). Furthermore, an investigation was conducted to determine the concentrations of various OCPs residues (specifically DDT, DDE, Aldrin, Lindane, Heptachlor, Dieldrin and BHC) in different organs of *Lates calcarifer* during both the dry and rainy seasons in the Ganges–Brahmaputra–Meghna estuary of Bangladesh (Rahman, 2005). The results revealed that the residues were detected in the following order: highest in eggs, followed by the gut, muscle, and liver. The detected pesticide residues exhibited the following ranking:  $\sum$ DDT > Heptachlor > Dieldrin > Aldrin. Elevated amounts of residues were observed in the dry season as a result of the heightened fat content present in fish specimens (Jabber et al., 2011).

### **Immunotoxic effects induced by pesticides in fish**

Numerous aquatic species, including algae, shellfish, fish, as well as mammals, experience physiological impacts as a consequence of pesticide exposure originating from the agricultural sector. The bioaccumulation of pesticides in water bodies results in their subsequent transmission to higher trophic levels within the food chain. It is common to detect biomagnification of pesticides when fish are present because of their position at the top of the aquatic food chain (Henny et al., 2003; Yang et al., 2021). Approximately half of the pesticides persist in fish for a duration exceeding 30 days, therefore rendering fish as valuable parameters of environmental contaminants (Guo et al., 2008). It has been established that numerous pesticides can cause sublethal toxicity in fish, such as endocrine disorders and impaired swimming abilities (Brewer et al., 2011; Yang et al., 2021). Pesticides released into water can impair the immune response of fish, thereby contributing to the devastation of the environment by rendering fish susceptible to pathogens like viruses, bacteria, and metazoans. Fish, being the initial phylogenetic group to possess both an innate as well as an adaptive immune system, are predominantly employed as a biological model for investigating the impact of external stressors on the immune response (Litman et al., 2005; Lafferty et al., 2015; Yang et al., 2021). The assessment of immunotoxicity caused by pesticides encompasses the examination of many criteria, such as the levels of immunoglobulins, alterations in immune cells, and the generation of cytokines. The immune parameters of fishes, such as haematology, lysozyme levels, and immunoglobulin M (IgM) concentration, are regulated by variables like photoperiod, temperature, and oxygen concentration (de Souza et al., 2016; Yang et al., 2021). Multiple investigations have been undertaken to evaluate the immunotoxicological impacts of pesticides on aquatic organisms, specifically fish (Figure 3). For instance, the effect of 3 pesticides (chlorothalonil, cypermethrin and pentachlorophenol) was observed on the innate immune response of *Oncorhynchus mykiss*. The results from the study indicated an on-going effect of pesticides on the immune system of fish, as evinced by increased levels of phagocytic leukocytes, respiratory burst, and phagocytic cells activity (Shelley et al., 2009). In the study, Chen et al. (2014) observed that prolonged exposure to Atrazine, chlorpyrifos, and a combination of the two chemicals can lead to the disruption of pro-/anti-inflammatory cytokine expression in the kidney, head and spleen of carp fish. According to a study, there was a significant rise in lysozyme activity observed in the liver and spleen of

beluga fish (*Huso huso*) when treated to diazinon acutely at 1.5 mg/L. Nevertheless, when exposed to this pesticide for a subacute and subchronic duration, there was a notable decline in lysozyme activity observed in the plasma, liver and kidney (Khoshbavar-Rostami et al., 2006). The application of Organophosphorus pesticides, phosalone also significantly affected the haematological variables (red blood cell, white blood cell, hemoglobin, corpuscular volume mean) and different immune parameters (Nitroblue tetrazolium, lysozyme, and myeloperoxidase activities) of carp (*Cyprinus carpio*) fish (Kaya et al., 2015; Shaikh et al., 2010). There exist multiple lines of data indicating that the immunological response of fish can be modified due to pesticide exposure.

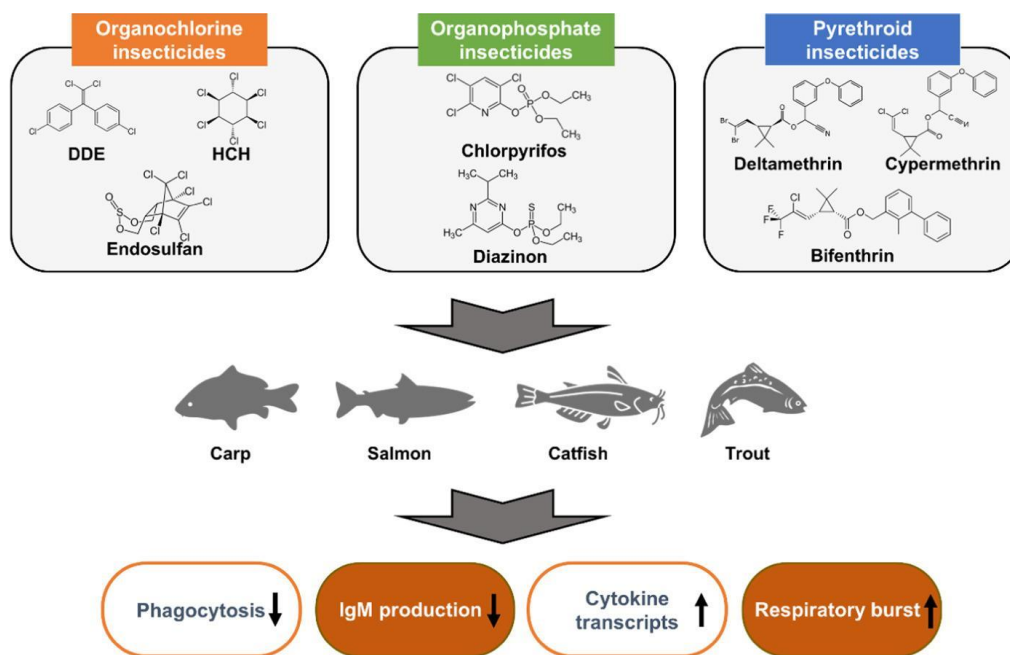


Figure 3. A summary of fish immunotoxic effects caused by pesticides (Yang et al., 2021).

### Pesticide transformation products on fish health

In recent years, there has been a development of novel pesticides that exhibit a more targeted mechanism of action, along with increased polarity and decreased persistence compared to their predecessors. Pesticides have the potential to undergo transformation in several environmental compartments, including crops, animals, and humans, resulting in the production of numerous degradation products. These degradation products are often referred to as transformation products (TPs), but alternative terminology such as metabolites or derivatives may also be employed (Vidal et al., 2009). Presently, there exists a growing apprehension surrounding the development of transformation products (TPs) due to the presence of evidence suggesting that these substances may possess more toxicity and persistence compared to their precursor molecules (Belfroid et al., 1998; Vidal et al., 2009). Pesticides undergo biotic and/or abiotic transformation processes, which determine whether they are transformed or eliminated based on factors such as transit, persistence, and destination. The transformation routes encompass a range of processes, such as (de)methylation, (de)alkylation, reduction, oxidation, hydrolysis, hydroxylation, and cleavage, and so forth (Figure 4) (Vidal et al., 2009; Anagnostopoulou et al., 2022).

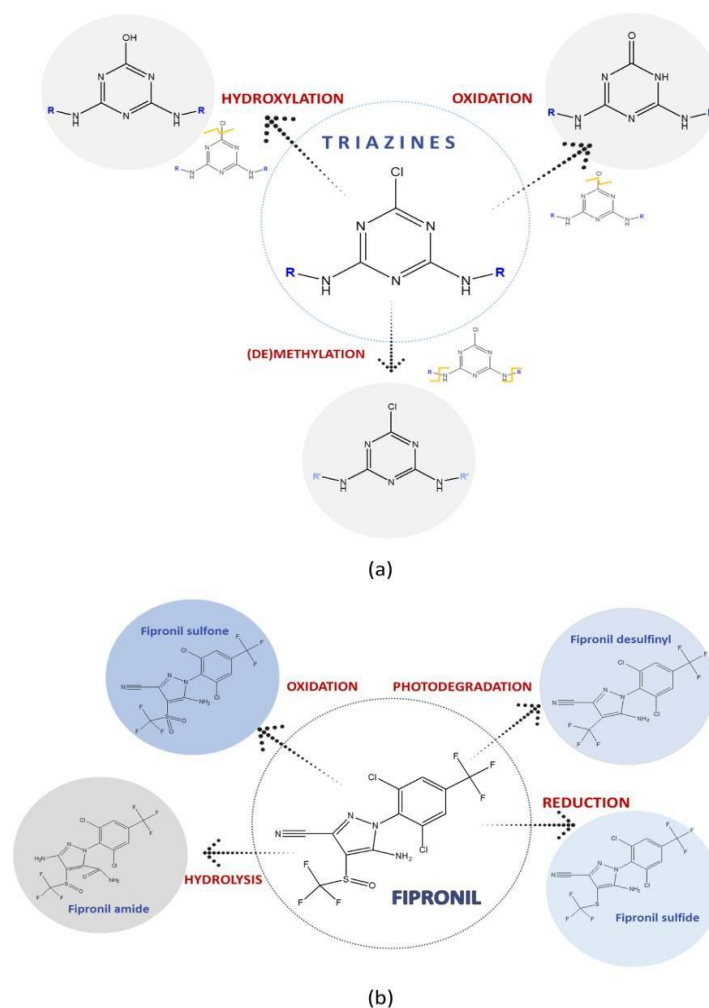


Figure 4. Suggested transformation pathways for (a) triazines, (b) fipronil

In the context of the environment, photodegradation plays a significant part in the degradation procedure of pesticides. This process is influenced by several elements such as climate conditions and the presence of photosensitisers (Zhao and Hwang, 2009). Multiple scholars have conducted a comprehensive review of the transformation products derived from pesticides (Vidal et al., 2009; Anagnostopoulou et al., 2022). The TP also exert a significant impact on the water environment and fish populations. For instance, a study was conducted on a small lentic water body to examine the occurrence of 20 pesticides and 20 transformation products in water, sediment, and fish samples. The findings indicated that the water samples exhibited the highest concentrations of metazachlor-OXA, whereas the sediment samples contained elevated levels of benzamide. The concentrations of the transformation products of atrazine, flufenacet, imidacloprid, metazachlor, and metolachlor were found to be higher compared to their respective parent chemicals. A reduced number of contaminants were seen in fish, with the primary accumulation occurring in organisms being prosulfocarb throughout the cycle (Slaby et al., 2022). In a separate study, a comparison was made between the toxicity of TPs and the parent molecule on fish, daphnids, and algae. The findings revealed that most (70%) of TPs exhibited either comparable or reduced toxicity when compared to the parent substance. Nevertheless, a considerable percentage (30%) of these TPs demonstrate elevated levels of toxicity in comparison to their original compound whereas 4.2% of the transformation products demonstrate toxicity levels that surpass the original compound by more than tenfold (Sinclair and Boxall, 2003).

### Effect of cypermethrin on fish

Cypermethrin, a synthetic pyrethroid, is a widely utilized insecticide with broad-spectrum efficacy. It finds considerable application in residential, industrial, and agricultural areas for the purpose of managing various insect pests (Kakko et al., 2003). There is compelling evidence indicating that, this novel insecticide, when applied correctly, can repel and control mosquitoes, with the best results being seen in preventing several different types of malarial parasites (Bekele, 2018). Furthermore, on a global scale, aquaculturists employ the utilization of this particular pesticide in order to effectively manage parasite illnesses, specifically targeting planktonic marine copepods (Boxshall and Defaye, 2008). Cypermethrin readily permeates the nervous system of animals and induces cellular oxidative damage by stimulating the generation of free radicals and decreasing the body's antioxidant effects (Afolabi et al., 2019).

Cypermethrin enters natural water bodies through agricultural runoff as a result of the indiscriminate utilization of these substances which has a consequential effect on several aquatic creatures that are beyond the intended recipients (Figure 5) (Kakko et al., 2003; Tiwari et al., 2012). Multiple studies have demonstrated that cypermethrin exposure triggers the genotoxicity and oxidative tension in *Danio rerio*, results in abnormalities in *Labeo rohita* during early developing phases, leads to immunotoxic effects in *Cyprinus carpio*, causes DNA destruction and histopathological changes in *C. carpio*, induces liver damage in *Catla catla* (Shaikh et al., 2010; Farag et al., 2021). A study was conducted to evaluate the immunomodulatory impact of cypermethrin on fingerlings of *Cyprinus carpio* L.. The results indicated a significant decrease in various immunological parameters, including leukocyte count, lymphocyte ratio, serum protein level, and phagocytic activity, subsequent exposure to cypermethrin (Soltanian and Fereidouni, 2017). Moreover, in a separate study, it was observed that cypermethrin has significant piscicidal properties when exposed to fingerlings of the fish species *Labeo rohita*. This exposure has been found to have detrimental effects on the behavioral patterns of the fish, causing a shift in their respiratory mechanism from aerobic to anaerobic pathways, restrict energy generation in the fish by suppressing the synthesis of ATP (Tiwari et al., 2012). The findings of a study indicate that prolonged exposure to cypermethrin may result in a range of pathological variations in the kidney of fish *Catla catla*, potentially disrupting the normal function renal excretion (Sharma et al., 2021). Histopathological alterations were seen in *Cyprinus carpio* L. as a result of cypermethrin toxicity. The aforementioned alterations encompassed lamellar cell hyperplasia, lamellae telangiectasia, and gill hypertrophy caused by cellular infiltration. Additionally, the liver exhibited bleeding, diffuse hydropic degeneration, and focal necrosis (Arslan et al., 2017).

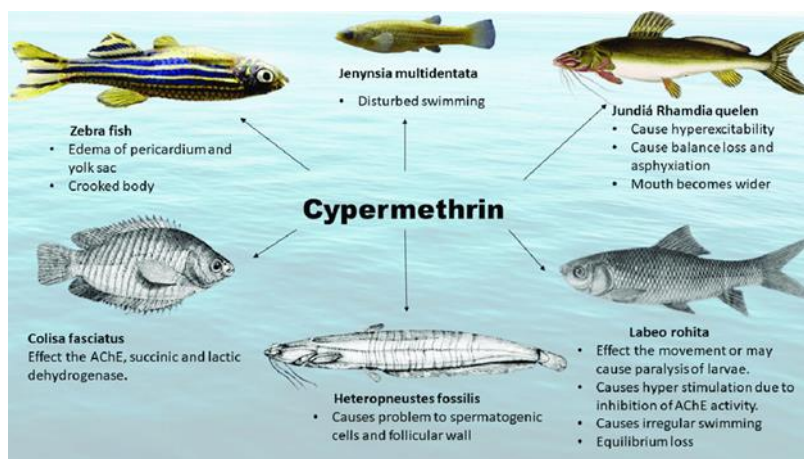


Figure 5. Effect of cypermethrin on fish (Kaur and Singh, 2021)

### Conclusion

Pesticide pollution presents a substantial threat to both the aquatic environment and many different organisms such as fish. The utilization of pesticides has been found to have detrimental impacts on various elements of fish, leading to significant losses in sustainable aquaculture practices. The toxicity of pesticides has negative effects on fish populations and raises significant health concerns for consumers due to the bioaccumulation of these chemicals in fish tissues. There has been an important shift in scientific focus on the transformation products (TP) of pesticides,

as their understanding of environmental destiny, appearance, and toxicity remains in its early stages. An expanding corpus of research indicates that pesticide transformation products may exhibit higher levels of toxicity, mobility, or persistence compared to the original parent substances. The scarcity of reference standards has resulted in a limited availability of toxicity data for TPs. Consequently, there remains a need for further exploration of the toxicity of TPs towards non-target organisms.

### Conflict of Interest

None of the authors present any conflicts of interest.

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