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HAMPERED SURVIVAL STRATEGIES AND ALTERED FISH BEHAVIOUR UNDER THE THREAT OF FLUOXETINE, MICROPLASTICS, MERCURY TOXICITY, THERMAL DISCHARGE, AND PESTICIDES

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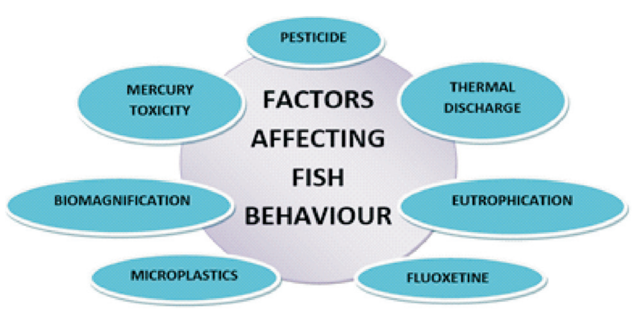
ABSTRACT

Human activities have caused significant ecological disruptions in aquatic environments, affecting fish behavior and threatening ecosystem stability. Mercury pollution, stemming from industrial and mining activities, infiltrates water bodies and accumulates in fish tissues, disrupting their neurological functions. This leads to altered behaviors such as disoriented swimming, impaired predator avoidance, and compromised foraging, jeopardizing their survival and ecological interactions. The bio magnification of mercury intensifies its toxic effects up the food chain, particularly affecting predatory fish. Microplastics, ubiquitous in water bodies due to human consumption and waste, pose another significant threat. Fish ingest these particles, which accumulate in their digestive systems and induce stress responses that alter behavior, reduce feeding activity, and impair reproduction. Thermal water discharge, a consequence of industrial processes and power generation, causes thermal stress in fish. This alters their behavior, forces changes in habitat and migration patterns, and exacerbates oxygen depletion, further compromising fish health. Pesticides entering waterways via runoff disrupt fish neurotransmitter systems and affect sensory perception, motor coordination, and reproductive behavior. Pharmaceutical pollutants like fluoxetine, an antidepressant, disrupt fish neurotransmitter systems, affecting behaviors such as swimming patterns, reduced foraging, and impaired predator avoidance. These pollutants can cascade through aquatic food webs, influencing community dynamics. Fish suffocate due to algal blooms that reduce oxygen levels, changing their behavior and habitat suitability. Eutrophication is caused by wastewater discharge and agricultural runoff. Addressing these multifaceted threats through sustainable practices is critical to preserving aquatic ecosystems and ensuring the long-term health of fish populations worldwide.

KEYWORDS: Fish behaviour, Anthropogenic activities, Fluoxetine, Microplastic, Mercury.

Graphical Abstract



Graphical Abstract: Alteration in the fish behavior under the threat of pesticides, thermal discharge, fluoxetine, microplastics, mercury toxicity, eutrophication and biomagnification.

INTRODUCTION

Human activities have wielded significant transformations upon aquatic realms, ushering in novel trials for fish populations. Within this scholarly exposition, we plumb the labyrinthine interplay connecting human-generated stressors and piscine conduct, casting a particular spotlight upon the impact of fluoxetine exposure, microplastic assimilation, thermal discharge, pesticides, and mercury's pernicious toxicity. Fluoxetine, a frequently prescribed antidepressant, infiltrates waterways by way of wastewater efflux from healthcare facilities and industrial sources, perturbing the neuroendocrine pathways of fish. This perturbation of neurotransmitter equilibrium can incite shifts in dietary habits, aggression, and procreative manners. The study scrutinizes inquiries that explore the repercussions of diverse fluoxetine densities across various piscine species, thus illuminating the intricate dimensions of this phenomenon. A growing worry is about microplastic pollution, these tiny particles that don't break down are affecting our aquatic bodies. Fish inadvertently imbibe these microplastics, thereby engendering potential for bodily harm, intestinal blockage, and chemical exposure. The analysis amasses proof of transmuted locomotion patterns, diminished foraging efficacy, and hampered predator-prey kinetics, all stemming from behavioral modifications catalyzed by microplastics. Because of their extensive pollution, capacity to pass through the biological barrier, and ingestion by aquatic creatures, microplastics (MPs) and nanoplastics (NPs) have drawn attention from all over the world. However, nothing is known about its toxicity, bioaccumulation, and interactions with other environmental contaminants. Because of their tiny size, ease of breeding, short life cycle, and low maintenance costs, zebrafish are being utilized more and more to investigate the bioaccumulation and toxicity of environmental pollutants (Bhagat *et al.*, 2020). Mercury, an omnipresent heavy weight metal, presents substantial menaces to aqueous ecosystems (Kumar *et al.*, 2023). Fish, in particular, exhibit susceptibility to mercury's toxicity, which imperils their nervous system and sensory faculties. The manuscript cogently evaluates explorations delving into how mercury pollution reshapes piscine demeanor, encompassing compromised predator discernment, curtailed evasive responses, and enfeebled reproductive triumph. This evaluation emphasizes the correlation of human activities and their combined impact on fish behavior (Fig. 1). Surveying inquiries spanning taxonomic and ecological variances accentuates the exigency for a comprehensive apprehension of the latent mechanisms.

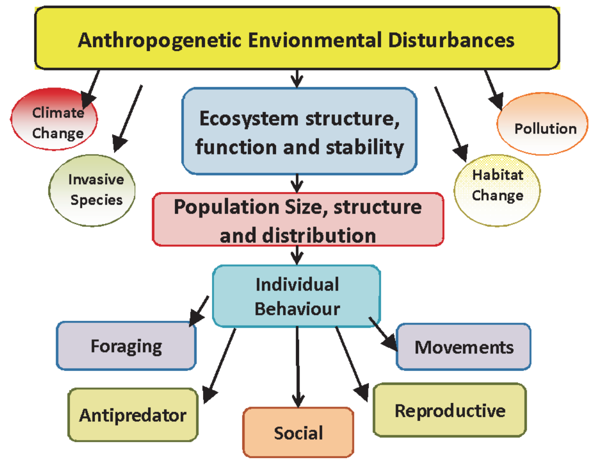


Fig 1. Contrasting effects of human activity on ecosystem

Fish frequently react to environmental changes brought about by humans with behavioral changes, which are crucial in determining whether they succeed in adapting or fail. It is essential to comprehend these behavioral reactions for efficient management and conservation. The review examines the relationship between fishing and fish behavior, contrasting active and passive techniques (such as longlines and trawls). According to the study, fishing affects not just particular behaviors but also a variety of behavioral, physiological, and life-history changes that can affect entire populations and ecosystems. These changes in behavior may have important ecological ramifications for survival, predation risks, foraging, and parental care. We indicate areas for further research and emphasize the significance of examining these effects for population resilience and fisheries management (Wang *et al.*, 2022). Human activities such as water pollution, eutrophication are known to alter temperature, dissolved oxygen, concentration and pH of the aquatic body and significantly impact the fish behavior, foraging, avoidance of predators, movements, reproduction and their habitat choice. Even their abundance, population, species diversity and distribution are affected (Candolin and Rahman, 2023).

In summation, this all-encompassing analysis elucidates the intricate liaison between anthropogenic endeavors and piscine conduct. Through illuminating the behavioral vicissitudes wrought by fluoxetine, microplastic uptake, and mercury's venomous influence, it underscores the imperative for sustainable methodologies and preservation endeavors, thus safeguarding aqueous ecosystems and the manifold ichthyic species they harbor. Each of these pollutants interacts uniquely with fish physiology and behavior, illustrating the complex and interconnected impacts of human activities on aquatic ecosystems. Understanding these effects is crucial for implementing effective mitigation strategies and preserving the health and balance of aquatic environments. The diverse impact of anthropogenic pollutants on fish behavior has been highlighted in Table 1.

Fluoxetine

Fluoxetine, a widely used antidepressant, works by increasing serotonin levels in the brain to regulate mood and anxiety (Jacobsen *et al*., 2023). These drugs can also be found in wastewater from industrial and research facilities. They enter the environment through various pathways. These selective serotonin reuptake inhibitor (SSRI) antidepressants are of increasing concern worldwide due to their ubiquitous occurrence and detrimental effects on aquatic organisms (Xie *et al*., 2024). First of all, even after passing through treatment facilities, fluoxetine taken by individuals may wind up in wastewater through urine and feces. Second, the incorrect disposal of leftover medication, such as tossing it away or flushing it down the toilet, contributes to its accumulation in water and soil systems. Furthermore, fluoxetine may be released into the environment by enterprises that use it in their processes through their effluents. Finally, fluoxetine may find its way into the environment through polluted irrigation water or agricultural runoff if it is used in aquaculture, posing risks to aquatic life as emerging contaminants. Studies have shown that fluoxetine negatively affects fish, altering their physiology, behavior, and brain chemistry (Correia *et al.,* 2023a). It can even feminize male fish, leading to intersex fish with female reproductive organs, potentially impacting their ability to reproduce and the overall health of aquatic ecosystems. Fluoxetine, a commonly prescribed antidepressant belonging to the selective serotonin reuptake inhibitor (SSRI) class, exerts a significant influence on aquatic life when it infiltrates waterways through diverse channels (Yang *et al*., 2017; Ferreira *et al*., 2023). This pharmaceutical agent, while aiding human well-being, can subtly disrupt the delicate balance of aquatic ecosystems. Fish, in particular, bear the brunt of its impact, as studies have revealed alterations in their behavior, physiology, and reproductive processes upon exposure to fluoxetine. Remarkably, this antidepressant can feminize male fish, leading to the emergence of intersex individuals harboring both male and female reproductive traits (Yang *et al*., 2021). Moreover, fluoxetine's effects extend to neurological aspects, influencing gene expression and neurotransmitter levels in fish brains, thereby affecting their intricate behavioral responses and survival strategies in their natural environment. The consequences of fluoxetine's interaction with aquatic organisms warrant meticulous attention, as they could potentially reshape fish populations and disrupt the harmonious equilibrium of entire ecosystems. To safeguard the delicate balance of water environments, it becomes imperative to implement responsible measures for drug disposal and water treatment, ensuring that this remarkable pharmaceutical's entry into the aquatic realm does not imperil the well-being of aquatic life.

Fluoxetine inhibits re-uptake of serotonin so that extracellular serotonin levels in the brain bring about behavioural changes (Gould *et al*., 2021).

Table 1. Effects of Chemical/Metals from anthropogenic activities on Fish behavior

S. No.	CHEMICAL/METAL	EFFECTS ON FISH BHEAVIOR
1.	FLUOXETINE	• Serotonin Levels
2.	MERCURY	• Neurological Damage
		• Altered Feeding Pattern
3.	PESTICIDE	• Ingestion Related Toxicity
		• Impaired Neurological Damage
4.	THERMAL DISCHARGE	• Impaired Growth
		• Reduced Feeding
5.	MICROPLASTIC	• Altered Feeding Pattern
		• Reproductive Impairments

Boldness in terms of tendency to take risks for fitness gains is increased in fluoxetine exposed fish. Such fish are found to be more active in presence of a predator. Corresponding acute levels of fluoxetine are found to increase metabolic rates too while long term exposures subsequently led to decreased metabolic rates (Tan *et al*., 2020). Serotonin mediated this stress response by inhibiting the secretion of adenocorticotropic-releasing hormone from the adrenal cortex (Miranda *et al*., 2023, Correia *et al*., 2023a) thereby, affecting anxiety and hence influencing boldness. Fluoxetine and its metabolites such as non-fluoxetine are found to accumulate in the brain, muscle and plasma of fish (Pan *et al*., 2018; Yan *et al.,* 2020). SSRI (Selective Serotonin Re-uptake Inhibitor) are therefore not only duration-dependent but also have generation-dependent effects which are yet to be explored to have further insights into exact mechanisms Guppies in high fluoxetine environment showed higher scaled mass index than in corresponding controlled males (Fergusson *et al*., 2024).

Effect of a global pharmaceutical pollutant such as fluoxetine on the behavioural individuality and plasticity of fish can vary between the sexes. Fluoxetine was reported to decrease variations in the behavioural individuality of males in comparison to female and could affect behavioural plasticity in females as compared to males (Polverino *et al*., 2023). The underlying mechanism says the male and females have different neuro physiological responses to this psychoactive drug. Fluoxetine directly modulates the functions of serotonergic system of fish (Ferreira *et al*., 2023). The serotonergic system differs between the sexes and is responsible for bringing behavioural changes accordingly (Ferriera *et al.,* 2023) suggesting that males and females are not equally vulnerable to the spread of this pollutant. Therefore, pharmaceuticals pollution decreases the reproductive activities of fish such as decreased offspring production and population growth (Saaristo *et al*., 2018).

In a compelling study, the fascinating effects of fluoxetine on fish behavior were investigated. The research revealed that environmentally acceptable levels of fluoxetine exposure heightened the locomotor activity of mosquitofish, significantly reducing the time they needed to enter a predator's "strike zone," regardless of the predator's presence (de Farias *et al*., 2020). Surprisingly, the fluoxetine-exposed fish displayed less freezing behavior after a simulated predator strike, indicating altered responses to potential threats. Moreover, fluoxetine had no effect on the fish's escape performance during C-start movements (Zanghi *et al*., 2023). Intriguingly, previous studies showcased different outcomes when exposing other species to fluoxetine, suggesting complexities in the behavioral effects of both short-term and long-term exposure (Correia *et al*., 2023b). Significantly, the study shed light on an intriguingly non-monotonic dose-response relationship, wherein solely fish exposed to the lower dosage of fluoxetine exhibited a noteworthy surge in activity levels compared to their unexposed counterparts. This fascinating parallel can be drawn to findings observed in other encounters with low-dose antidepressants and endocrine-disrupting chemicals. Delving further into the investigation, the researchers explored the interplay of fluoxetine and temperature treatments on guppies' reproductive behaviors and activity patterns. Curiously, the male guppies' performance of sneak copulations was distinctly influenced by fluoxetine treatment, whereas temperature treatment significantly impacted their propensity for concealed copulations. Shoal cohesion among guppies varied with temperature and turbidity levels, indicating complex interactions affecting social dynamics. Mechanistically, prey speed correlated negatively with predator-prey distances in warmer and interaction treatments, suggesting adaptive responses to perceived predation risk. These findings underscore the nuanced effects of temperature and turbidity on predator-prey interactions and social behavior in fish, emphasizing the ecological relevance of understanding multiple stressor effects in aquatic environments (Zanghi *et al*., 2023). Future research should explore additional ecological contexts and species interactions to further elucidate the broader impacts of environmental stressors on aquatic communities. Nevertheless, no conspicuous interaction emerged between fluoxetine and temperature treatments concerning the duration of the first male sneak copulation. Intriguingly, temperature significantly impacted fish activity levels, reducing them during cold-temperature therapy compared to control and heat-stress treatments. However, fluoxetine exposure did not show a significant effect on fish activity levels. Overall, this compelling experiment sheds light on the intricate interplay between fluoxetine, temperature, and fish behavior, offering valuable insights into the potential implications for aquatic ecosystems and wildlife.

Previous study shows that even low, environmentally relevant concentrations of fluoxetine can profoundly affect both the genetic and behavioral aspects of zebrafish larvae (Ferreira *et al*., 2023). Fluoxetine exposure led to significant changes in genes associated with neurotransmission, potentially affecting brain function and development. Stress response genes were also altered, suggesting a disruption in the larvae's ability to manage stress. Additionally, zebrafish larvae exposed to fluoxetine exhibited changes in swimming behaviors, indicating possible impacts on their locomotion and exploratory activities. Alterations in social behaviors were noted as well, which could have implications for their survival and interactions within their environment. The concentrations of fluoxetine used in the study were chosen to reflect levels commonly found in natural aquatic environments due to pharmaceutical pollution. These findings underscore the ecological risks posed by pharmaceutical contaminants, highlighting the urgent need for improved wastewater management and pollution control strategies to mitigate these impacts on aquatic ecosystems. The researchers discovered that fish exposed to psychoactive compounds exhibit reduced behavioral distinctiveness, which means that the distinctive characteristics that usually set one fish apart from another are less noticeable. Furthermore, behavioral plasticity- the capacity of fish to modify their behavior in response to environmental changes-is hampered by these toxins. Because of this impairment, fish exposed to these compounds may find it difficult to adapt to new or changing conditions in their habitat, which could lower their chances of surviving. The fact that these behavioral alterations are sex-specific is one of the study's important conclusions. The degree and type of behavioral changes that males and females experience in reaction to the contaminants differ (Polverino *et al*., 2023).

Microplastics

Microplastics, tiny particles smaller than 5mm, infiltrate into marine ecosystems through human-induced activities, often carrying toxic substances like pesticides, pollutants, and heavy metals. These harmful particles affect fish behavior when ingested directly or through their prey. A pioneering study revealed how microplastics alter the swimming velocity and resistance time of fish (Sulaiman *et al*., 2023). Through a variety of mechanisms, microplastics have a significant impact on the dynamics of fish movement. To begin with, the physical contact between them and the bodies of fish produces a drag that impedes fluid flow and requires more energy to overcome, which reduces swimming speed. In addition, fish that are used to a particular depth may find it difficult to adjust their speed in order to adapt to the changing conditions due to microplastics changing the buoyancy of the water close to the surface. Furthermore, microplastics are pernicious because they may contain hazardous chemical pollutants that harm fish health and impair their ability to swim. Indirectly, behavioral changes brought on by microplastics, including changed interactions or avoidance behaviors, take energy away from swimming and may reduce total speed. Moreover, exposure to microplastics can cause physiological stress that can interfere with energy allocation and metabolic processes, making swimming performance even more difficult. Overall, fish have a significant problem due to the ubiquitous presence of microplastics in aquatic environments, which affect their swimming speed and resistance time through complex interactions between physical, chemical, behavioral, and physiological factors (Bhuyan *et al*., 2022). The sneaky aspect of microplastics also includes the possibility that they contain hazardous chemical pollutants, endangering fish health and diminishing swimming ability. Microplastic-induced behavioral changes, including avoided contacts or redirected interactions, indirectly take energy away from swimming and may slow swimming speed as a whole. Even brief exposure to microplastics was found to exacerbate the swimming velocity of zebrafish, particularly when combined with mercury, impacting their swimming performance (Zhu *et al*., 2022). The capacity of microplastics to absorb and release pollutants in marine settings raises significant concerns regarding their interactions with diverse contaminants and the potential risks they pose to marine organisms (Naidoo and Glassom, 2019). The study confirmed that short-term exposure to microplastics and mercury, individually or in combination, led to behavioral changes in fish, likely affecting their metabolic, endocrine, and neurological systems (Zhang *et al*., 2023). In an intriguing study, the effect of plastic nanoparticle size on fish was reported (Naz *et al*., 2024). Surprisingly, the spotlight fell on amino-modified positively charged polystyrene nanoparticles, precisely measuring 52 nm, which significantly affected *Daphnia*, while their larger counterparts (ranging from 120 to 330 nm) displayed no discernible impact. The researchers chose particle size as the pivotal factor governing toxicity, disregarding mass, surface area, or particle number. Delving deeper into the enigma of plastic nanoparticle effects on the entire food chain, the team revealed that fish exposed to 53 nm particles exhibited a noticeable decline in feeding rates and activity, whereas those exposed to 180 nm particles demonstrated an unexpected acceleration in feeding and activity levels, contrary to conventional expectations. Reduced feeding efficiency and prolonged swimming durations in fish exposed to 53nm particles could lead to inefficient energy utilization and increased predation vulnerability in natural environments, impacting fish fitness and ecosystem function (Zaman et al., 2024). These groundbreaking studies shed light on the complex interactions between microplastics and nanoplastics and their profound effects on fish behavior and overall ecosystem health.

Mercury Toxicity

In the realm of aquatic research, the impact of mercury on fish behavior has been extensively explored. The study describes how fish health problems are caused by mercury contamination, which comes from mining, industrial processes, and waste disposal. The pollution can be either organic (methyl mercury) or inorganic (mercuric chloride). Mercury exposure seriously damages a number of organs. It impairs respiratory efficiency in the gills by causing hyperplasia, lamellar fusion, and necrosis. Hepatocellular degeneration, necrosis, and bile duct hyperplasia are all seen in the liver, which interferes with detoxification and metabolism. Waste excretion is hampered by renal tubular degeneration and glomerular atrophy in the kidneys. Neurological deficits result from gliosis and neuronal degeneration in the brain. Additionally impacted, muscle tissues exhibit fibrosis and atrophy, impairing muscle function and movement. Mercury attaches to thiol groups in proteins and enzymes, producing significant cellular damage. Oxidative stress and the disruption of enzymatic processes are linked to the mechanisms of mercury toxicity. The entire aquatic ecosystem may be impacted by these pathological alterations, which can have serious ecological repercussions by influencing fish populations' ability to survive, thrive, and reproduce. In order to safeguard aquatic life, the study highlights the significance of employing these histopathological markers as markers of mercury contamination in aquatic ecosystems and the necessity of efficient monitoring and mitigation techniques (Zulkipli *et al*., 2021). In a study, five groups of 225 juvenile *Nile tilapia* were taken by the researchers, and each group was given varying doses of MeHg chloride (0, 0.5, 1, 1.5, and 2 mg/kg diet) for 30 days. Significant behavioral changes were observed in the exposed fish, according to the study, including an increase in biting, scratching, and fin tugging and a decrease in swimming behavior. Additionally, the behaviors of butting, mouth pushing, and chasing increased. Biochemically, the study found that all exposed groups had lower levels of serum immunoglobulin M (IgM) and brain acetylcholine esterase (AChE). Serum lysozyme (LYZ), nitric oxide (NO), superoxide dismutase (SOD), malondialdehyde (MDA), protein carbonyl (PCO), and 8-hydroxy-2-deoxyguanosine (8OH2dG) levels, on the other hand, were higher, suggesting oxidative stress and DNA and protein damage. Significant changes in the expression of immune-related genes such TNF-α, IL-1β, IL-8, and IL-10 were also seen in the study. These results demonstrate that even low levels of dietary MeHg can cause significant immunological and neurobehavioral impairments in *Nile tilapia*, affecting their general health and possibly affecting fish populations in contaminated environments, underscoring the possible ecological threat posed by MeHg contamination (Zeid *et al*., 2021). According to the study, adult zebrafish reproductive activities, such as spawning frequency, courtship displays, and reproductive success, are considerably suppressed by early life exposure to mercury. It was shown that these behavioral deficits were dose-dependent, with more noticeable effects occurring at greater mercury concentrations. A major cause for these alterations was found to be the disturbance of the hypothalamic-pituitary-gonadal (HPG) axis, which controls reproductive behaviors. This was demonstrated by changes in the expression levels of genes involved in the production and signaling of reproductive hormones. According to the study, adult zebrafish reproductive activities, such as spawning frequency, courtship displays, and reproductive success, are considerably suppressed by early life exposure to mercury. It was shown that these behavioral deficits were dose-dependent, with more noticeable effects occurring at greater mercury

concentrations. A major cause for these alterations was found to be the disturbance of the hypothalamic-pituitary-gonadal (HPG) axis, which controls reproductive behaviors. This was demonstrated by changes in the expression levels of genes involved in the production and signaling of reproductive system (Chen *et al.*, 2021).

Pesticides

Pesticides enter aquatic habitats through groundwater discharge and runoff from urban, industrial, and agricultural regions. These substances have a significant impact on fish behavior after they are introduced, mostly through direct neurotoxic effects but also indirectly through changes in food supply and habitat quality (Khoshnood, 2024). Fish neurotransmitter systems are disrupted by pesticides such as organophosphates and pyrethroids, which affect how fish respond to environmental cues and basic activities like feeding and mating (Neylon *et al.*, 2022). Furthermore, several pesticides bio accumulate in fish tissues, extending exposure and eventually worsen behavioral consequences. By drastically reducing insect populations, which are essential sources of food for fish, pesticides indirectly disrupt aquatic food webs by causing food shortages and behavioral changes in eating. Moreover, fish behavior is further impacted by habitat degradation brought on by chemical contamination, which includes decreased aquatic vegetation and increased sedimentation, which reduces hiding and breeding places. To summarize, the introduction of pesticides into aquatic environments causes both direct and indirect changes in fish behavior. It is essential to comprehend these dynamics in order to mitigate the ecological effects of pesticide contamination and protect fish populations (Mondal and Samanta, 2015).

Thermal Discharge

Through a variety of man-made and natural mechanisms, hot water can enter the aquatic environment and have a major impact on fish behavior. Thermal pollution, which happens when human activities like industrial processes or power generation release heated water into water bodies, is one of the main sources of hot water in aquatic ecosystems. In addition, hot water can enter aquatic ecosystems naturally through geothermal springs or volcanic activity. The aquatic environment can change as a result of hot water discharge into rivers, lakes, or the ocean. These changes can affect fish behavior by affecting the water's temperature, dissolved oxygen content, and nutritional availability. There is a wealth of research on the impact of hot water on fish behavior. White, 2019 conducted a study on the influence of thermal stress on the predator-prey interactions of largemouth bass (*Micropterus salmoides*) and bluegill sunfish (*Lepomisma crochirus*), which examined the effects of temperature stress on largemouth bass and bluegill sunfish predator-prey interactions in warm aquatic habitats (White, 2019). Fish's physiological processes, oxygen requirements, and metabolic rates can all be directly impacted by hot water. Since fish are ectothermic, the environment around them controls their body temperature. Fish that are exposed to hot water may suffer from thermal stress, which raises their oxygen and metabolic needs. Fish may thus display altered eating habits, heightened swimming activity, or a decreased ability to withstand stress (Neubauer and Ken, 2019). Hot water can also alter the distribution of resources and the availability of fish habitat by upsetting the thermal stratification of water bodies (Wells *et al.*, 2022). For example, in order to avoid thermal stress, certain fish species may seek sanctuary in deeper, colder waters, while others may be compelled to go into shallower, warmer waters. Fish population redistribution may have an effect on community structure and predator-prey dynamics. Because hot water alters fish's habitat and food supplies, it can also have an indirect effect on their behavior. Warm water can hasten the growth of aquatic plants and algae, resulting in algal blooms and alterations in the purity of the fish's capacity to find food and their ability to successfully feed themselves may be affected by these changes in the availability of prey (Griffith and Gobler, 2019). Hot water can also harm spawning grounds, cause temperature shock to delicate species, and decrease the amount of refuge and shelter available, all of which can lead to the degradation of aquatic environments (Woolway *et al.*, 2022).

Effect on Ecosystem

Ecosystems are profoundly impacted by anthropogenic activities through a variety of mechanisms. These activities include resource extraction, urbanization, agriculture, and industrial processes, all of which introduce pollutants, change the environment, and interfere with natural cycles.

For example, particulate matter and greenhouse gases released by industrial pollutants contribute to air pollution and climate change. Urbanization affects hydrological cycles and modifies regional temperatures by causing habitat fragmentation, biodiversity loss, and an increase in impermeable surfaces. Nutrient balances and biodiversity are impacted by the introduction of pesticides and fertilizers into soil and water systems through agricultural activities. Resource extraction ruins aquatic and terrestrial ecosystems, resulting in sedimentation, erosion, and water body contamination. When taken as a whole, these human-induced stresses alter the composition and capabilities of ecosystems, creating formidable obstacles to the preservation of biodiversity and the robustness of ecosystems (Pauli and Sih, 2017; Prakash and Verma, 2022).

Eutrophication

The phenomenon of eutrophication has been extensively studied, with many studies examining its causes and effects. Studies give a thorough description of the eutrophication process, its effects on the environment, and its spatial distribution worldwide (Yan *et al.*, 2020). The study demonstrates how human-caused nutrient enrichment speeds up primary production in aquatic environments, resulting in algal blooms, oxygen depletion, and changes in water quality. Studies have indicated that eutrophication can impact fish behavior in a big way in a variety of ways (Akinnawo, 2023). The studies examine how nutrient enrichment affects fish communities in freshwater environments and how fish behavior, including foraging habits, reproductive tactics, and habitat selection, can be influenced by eutrophication-induced changes in habitat shape, food availability, and water quality (Jarvenpaa, 2020). The reduction of oxygen brought on by eutrophication can significantly impact the behavior of fish. A study shows how nutrient pollution causes hypoxic (low oxygen) zones to spread throughout marine habitats (Ahmad *et al.*, 2024). The study describes how fish populations can be stressed by hypoxia, which can also interfere with predator-prey relationships and change fish migratory and dispersal patterns as they search for oxygen-rich locations. Fish health and behavior are seriously threatened by toxic algal blooms, which are another effect of eutrophication.The relationship between nutrient loading, algal bloom formation, and the generation of toxic algal compounds is investigated in a study. The article explains how fish exposure to these poisons can cause physiological stress reactions that change their behavior, decrease their appetite, and raise their mortality rates. Eutrophication affects fish behavior, and knowing how it impacts is crucial for conservation and fisheries management. The relationship between climate change and the dynamics of dangerous algal blooms and eutrophication is discussed in studies. In order to lessen the effects of eutrophication on fish populations and aquatic ecosystems, the study highlights the necessity for coordinated approaches to nutrient management, habitat restoration, and

Fig. 2. Impact of human interventions on ecosystem through altered fish behavior.

adaptive management techniques (Ahmad *et al*., 2024).

Biomagnification

The process of certain pollutants, like pesticides, heavy metals, and persistent organic pollutants, becoming more concentrated as they go up the food chain is known as biomagnification. Higher trophic level species ingest greater amounts of prey that contains these pollutants, which causes an accumulation of the pollutants in their tissues at a higher level than that of the surrounding environment, which is why this phenomenon happens. Primary producers like algae and plankton, which are at the base of the food chain, have the ability to absorb trace levels of contaminants from dirt or water. These primary producers are consumed by herbivorous animals, which therefore collect a somewhat higher quantity of contaminants. Pollutant concentrations rise as herbivores are eaten by predators, and this cycle of accumulation persists as one climbs the food chain. Because certain species are disproportionately affected by bio magnification, it can upset the equilibrium of ecosystems. Large fish and birds of prey are examples of predators at the top of the food chain that are especially susceptible to the impacts of bio magnification. Excessive pollution concentrations in their tissues can cause immunological dysfunction, reproductive troubles, and general fitness reductions, which may lead to local extinctions or population declines. Because of their place in the food chain and capacity to absorb contaminants from a variety of sources, such as sediment, water, and food, fish-especially predatory species-are particularly vulnerable to bio accumulating pollutants. Fish can therefore store large amounts of contaminants in their tissues, endangering not only their own health but also the health of creatures that eat them, such as humans. Fish behavior can also be impacted by some contaminant's bio magnification. Pollutants such as mercury and polychlorinated biphenyls (PCBs) have the potential to cause neurological impairments in fish, which can result in changed behavior including disorientation, poor avoidance of predators, and decreased efficiency of foraging. The dynamics of predator-prey relationships and community structure may be impacted by these behavioral shifts; they may create a ripple effect in the changing environment (Wang *et al.*, 2022).

Human induced algal blooms result into hampered mate detection and limiting of population growth (Candolin, 2019). Pollutants such as noise, artificial light and chemicals result into increased stress levels and reduced resistance to infections hence altering population dynamics of the host as well as the infectious parasitic agent (Budria and Candolin, 2014; Byers, 2021).

CONCLUSION

In the depths of this comprehensive review, we embark on a captivating journey through the labyrinthine expanse of mercury toxicity, microplastic effects, and fluoxetine exposure in the aquatic realm, revealing a tapestry of challenges that intertwine in intricate harmony. These pollutants, borne from human activities, cast their shadows upon the fish populations, weaving a tale of distinct yet interwoven threats to their fragile habitats. With a mesmerizing cadence, the heavy metal mercury takes center stage, wielding its toxic form, methylmercury, to orchestrate a profound symphony of effects on fish health, behavior, and reproduction. As the phenomenon of bio magnification casts its spell, mercury's malevolent touch intensifies with each trophic level, imperiling not only larger predatory fish but also those who tread the fine line of human consumption. In the background, the ethereal dance of microplastics ensues, their diminutive fragments whispering an alarming melody. Amidst the aquatic expanse, these minuscule particles stealthily infiltrate, wielding their influence on fish behavior and physiology, unsettling the delicate balance of entire food webs. When microplastics and mercury combine, their effects create a powerful impact on fish behavior and ecosystem health. A new dimension emerges with the entrancing entrance of fluoxetine, a widely used antidepressant. This captivating interloper infiltrates water sources, emerging as an emerging contaminant, intertwining with aquatic life in curious ways. Unraveling the enigma of fluoxetine's impact on fish physiology, behavior, and reproduction, it casts a mysterious aura on the equilibrium of aquatic ecosystems. In the face of these unfolding environmental sonatas, a call to arms resounds, for a collective effort is imperative. Across the seas and beneath the tides, stringent regulations must unfurl, curbing mercury's haughty emissions, while the terrestrial landscapes witness the artistry of responsible plastic waste management. As we traverse the uncharted waters, the call for further research and risk assessment models grows strong, seeking to discern the intricate tapestry of interactions among these elements, predicting the fate of fish populations. Our findings unveil a captivating revelation: the simultaneous exposure to both microplastics and mercury may act synergistically to further hinder fish swimming abilities. Such captivating interactions could potentially lead to a chain of effects, altering the very essence of fish life in ways yet to be fully understood. Pesticides, eutrophication, thermal water discharge, and bio magnification all have different but related effects on fish behavior, which in turn shapes aquatic ecosystems. Because of their neurotoxic effects, pesticides can alter fish behavior, making it more difficult for them to feed, reproduce, and evade predators. Temperature gradients in the water are changed by thermal water outflow, which affects fish migration and dispersal patterns as well as physiological functions including metabolism. Algal blooms are fueled by eutrophication, which causes habitat degradation and oxygen depletion, causing fish to relocate or adapt in order to survive. Pollutants like mercury and persistent organic pollutants (POPs) have the potential to cause neurological impairments and changed social interactions in fish behavior due to bio magnification, which enhances their negative effects as they accumulate up the food chain. When taken as a whole, these stressors show how fish behavior is sensitive to human disruptions and emphasize the need for integrated management approaches to protect aquatic ecosystems and the services they offer.

FUTURE PERSPECTIVE

To further our understanding of human impacts on aquatic ecosystems, research into the effects of fluoxetine, microplastics, and mercury toxicity on fish behavior and survival strategies is essential. Research has indicated noteworthy disturbances in the physiology and behavior of fish, such as modified feeding habits, hindered ability to avoid predators, and reduced success in reproducing. In order to better understand how these contaminants affect fish biology, particularly how they affect neurotransmitter systems, hormone routes, and metabolic processes, further research must be done. It is also critical to look at the ecological effects of these disruptions since they have the ability to change community dynamics, cascade across food webs, and compromise ecosystem resilience. Researchers must also evaluate the combined effects of various pollutants because their combined effects have the potential to worsen ecological harm. Identifying pollution levels in aquatic habitats and putting protective measures in place to lessen their negative impacts would need the development of reliable monitoring methods and efficient mitigation solutions. In the end, incorporating scientific discoveries into management strategies and policies can help to maintain aquatic ecosystem's integrity and health for upcoming generations.

Authors Contributions

Concept and design- V.T., R.S., N.K.D., manuscript preparation-V.T., manuscript editing - R.S., N.K.D., manuscript review- R.S., N.K.D. All authors have read and agreed to the published version of the manuscript.

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REFERENCES

Akinnawo, S.O. 2023. Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. *Environmental Challenges.* 12: 100733, https://doi.org/10.1016/j.envc.2023.100733.

Ahmad, N.B., Jaafaru, M.S., Isa, Z., Abdulhamid, Y., Kakudi, R.A., Ugya, A.Y. and Meguellati, K. 2024. High pollution loads engineer oxygen dynamics, ecological niches, and pathogenicity shifts in freshwater environments. *Journal of Hazardous Materials Advances.* 14: 100425, https://doi.org/10.1016/j.hazadv.2024.100425.

Bhuyan, M.S. 2022. Effects of Microplastics on Fish and in Human Health. *Front. Environ. Sci.* 10. https://doi.org/10.3389/fenvs.2022.827289

Bhagat, J., Zang, L., Nishimura, N. and Shimada, Y. 2020. Zebrafish: An emerging model to study microplastic and nanoplastic toxicity. *Science of The Total Environment*. 728: 138707, https://doi.org/10.1016/j.scitotenv.2020.138707.

Budria, A. and Candolin, U. 2014. How does human-induced environmental change influence host-parasite interactions? *Parasitology.* 141(4): 462-474. https://doi.org/10.1017/s0031182013001881.

Byers, J.E. 2021. Marine parasites and disease in the era of global climate change. *Annual Review of Marine Science.* 13: 397-420. https://doi.org/10.1146/

annurev-marine-031920-100429.

Correia, D., Domingues, I., Faria, M. and Oliveira, M. 2023a. Effects of fluoxetine on fish: What do we know and where should we focus our efforts in the future? *Science of the Total Environment*. 857 (2): 159486. https://doi.org/10.1016/j.scitotenv. 2022. 159486.

Correia, D., Bellot, M., Prats, E., Gómez-Canela, C., Moro, H., Raldúa, D., Domingues, I., Oliveira, M. and Faria, M. 2023b. Impact of environmentally relevant concentrations of fluoxetine on zebrafish larvae: From gene to behavior. *Chemosphere*. 345: 140468, https://doi.org/10.1016/j.chemosphere. 2023.140468.

Chen, Q., An, J., Xie, D., Gong, S., Lian, X., Liu, Z., Shen, Y. and Li, Y. 2021. Suppression and recovery of reproductive behavior induced by early life exposure to mercury in zebrafish. *Comp Biochem Physiol C Toxicol Pharmacol*. 239: 108876. doi: 10.1016/j.cbpc.2020.108876.

Candolin, U. 2019. Mate choice in a changing world. *Biological Reviews*. 94(4): 1246-1260. https://doi.org/10.1111/brv.12501.

Candolin, U. and Rahman, T. 2023. Behavioural responses of fishes to anthropogenic disturbances: Adaptive value and ecological consequences. *Journal of Fish Biology*. 103 (4): 773-783. doi: 10.1111/jfb.15322

de Farias, N.O., Oliveira, R., Moretti, P.N.S, Pinto, J.M., Oliveira, A.C., Santos, V.L., Rocha, P.S., Andrade, T.S. and Grisolia, C.K. 2020. Fluoxetine chronic exposure affects growth, behavior and tissue structure of zebrafish. *Comp Biochem Physiol C Toxicol Pharmacol*. 237:108836. doi: 10.1016/j.cbpc.2020.108836.

Ferreira, C.S.S., Soares, S.C., Kille, P. and Oliveira, M. 2023. Identifying knowledge gaps in understanding the effects of selective serotonin reuptake inhibitors (SSRIs) on fish behavior. *Chemosphere*. 335: 139124. doi: 10.1016/j.chemosphere.2023.139124

Fergusson, K.N., Tanner, J. L., Brand, J.A., Hannington, S.L., Pettersen, A.K., Sundin, J., Saaristo, M., Bertram, M.G., Martin, J.M., Wong, B.B.M. 2024. Effects of long-term fluoxetine exposure on morphology, but not behaviour or metabolic rate, in male guppies (*Poecilia reticulata*). *Aquat Toxicol*. 276: 107082. doi: 10.1016/j.aquatox.2024.107082.

Griffith, W.A. and Gobler, C.J. 2019. Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. *Harmful Algae*. 91: doi: 10.1016/j.hal.2019.03.008

Gould, S.L., Winter, M.J., Norton, W.H.J. and Tyler, C.R. 2021. The potential for adverse effects in fish exposed to antidepressants in the aquatic environment. *Environ. Sci. Technol*. 55: 16299-16312. https://doi.org/10.1021/acs.est.1c04724.

Jacobsen, J.P.R. 2023. Serotonin and depression-an alternative interpretation of the data in Moncrieff et al, *Molecular Psychiatry*. 28: 3158-3159. https://doi.org/10.1038/s41380-023-02090-3

Jarvenpaa, M. 2020. *Eutrophication interferes with sand goby mating success, sexual selection, and parental care*. Faculty of Biological and Environmental Sciences, Doctoral Program in Wildlife Biology.

Kumar, V., Umesh, M., Shanmugam, M.K., Chakraborty, P., Duhan, L., Gummadi, S.N., Pasrija, R., Jayaraj, I. and Dasarahally Huligowda, L.K. 2023. A Retrospection on Mercury Contamination, Bioaccumulation, and Toxicity in Diverse Environments: Current Insights and Future Prospects. *Sustainability*. 15: 13292. https://doi.org/10.3390/su151813292

Khoshnood, Z. 2024. A review on toxic effects of pesticides in Zebrafish, Danio rerio and common carp, *Cyprinus carpio*, emphasising Atrazine herbicide. *Toxicology Reports*. 13: 101694, https://doi.org/10.1016/j.toxrep.2024.101694.

Mondal, K. and Samanta, S. 2015. A Review on Arsenic Contamination in Fresh Water Fishes of West Bengal. *Journal of Global Biosciences*. 4(5): 2369-2374.

Miranda, J.P.G.A., Isaac, A.B.J., Silva, R.B., Toledo, L.C.S., Barcellos, L.J.G., Delicio, H.C. and Barreto, R. E. 2023. Acute effects of fluoxetine on stress responses and feeding motivation in Nile tilapia. *Fishes*. 8: 348-361. https://doi.org/10.3390/fishes8070348.

Naidoo, T. and Glassom, D. 2019. Sea-surface microplastic concentrations along the coastal shelf of KwaZulu-Natal, South Africa. *Marine Pollution Bulletin*. 149: 110514. doi: 10.1016/j.marpolbul.2019.110514

Naz, S., Manan, A., Chatha, M., Khan, N.A., Ullah, Q., Zaman, F. and Qadeer, A. 2024. Unraveling the ecotoxicological effects of micro and nano-plastics on aquatic organisms and human health, *Front. Environ. Sci*. 12. https://doi.org/10.3389/fenvs.2024.1390510

Neylon, J., Fuller, J.N., van der Poel, C., Church, J.E. and Dworkin, S. 2022. Organophosphate Insecticide Toxicity in Neural Development, Cognition, Behaviour and Degeneration: Insights from Zebrafish. *J. Dev. Biol*. 10 : 49. https://doi.org/10.3390/jdb10040049

Neubauer, P. and Ken, A.H. 2019. Thermal performance of fish is explained by an interplay between physiology. *Behaviour and Ecology*. 7(1): coz025, https://doi.org/10.1093/conphys/coz025

Polverino, G., Aich, U., Brand, J.A., Bertram, M.G., Martin, J.M., Tan, H., Soman, V.R., Mason, R.T. and Wong, B.B.M. 2023. Sex-specific effects of psychoactive pollution on behavioral individuality and plasticity in fish, *Behavioral Ecology*. 34(6): 969-978. doi: 10.1093/beheco/arad065

Prakash, S. and Verma, A.K. 2022. Anthropogenic Activities and Biodiversity Threats, *International Journal of Biological Innovations*. 4(1): 94-103. https://ssrn.com/abstract=4048276

Pauli B.D. and Sih, A. 2017. Behavioural responses to human-induced change: Why fishing should not be ignored. *Evolutionary Applications*. 10(3), doi: 10.1111/eva.12456

Pan, C., Yang, M., Xu, H., Xu, B., Jiang, L. and Wu, M. 2018. Tissue bio-concentration and effects of fluoxetine in zebrafish (*Danio rerio*) and red crucian cap (*Carassius auratus*) after short-term and long-term exposure. *Chemosphere.* 205: 8-14. https://doi.org/10.1016/j.chemosphere.2018.04.082

Sulaiman, B., Woodward, J.C., and Shiels, H.A. 2023. Riverine microplastics and their interaction with freshwater fish, *Water Biology and Security*. 2(4): 100192, https://doi.org/10.1016/j.watbs.2023.100192.

Saaristo, M., Brodin, T., Balshine, S., Bertram, M.G., Brooks, B.W. and Ehlman, S.M. 2018. Direct and indirect effects of chemical contaminants on the behaviour, ecology and evolution of wildlife. *Proceedings of the Royal Society B-Biological Sciences*. 285(1885): 10. https://doi.org/10.1098/rspb.2018.1297.

Tan, H., Polverino, G., Martin, J.M., Bertram, M.G., Wiles, S.C., Palạcios, M.M., Bywater, C.L., White, C.R. and Wong, B.B.M. 2020. Chronic exposure to a pervasive pharmaceutical pollutant erodes among-individual phenotypic variation in a fish. *Environ. Pollut.* 263: 114450 https://doi.org/10.1016/j.envpol.2020.114450

Wang, Y., Zhou, X., Chen, J., Xie, B. and Huang, L. 2022. Climate-induced habitat suitability changes intensify fishing impacts on the life history of large yellow croaker (*Larimichthys crocea*). *Ecol Evol.* 12(10): e9342. https://doi.org/10.1002/ece3.9342

White, D.P. 2019. Effects of environmental warming on lentic freshwater communities and the behavioral and physiological responses by fishes to warming.

Wells, M., Kuai, Y. and Shi, Y. 2022. Thermal stratification in lakes determines where fish are, but also modifies how well acoustic telemetry can detect them. CMOS Bulletin SCMO on July 31, 2022. Posted in Members, What's Current.

Woolway, R.I., Sharma, S. and Smol, J.P. 2022. Lakes in hot water: the impacts of a changing climate on aquatic ecosystems. *Bio Science*. 72(11): 1050-1061, https://doi.org/10.1093/biosci/biac052

Xie, Z., Nie, Y., Dong, M., Nie, M. and Tang, J. 2024. Integrated physio-biochemical and transcriptomic analysis reveals the joint toxicity mechanisms of two typical antidepressants fluoxetine and sertraline on Microcystis aeruginosa. *Sci Total Environ*. 926: 171802. doi: 10.1016/j.scitotenv.2024.171802.

Yang, Y., Ok, Y.S., Kim, K.H., Kwon, E.E. and Tsang, Y.F. 2017. Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review. *Sci Total Environ.* 596-597: 303-320. doi: 10.1016/j.scitotenv.2017.04.102.

Yang, L., Guo, M., Xin, C., Ren, X., Wang, L. and Liu, Y. 2021. Comparison of trace element concentrations in freshwater fish and marine fish consumed in Shandong Province, China, and their potential risks to human health. *Marine Pollution Bulletin.* 165: 112114, https://doi.org/10.1016/j.marpolbul.2021.112114.

Yan, Z.H., Zhang, X. D., Bao, X.H., Ling, X., Yang, H.H., Liu, J. C., Lu, G.H. and Ji, Y. 2020. Influence of dissolved organic matter on the accumulation, metabolite production and multibiological effects of environmentally relevant fluoxetine in crucian carp (*Carassius auratus*). *Aquat. Toxicol.* 226: 105581 https://doi.org/10.1016/j. aquatox.2020.105581.

Zanghi, C., Munro, M. and Loannou C.C. 2023. Temperature and turbidity interact synergistically to alter anti-predator behaviour in the Trinidadian guppy. *Zenodo.* doi: 10.5061/dryad.5tb2rbp8x

Zhu, J., Zhang, Y., Xu, Y., Wang, L., Wu, Q., Zhang, Z. and Li, L. 2022. Effects of microplastics on the accumulation and neurotoxicity of methylmercury in zebrafish larvae. *Mar Environ Res*. 176: 105615. doi: 10.1016/j.marenvres.2022.105615.

Zhang, C., Wang, F., Wang, Q., Zou, J. and Zhu, J. 2023. Species-specific effects of microplastics on juvenile fishes. *Front. Physiol.* 14: 1256005. doi: 10.3389/fphys.2023.1256005

Zaman, M., Khan, F.U., Younas, W., Noorullah, M., Ullah, I., Li, L., Zuberi, A. and Wang, Y. 2024. Physiological and histopathological effects of polystyrene nanoparticles on the filter-feeding fish *Hypophthalmichthys molitrix*. *Sci Total Environ.* 912: 169376. doi: 10.1016/j.scitotenv.2023.169376.

Zulkipli, S.Z., Liew, H.J., Ando, M., Lim, L.S., Wang, M., Sung, Y.Y. and Mok, W.J. 2021. A review of mercury pathological effects on organs specific of fishes. *Environmental Pollutants and Bioavailability*. 33(1): 76-87. https://doi.org/10.1080/26395940.2021.1920468

Zeid, E.H.A., Khalifa, B.A., Said, E.N., Arisha, A.H. and Reda, R.M. 2021. Neurobehavioral and immune-toxic impairments induced by organic methyl mercury dietary exposure in Nile tilapia *Oreochromis niloticus*. *Aquat Toxicol.* 230: 105702. doi: 10.1016/j.aquatox.2020.105702.