ANSF APPLIED AND NATURAL SCIENCE FOUNDATION

Journal of Applied and Natural Science
17(3), 961 - 972 (2025)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

Review Article

A review on aquatic ecotoxicity of profenofos with reference to environmental fate and impact on fish

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Article Info
https://doi.org/10.31018/jans.v17i3.6775
Received: April 23, 2025
Revised: July 18, 2025
Accepted: July 30, 2025

How to Cite

Chauhan, A. *et al.* (2025). A review on aquatic ecotoxicity of profenofos with reference to environmental fate and impact on fish. *Journal of Applied and Natural Science*, 17(3), 961 - 972. https://doi.org/10.31018/jans.v17i3.6775

Abstract

Profenofos (PFF), a widely used organophosphorus insecticide in agriculture, has raised serious environmental concerns due to its persistence and toxicity in aquatic ecosystems. This review critically examines the environmental fate, transformation pathways, and ecotoxicological effects of PFF, with a particular focus on fish. PFF enters aquatic environments through runoff, leaching, and direct application, where it undergoes hydrolysis and microbial degradation, producing metabolites such as 4-bromo-2-chlorophenol and dichlorvos. These compounds exhibit bioaccumulative and toxic properties, affecting key physiological systems in aquatic organisms. As sensitive bioindicators, fish experience a range of toxic effects, including oxidative stress, neurotoxicity, impaired respiration, reproductive dysfunction, and behavioral anomalies, even at sublethal concentrations. The compound's potential for biomagnification poses risks to higher trophic levels, including piscivorous birds and humans. This review identifies neurotoxicity, reproductive failure, and metabolic disruption in fish as the most prominent adverse outcomes of PFF exposure. However, limited data on chronic low-dose exposure, trophic transfer dynamics, and endocrine disruption mechanisms represent key knowledge gaps that require further investigation. Despite existing regulations, gaps persist in long-term monitoring, risk assessment, and identifying safe alternatives. This review emphasises the urgent need for integrated pest management (IPM), enhanced pesticide formulations, and stricter environmental policies to mitigate the ecological impacts of PFF and protect aquatic biodiversity.

Keywords: Organophosphorus, Profenofos, Aquatic ecosystem, Invertebrates, Fish

INTRODUCTION

Aquatic ecosystems are crucial components of the biosphere, supporting biodiversity and playing vital ecological roles in the cycling of nutrients, water purification, and habitat maintenance for numerousspecies (Irfan and Alatawi, 2019). Nevertheless, these ecosystems are increasingly threatened by human activities, especially the heavy application of pesticides in agriculture. Of these, organophosphorus (OP) insecticides have been a significant source of environmental concern due to their persistence, potential for bioaccumulation, and high toxicity to non-target organisms (Sidhu *et al*, 2019). Profenofos (PFF), a widely used organophosphate (OP) insecticide and acaricide, is extensively employed in agricultural environments globally (Kushwaha *et al*, 2016). OPs, which are known by their ester derivatives of phosphoric, thiophosphoric, and phosphoramidic acids, are powerful neurotoxins that inhibit acetylcholinesterase (AChE) activity, causing neurophysiological impairments in both target and non-target species (Raj *et al*, 2024). Originally introduced as substitutes for persistent and highly toxic chlorinated insecticides, OPs gained popularity due to their rapid degradation upon application and broad spectrum of efficacy (Paidi *et al*, 2021).

Profenofos [chemical name: O-(4-bromo-2-chlorophenyl) O-ethyl S-propyl phosphorothioate; molecular formula: $C_{11}H_{15}BrClO_3PS$; molecular weight: 220.98] is one of the widely used OP insecticides in agroecosystems (Ismail *and* Khalil, 2020). The chemical structure of PFF is shown in Fig. 1. It is used to treat a diverse range of crops, including vegetables, fruit, and cereals, as well as in domestic use for pest management (Radwan *et al*., 2005). PFF was introduced in the United States in 1982 as a problem-solving tool for controlling insect pests resistant to other OPs, such as chlorpyrifos (Cáceres *et al*, 2010). Its molecular constitution enables the addition of functional groups, creating various derivatives and metabolites. Interestingly, PFF residues have been reported in plant matrices, such as okra, gooseberries, chilli, cauliflower, and coriander, exposing terrestrial and aquatic ecosystems to potential risk (Mathew *et al*, 2024).

*A*s shown in Fig. 2, PFF exhibits high dispersal potential upon environmental exposure due tots physicochemical characteristics (Verma and Chatterjee, 2021). It is influenced by various pathways, including runoff to the surface, atmospheric deposition, leaching into groundwater, and direct application in aquatic ecosystems (Pérez-Lucas *et al*, 2019). When PFF is introduced into aquatic ecosystems, it undergoes photodecomposition and hydrolysis, yielding toxic metabolites such as 4-bromo-2-chlorophenol (BCP), which tend to exhibit greater toxicity compared to the parent compound. PFF in the water column of surface waters is partitioned between the water column, sediments, and aquatic life, where it accumulates and may also biomagnified through trophic levels (Ray and Shaju, 2023). PFF contamination is of significant professional importance in aquatic life, especially in fish, which are important biomarkers of pesticidal-induced toxicity in freshwater and marine ecosystems (Ismail *et al*., 2009).

The toxic implications of PFF in aquatic fauna are also becoming increasingly important, given its capacity to inhibit AChE activity, which leads to neurotoxicity, oxidative stress, metabolic impairment, and reproductive dysfunction in aquatic animals and other aquatic life (McDaniel and Moser, 2004). Developmental abnormalities, immune suppression, endocrine disturbances, and mortality in various aquatic animals are associated with FF exposure (Khan, 2020). Moreover, the accumulation of PFF and its metabolites in the tissues of aquatic animals poses a threat to trophic passage, eventually reaching higher trophic levels, including avian consumers and humans (Tison *et al*, 2024). Considering these effects, it is essential to examine PFF's mechanistic actions of toxicity, their environmental implications, and potential remedial strategies.

The review is based on the existing literature on PFF's ecotoxicological effects on fish, which cause physiological, biochemical, and behavioural changes that threaten aquatic biodiversity and ecosystem integrity. The review examined the environmental transport and fate mechanisms of PFF in aquatic ecosystems, including its persistence, transformation, and bioaccumulation; explored the toxicokinetic and toxicodynamic interactions of PFF in aquatic life, especially in fish, by analyzing its physiological and biochemical effects; examined the effects of PFF exposure on the health of fish and population dynamics, including neurotoxicity, oxidative stress, reproductive toxicity, and immunosuppressive effects; examine the larger-scale ecological implications of PFF contamination, with a focus on its biomagnification and trophic transfer in food webs; and integrate current discoveries of PFF-induced aquatic toxicity to identify new trends in research, knowledge gaps, and directions in ecotoxicological risk assessment and pesticide regulation. Thus, this review aims to provide a comprehensive assessment of the aquatic ecotoxicity of PFF, the risks it poses to fish, and the broader environmental implications of its use.

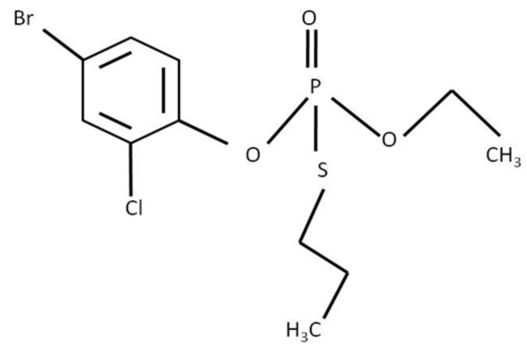

Fig. 1. *Profenofos (O-(4-bromo-2-chlorophenyl) O-ethyl S-propyl-phosphorothioate) (Source: https://pubchem.ncbi.nlm.nih.gov/compound/Profenofos; recreated by authors)*

METHODOLOGY ADOPTED FOR LITERATURE

This review was conducted through a structured search and critical appraisal of published scientific literature from major databases, including Scopus, Web of Science, PubMed, and Google Scholar. Keywords such as "profenofos," "aquatic toxicity," "organophosphates," "fish biomarkers," "bioaccumulation," and "environmental fate" were used to retrieve only relevant studies published between 1990 and 2025. The inclusion criteria emphasised peer-reviewed original research and review articles focusing on the toxicological effects of profenofos on aquatic organisms, particularly fish. Articles were screened for methodological robustness, data relevance, and ecological significance. The selected studies formed the basis for synthesis, comparative analysis, and the identification of critical knowledge gaps in the field.

IMPACTS ON AGROECOSYSTEMS: TARGET AND NON-TARGET SPECIES

Target species refer to the specific pest organisms that PFF is intended to control, such as insect pests and mites affecting crops. Non-target species include beneficial insects, pollinators, natural predators, and other organisms unintentionally exposed to PFF. PFFs are used for a wide range of applications in agroecosystems, including insecticides, acaricides, defoliants, sol-

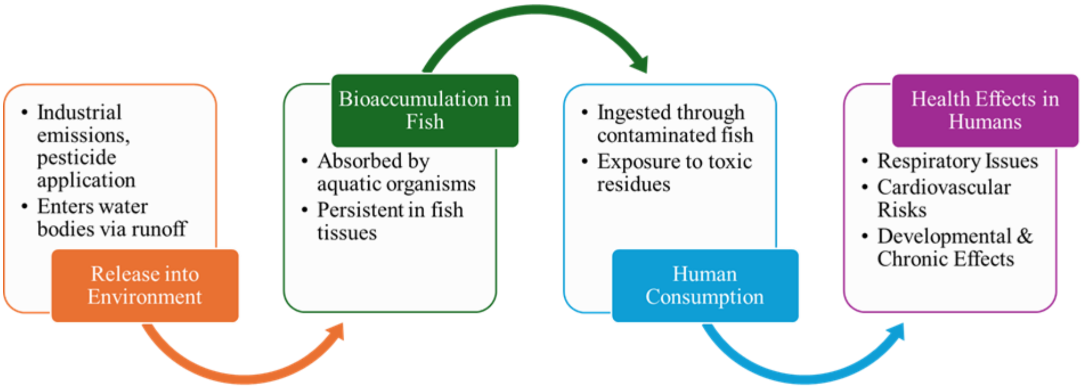

Fig. 2. *Route of profenofos exposure and impacts on human physiological systems*

vents, plasticisers, and fire retardants(Nwagu, 2023). Despite restrictions on the application of PFF in specific areas, it is still extensively used in managing a wide category of agricultural pests (Fig. 3). It is especially useful in controlling cotton bollworm (*Helicoverpa zea*), tobacco budworm (*Heliothis virescens*), spider mites (*Tetranychus urticae*), nut-infesting eriophyid mite (*Aceria guerreronis*), armyworm (*Mythimna unipuncta*), whiteflies (*Trialeurodes vaporariorum*), cotton aphid (*Aphis gossypii*), plant bugs (*Lygus lineolaris*), and leafhoppers (*Halticus bractatus*) (Kushwaha *et al* ., 2016).

PFF is used globally in both developed and developing countries, such as in the United States, India, China, Thailand, Vietnam, Pakistan, Australia, Japan, Egypt, and Brazil, mainly for cotton (*Gossypium hirsutum* L.) and coconut (*Cocos nucifera* L.) pest management (Malinga and Laing, 2024). It is estimated that the annual global PFF usage in cotton fields alone accounts for approximately 352,000 kg, of which almost 85% of the active ingredient was aimed at Lepidopteran insects (Eriksson, 2019). Apart from cotton, PFF is used as a foliar spray on various crops, including vegetables, fruits, salad greens, onions, foliaceous plants, and rice, which demonstrates the wide scope of PFF's application in pest protection across different agricultural systems (Russell, 2004). Even though PFF is efficient in controlling pests, its application in agroecosystems is problematic in terms of its effects on non-target species, environmental persistence, and indirect toxicity towards beneficial species. The widespread use of PFF has been associated with negative environmental effects, including reduced populations of pollinators, depletion of natural predator species, and pollution of surrounding soils and water resources (Singh *et al*,

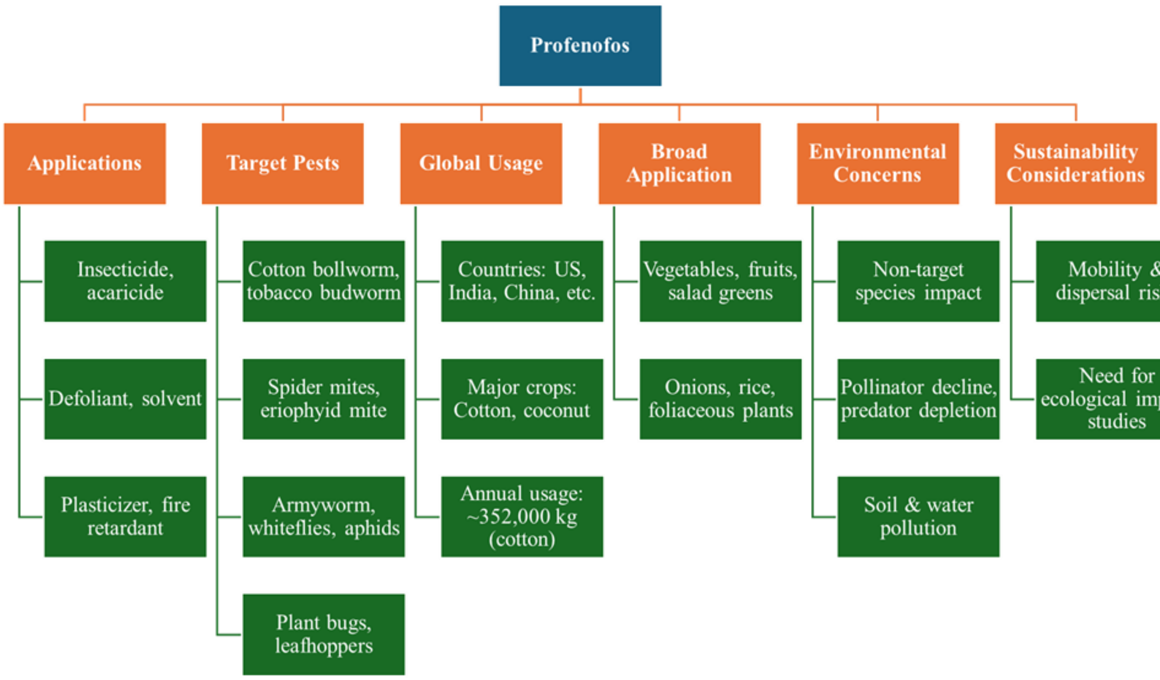

Fig. 3. *Profenofos applications, target pests, global usage, environmental concerns, and sustainability considerations in agroecosystems*

2023). Due to PFF's high mobility and environmental dispersal potential, it is crucial to investigate its indirect ecological effects to ensure sustainable agricultural practices and assess pesticide risks.

BIOTRANSFORMATION AND BIOACCUMULATION IN AQUATIC SYSTEMS

PFF is water-soluble, allowing it to spread rapidly in aquatic ecosystems (Fig. **4**). Due to its relatively short half-life in water, PFF undergoes significant transformations through hydrolysis, microbial activity, and photodegradation (Zhang *et al*, 2024). (Ghazala *et al* ., 2014) reported that PFF dissolves in water at a concentration of 1 mg/L, as analyzed using high-performance liquid chromatography (HPLC) in both water and solvent samples. Once introduced into aquatic systems, PFF undergoes hydrolysis, producing two key secondary metabolites: dichlorvos and 4-bromo-2-chlorophenol (Dadson *et al*, 2013). These metabolites possess distinct toxicological characteristics compared to the parent compound, potentially altering their bioavailability and overall ecological impact. The rate and pathways of PFF degradation are influenced by environmental factors such as pH, microbial activity, temperature, and exposure to reactive agents (Verma and Chatterjee, 2021). Microbial degradation plays a critical role in PFF breakdown, significantly reducing its environmental persistence. However, when introduced into surface waters through agricultural runoff, atmospheric deposition, or direct application, PFF can persist and accumulate before fully degrading (Singh *et al* ., 2023). Its transformation products, including dichlorvos and 4-bromo-2-chlorophenol, may either remain in aquatic ecosystems or undergo further degradation, influencing their bioavailability to non-target organisms such as aquatic invertebrates and fish (Verma and Chatterjee, 2021). The bioaccumulation of PFF and its metabolites in aquatic organisms raises significant ecotoxicological concerns. The accumulation of these compounds in fish tissues can lead to sublethal effects, including behavioural changes, reproductive impairment, and immune system suppression, ultimately affecting population stability and overall ecosystem health (Mohamed *et al*., 2020). Therefore, studying PFF's transformation pathways and bioaccumulation potential is essential for assessing its long-term environmental risks and developing effective strategies to mitigate its impact on aquatic biodiversity.

IMPACT ON FISH

Table 1 shows the effects of PFF exposure on various hydrobiological parameters of fish species. PFF has significant toxic effects on non-target aquatic organisms, including both invertebrates and vertebrates (Moura and Souza-Santos, 2020). Once introduced into aquatic environments, PFF accumulates in sediments, benthic deposits, and surface water layers, acting as a long-term contamination source in rivers, lakes, and ponds (Tilak, 2019). These sedimentary reservoirs continuously release PFF and its metabolites into the water column, leading to prolonged exposure to aquatic life. Planktonic communities and benthic invertebrates—key primary consumers in aquatic ecosystems—are particularly vulnerable (Sánchez-Bayo, 2021). Since plankton forms the foundation of aquatic food webs, its contamination with PFF leads to bioaccumulation and subsequent biomagnification across higher trophic levels, including fish. This can cause behavioural and physiological disruptions, contributing to species decline and ecosystem instability (Rico-Martínez *et al* ., 2022).

Beyond behavioural changes, even sublethal exposure to PFF induces physiological and biochemical disturbances in fish. Experimental studies have revealed that even low concentrations of PFF can interfere with es-

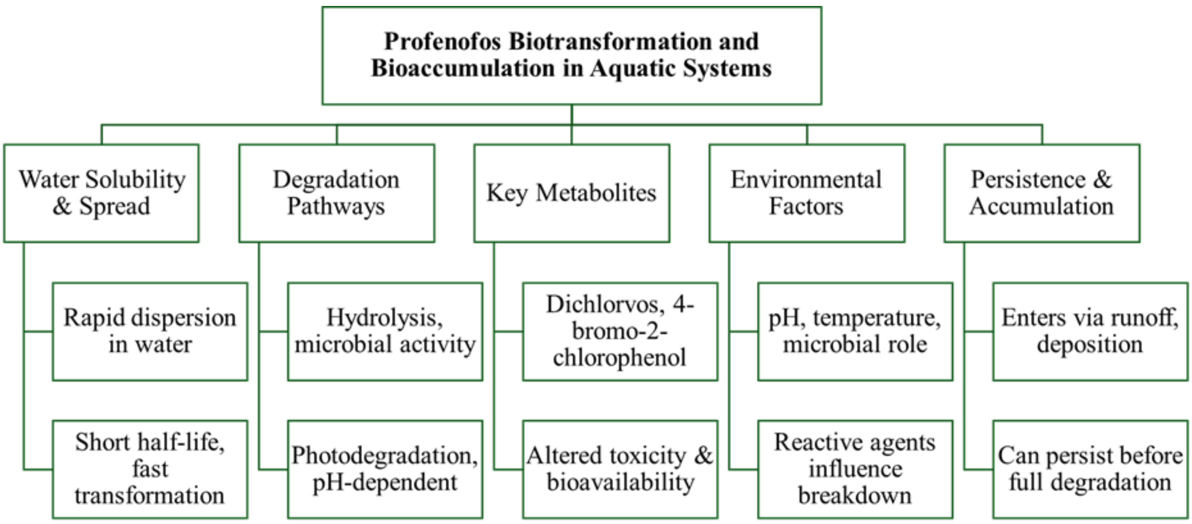

Fig. 4. *Profenofos transformation pathways, key metabolites, bioaccumulation risks, and environmental impact in aquatic systems*

Table 1. Profenofos (PFF) exposure effects on various hydrobiological parameters and fish species

Fish Species	Duration of Exposure	LC_{50}	Parameter studied	Impacts and target systems	References
Channa gachua	21 days	0.5-2.0 mg/L	Temperature	Gill structure	Rai (2025)
Oreochromis mossambicus	96 hrs	2.00 µL/L to 2.80 µL/L	-	Alterations in the liver, kidney, and brain tissues	Pawar and Shrivastava (2023)
Ctenopharyngodon Idella	21 days	1.8 µg/ L and 3.6 µg/ L	-	Affected physiological functions and tissue integrity	El-bouhy *et al*. (2023)
Oreochromis Nilotic	7 days	0 to 0.15 mg/L	-	Hematological and histological alterations	Dayananda, and Surendran (2022)
Clarias gariepinus	96 hrs	3.0 mg/L	-	Induced oxidative stress parameters	Nwamba *et al*. (2024)
Oreochromis niloticus	48 hrs	0.046 mg/L	-	High mortality and slow activities	Vroumsia *et al*. (2014)
Labeo rohita	48 hrs	0.31 mg/L	physico-chemical analysis	Damage to kidney and liver	Mishra *et al*. (2025)
Labeo rohita	28 days	0.6 mg/L	-	Histological changes in kidney, gills and liver	Mahmood *et al* . (2023)
Oreochromis niloticus	96 hrs	0-40%	-	Toxic effects on blood of fish	Al-Emran *et al* (2022)
Paratya Australiensis	24 hrs	0.10 µg /L	Temperature	AChE activity at the end of the recovery phase remains depressed	(Abdullah *et al* ., 1994)
Gambusia affinis	4,8,12, 16 and 20 days	0.25, 0.5, 0.75, 1.0, and 1.25 mg/L	Temperature, pH, dissolved oxygen, total hardness, chlorides	Alterations in locomotor behavior and gill architecture	(Begum *et al* ., 2006)
Barbonymus Gonionotus	96 hrs	0.1 mg/L	Temperature, DO, pH	Major effects in the kidneys include vacuolation of epithelial cells of uriniferous tubules and degeneration of glomeruli	(Islam *et al* ., 2019)
Cyprinus carpia	96 hrs	62.4 µg /L	Temperature, pH	Very high toxicity to the fingerlings as compared to other stages of fish	(Ismail *et al* ., 2009)
Therapon jarbua	24, 48, 72 and 96 hrs	21.5, 43.0, 86.0, 172.0, 344.0 µg /L	Salinity, Temperature, Dissolved oxygen and pH	Possible genotoxicity even in low concentration.	(Janaki Devi *et al* ., 2012)
Paraelphura jacquemontii	96hrs	0.0038 mg/L	Temperature	Several alterations in the histo-architecture of the gills	(Maharajan *et al* ., 2013)
Catla catla	7 days	0.04, 0.06, 0.08, 0.10, 0.12, 0.14 and 0.16 mg/L	Temperature	Altered rates in respiration of freshwater fish	(Maharajan *et al* ., 2013)
Labeo rohita	10 µg /L	96 hrs	Turbidity, Silica, Calcium hardness, SO_4, Chloride, Fluoride, Iron, Dissolved oxygen, Temperature	Reduction in RBC and haemoglobin values; increased total leucocyte count (TLC); increased lymphopoiesis	(Nagaraju *et al* ., 2013)
Channa punctatus	96 hrs	1.15 mg/L	Temperature, pH, DO	Assessment of DNA damage by micronucleus assay	(Atindra *et al* ., 2014)
Channa striatus	96 hrs	1.25 mg/L	Temperature, pH, Dissolved oxygen, Total hardness	Hypertrophy of hepatocytes, necrosis, blood congestion, vacuolation, cellular degeneration, damage of nuclei in the liver	Suja *et al* . (2019)

Contd…...

Nile tilpia	96hrs	0.87 mg/L	pH, Temperature, and hardness $CaCO_3$	Glucose levels increased proportionally with time of chronic exposure; liver and muscle glycogen decreased dramatically.	(Sharafeldin *et al* ., 2014)
Barbonymus gonionotus	7, 15, and 30 days	0.2, 0.1, 0.05, 0.06, 0.07, and 0.08 mg/L	Temperature, Dissolved oxygen and pH	Harmful impacts on nourishment and health	(Islam *et al* ., 2019)
Clarias gariepinus	96hrs	5.98 mg/L	Temperature	Abnormal skin pigmentation; neurotoxicity	(Bakhshwan *et al* ., 2009)
Notopterus notopterus	96hrs	0.7 µg /L	Temperature, pH	Histological alterations in the kidney	(Tazeen and Kulkarni, 2019)
Labeo rohita	24hrs and 96hrs	1.8 mg/L and 10 µg /L	Dissolved oxygen (DO)	Sublethal concentration of chlorantraniliprole pesticide effects on the levels of proteins, glycogen, free amino acids, and total lipids.	(Nagaraju *et al* ., 2013)

sential metabolic processes, leading to changes in oxygen consumption, haematological imbalances, and enzyme dysfunction (Al-Emran *et al*, 2022). The liver and kidneys—critical detoxification and excretory organs—are particularly susceptible to PFF-induced damage. Histopathological studies indicate that PFF exposure leads to cellular degeneration, necrosis, and structural alterations in these organs, thereby disrupting physiological stability (Mohamed *et al*., 2020). These effects impact individual fish health and pose serious population-level threats by reducing reproductive success and increasing vulnerability to environmental stressors, ultimately endangering the long-term sustainability of the species (Scholz *et al*, 2012).

PFF-induced toxicity can manifest in both acute and chronic forms, even at low dissolved concentrations. Studies indicate that at just 1 mg/L, PFF causes significant toxicity in the liver, kidneys, brain, and gills—the most vulnerable organs (Georgieva *et al* ., 2021). However, the severity of toxicity varies across species and tissues, depending on species-specific metabolic processes, bioavailability, and environmental conditions. Even exposure to sublethal doses can result in profound morphological, physiological, and behavioral alterations. Fish are highly sensitive bioindicators, often exhibiting rapid physiological and behavioural responses to disruptions in endocrine and enzymatic systems. In ecotoxicological studies, behavioral phenotyping serves as a crucial endpoint, with common symptoms including erratic swimming, hyperactivity, loss of equilibrium and movements, etc. (Stanley and Preetha, 2016)

PFF exposure also disrupts predator-prey dynamics by altering schooling behaviour and escape responses, rendering exposed fish more vulnerable to predation (Sandoval-Herrera *et al*, 2019). These behavioural impairments are closely linked to underlying neurophysiological and biochemical disturbances. One of the earliest indicators of pesticide toxicity is the alteration of respiratory metabolism, reflected in fluctuating oxygen consumption rates—an essential physiological response to toxicant exposure (Maharajan *et al*, 2013). Variations in oxygen uptake across different fish species highlight differing sensitivities to PFF toxicity. Haematological biomarkers, such as fluctuations in red blood cell counts, haemoglobin levels, and plasma enzyme activity, serve as early warning signs of toxic stress and declining fish health (Maharajan *et al*, 2013). The toxic effects of profenofos on fish vary across species, exposure durations, and concentrations. In *Channa gachua*, a 21-day exposure at 0.5–2.0 mg/L affected the gill structure, indicating respiratory stress (Rai, 2025). *Labeo rohita* demonstrated acute sensitivity, with a 48-hour LC50 of 0.31 mg/L, leading to renal and hepatic damage (Mishra *et al*., 2025). Chronic exposure for 28 days resulted in pronounced histopathological alterations in the kidney, gills, and liver (Mahmood *et al*., 2023). In *Oreochromis niloticus*, exposure to profenofos for 96 hours caused haematological toxicity, indicating systemic physiological stress (Al-Emran *et al*., 2022). These results emphasize species- and dose-specific vulnerabilities. A study on Mozambique tilapia (*Oreochromis mossambicus*) exposed to a profenofos-based insecticide (Profenofos 40% + Cypermethrin 4%) for 96 hours revealed significant histopathological alterations in the liver, kidney, and brain tissues, including cytoplasmic vacuolation, cellular degeneration, and damage to neural structures, indicating severe organ-specific toxicity (Pawar and Shrivastava, 2023). In grass carp (*Ctenopharyngodon idella*), exposure to sub-lethal concentrations of profenofos over 21 days led to behavioral abnormalities, microcytic hypochromic anemia, decreased serum protein levels, and histopathological changes in the liver, kidney, and muscles, suggesting that even low doses of profenofos can disrupt physiological functions and tissue integrity (El-bouhy *et al*. (2023). Similarly, Research on *Oreochromis niloticus* has demonstrated that exposure to profenofos leads to haematological and histological alterations, including changes in blood parameters and tissue structures, suggesting potential disruptions to the fish's physiological functions even at low pesticide concentrations (Dayananda and Surendran, 2022). In *Clarias gariepinus* fingerlings, profenofos exposure resulted in elevated oxidative stress markers and increased activities of antioxidant enzymes in liver tissues, highlighting the pesticide's capacity to induce oxidative damage and stress responses in aquatic organisms (Nwamba *et al*., 2024). Similarly, a study assessing the acute toxicity of profenofos on *Oreochromis niloticus* determined a 48-hour LC_{50} value of 0.046 mg/L, with observed behavioural changes, including erratic swimming and loss of balance, indicating the pesticide's high toxicity to this species (Vroumsia *et al*., 2014). The toxic effects of PFF are not limited to fish. Biochemical and histopathological damage has also been observed in avian species such as the great egret (*Egretta alba*) (Taha, 2022). In fish, PFF crosses the blood-brain barrier, leading to neurological impairments, hematological disturbances, renal toxicity, reproductive dysfunction, and, ultimately, mortality. In *Cyprinus carpio* (common carp), PFF has been shown to cause hepatotoxicity and cytotoxic effects (Mahmood *et al* ., 2023). Similarly, Gambusia affinis (mosquitofish) exposure has been linked to locomotor impairments, disrupted swimming patterns, and severe histopathological changes in major organs (Venkateswara Rao *et al* ., 2006). The cumulative toxic effects of PFF on fish populations not only compromise individual survival but also pose a significant threat to biodiversity, ecosystem function, and the stability of aquatic food webs (Chagnon *et al*., 2015).

IMPACTS ON FISH REPRODUCTION

PFF and its metabolites have a significantly negative impact on fish reproduction by disrupting endocrine regulation and gonadal function in zebrafish (Sultana *et al*., 2021). Fish rely on a delicate balance of environmental cues and hormonal signals to regulate key reproductive processes such as gamete maturation, gonadal development, and spawning. However, PFF contamination interferes with these critical mechanisms, leading to reproductive impairments that can severely affect population dynamics and biodiversity (Boudh and Singh, 2018). Exposure to PFF has been linked to alterations in gonadal structure and function, reduced egg viability, and developmental abnormalities in larvae. While PFF is primarily known as a neurotoxicant, emerging research suggests that it may also act as an endocrine disruptor, interfering with neuroendocrine signalling and reproductive physiology in non-target species, including fish (Kumar *et al*., 2023). The endocrine system plays a crucial role in coordinating reproduction, and any disruption can have severe consequences. Studies in mammals, such as rats and rabbits, have shown that PFF exposure reduces circulating levels of key reproductive hormones, including estradiol, progesterone, and testosterone, in Halticus bractatus (Kushwaha *et al*., 2016). Although direct evidence of PFF's endocrine-disrupting effects in fish is still limited, similar hormonal imbalances could significantly impact their reproductive success (Sultana *et al*., 2021). Additionally, Socha *et al*. (2024) demonstrated how endocrine-disrupting chemicals, including profenofos, impair fish reproduction by disrupting the hypothalamic-pituitary-gonadal axis, resulting in hormonal imbalances and reproductive dysfunctions. In another study, Pamanji *et al*. (2015) found that profenofos exposure in zebrafish embryos caused developmental malformations and reduced survival rates, indicating its potential to disrupt early reproductive development. Also, Pamanji *et al*. (2016) demonstrated that profenofos exposure led to oxidative stress and inhibited hatching enzyme activity in zebrafish embryos, suggesting interference with reproductive processes. Tazeen and Kulkarni (2018) observed histopathological changes in the ovaries of *Notopterus notopterus* exposed to profenofos, including atretic follicles and degenerative oocytes, indicating impaired reproductive capacity. Similarly, Anamika and Singh (2015) reported that profenofos exposure in *Channa gachua* resulted in ovarian damage, such as reduced oocyte size and necrosis, highlighting its detrimental effects on female reproductive health. The physiological effects of PFF exposure include gonadal atrophy, reduced fecundity, and developmental defects in embryos and juvenile fish (Ghafarifarsani *et al* ., 2024). Hormonal disruptions caused by PFF can delay or even prevent spawning, leading to declining fish populations and potential disturbances in the stability of aquatic ecosystems (Li *et al*, 2023). This reproductive failure is particularly concerning in freshwater environments, where fish play a critical role in maintaining ecological balance. A reduction in reproductive success can lead to population declines, ultimately impacting trophic interactions and overall biodiversity (Singh *et al*, 2023). Thus, PFF seriously threatens fish reproduction by interfering with both neural and endocrine pathways. Understanding its precise mechanisms and developing strategies to mitigate its impact is essential for conserving aquatic biodiversity and sustaining fish populations in contaminated ecosystems.

IMPACT ON HIGHER TROPHIC LEVELS

PFF and its metabolites strongly tend to bioaccumulate and biomagnify within aquatic food chains, amplifying their toxic effects from primary consumers to higher-level predators, including piscivorous birds, mammals, and humans (Ray and Shaju, 2023). Due to its lipophilic nature, PFF accumulates in the fatty tissues and skeletal muscles of fish, which serve as major food sources for larger predatory species (Kushwaha *et al*., 2016). This persistent accumulation leads to increased concentrations of PFF residues at higher trophic levels, often exceeding those found in water and sediments. When organisms at the top of the food chain consume contaminated fish, PFF residues can interfere with physiological and biochemical functions, leading to various health complications (Mahmood *et al*, 2023). In humans, exposure to PFF has been associated with neurological issues such as dizziness, blurred vision, cognitive dysfunction, and headaches. In severe cases, prolonged exposure to even sub-lethal levels may contribute to chronic illnesses, including neurodegenerative diseases, endocrine disruption, and cardiovascular disorders (Sharma and Mohanty, 2024). Additionally, PFF exposure has been linked to dermatological conditions like skin rashes, as well as musculoskeletal issues such as body aches and muscle cramps. Long-term exposure over months or years, even at low concentrations, can result in chronic toxicity across multiple bodily systems. Studies suggest a correlation between pesticide exposure and an increased incidence of reproductive, respiratory, and cardiovascular diseases (Fucic *et al*., 2021). Given the widespread agricultural use of PFF, its environmental persistence, and its potential for trophic transfer, it is crucial to assess its long-term effects on both aquatic and terrestrial organisms.

Beyond its direct toxic effects, PFF also disrupts predator-prey dynamics and alters the natural functioning of ecosystems (Singh *et al* ., 2023). Behavioral and physiological changes in aquatic organisms can destabilize food web interactions, leading to biodiversity loss and compromised ecosystem health. Additionally, PFF residues can spread beyond aquatic environments through runoff, atmospheric deposition, and physical transport, contaminating terrestrial ecosystems and posing further risks to wildlife (Punniyakotti *et al* ., 2024). Thus, given the persistent environmental risks posed by PFF, there is an urgent need for strict monitoring, regulation, and management of its use. Implementing strategies such as Integrated Pest Management (IPM) should be a priority to promote environmentally safer alternatives and reduce reliance on hazardous agrochemicals (Deguine *et al*., 2021). Strengthening pesticide policies, encouraging sustainable agricultural practices, and enhancing conservation efforts through ecosystem-based management are essential steps toward minimizing the long-term ecological and public health impacts of PFF exposure (Neupane and Pokhrel, 2021).

Conclusion

The study concluded that the wide application of PFF in agriculture poses several environmental risks. PFF's overuse in various agroecosystems has led to its dispersal in water bodies through runoff, leaching, and atmospheric deposition. Being rapidly biotransformed in water, PFF forms metabolites such as dichlorvos and 4-bromo-2-chlorophenol, which tend to exhibit greater or similar toxicological profiles to the parent chemical. These transformation processes lead to the bioaccumulation of PFF and metabolites in the organs of aquatic fauna, such as invertebrates, fish, and amphibians. The bioaccumulation of PFF and metabolites, in turn, depends on various parameters, including pH, temperature, and waterborne microbial load. Furthermore, biomagnification through trophic steps raises concerns about compromising ecosystem integrity and the health of piscivorous animals, including humans, due to the accumulation of PFF and/or PCBs in higher trophic-level species. Particularly, the damaging effects in fishes are multi-faceted and encompass direct organ toxicity, behavioural aberrations, and reproductive dysfunctions. This may have a long-term impact on fish, resulting in a decline in population viability. Sub-lethal exposure levels, too, may trigger significant biochemical and physiological dysfunctions, underscoring the PFF sensitivity of aquatic fauna, such as invertebrates, fish, and amphibians. These observations highlight the need to reassess existing PFF utilisation patterns and underscore the importance of an integrated pest management strategy that may reduce dependence on PFF and other harmful organophosphates. The conclusions drawn herein are expected to provide evidence-based measures to counteract pesticide contamination and ensure the sustainability of aquatic ecosystems.

ACKNOWLEDGEMENTS

The authors are grateful to their host institutions for providing necessary facilities.

Conflict of interest

The authors declare that they have no conflict of interest.

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