Uttar Pradesh Journal of Zoology

Volume 45, Issue 6, Page 29-45, 2024; Article no.UPJOZ.3284
ISSN: 0256-971X (P)

Impact of Pollution and Toxic Stress on Fish Health: Mechanisms, Consequences, and Mitigation Strategies

Sagar Gorakh Satkar [a], Anil Kumar [b], Anjana A. [c], Saiprasad Bhusare [c*], Ashish Sahu [a] and Rohit Kumar Gautam [d]

[a] Faculty of Fisheries, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi, Kerala- 682506, India.
[b] Department of Zoology, Baba Raghav Das Post Graduate College, Deoria, Uttar Pradesh -274001, India.
[c] ICAR-Central Institute of Fisheries Education, Mumbai- 400 061, India.
[d] Department of Zoology, Babasaheb Bhimrao Ambedkar University, Lucknow, Uttar Pradesh - 226025, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.56557/UPJOZ/2024/v45i63949

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://prh.mbimph.com/review-history/3284

Review Article

Received: 01/01/2024
Accepted: 04/03/2024
Published: 15/03/2024

ABSTRACT

Pollution poses a dire threat to fish health and aquatic ecosystems, permeating through various pathways and wreaking havoc on biological processes crucial for fish survival. Pollutants infiltrate fish through multiple routes, inducing direct toxicity and disrupting fundamental functions such as

---

*Corresponding author: Email: spbhusare97@gmail.com;

metabolism, hormonal regulation, and immune responses. These detrimental effects manifest in a plethora of consequences, including stunted growth, diminished energy reserves, heightened vulnerability to environmental stressors, reproductive impairments, increased susceptibility to diseases, and behavioral alterations that imperil their survival. To address this pressing crisis, proactive measures are indispensable, necessitating stringent regulations, the adoption of sustainable practices, and the enhancement of water treatment facilities to curtail the release of pollutants into aquatic environments. Simultaneously, reactive strategies must be deployed, focusing on remediation efforts to cleanse contaminated areas, facilitating the recovery of fish populations, and undertaking broader ecosystem restoration initiatives. Continuous research and vigilant monitoring play pivotal roles in discerning the nuanced impacts of pollution on fish health and gauging the efficacy of mitigation endeavors. Safeguarding fish populations is imperative for their well-being and preserving the health and equilibrium of the entire aquatic ecosystem, underscoring the urgency of concerted action to combat pollution's detrimental effects.

Keywords: Pollution; toxic stress; fish health; environmental contaminants; water quality; aquatic ecosystems; bioaccumulation; physiological responses.

1. INTRODUCTION

The insidious effects of pollution and the resulting toxic stress have severe consequences for fish populations and the ecosystems they inhabit. Pollutants infiltrate fish systems through a variety of mechanisms, some causing outright toxicity and others subtly disrupting fundamental biological processes [1]. Direct toxicity can damage organs, compromise cellular function, and even lead to mortality. More indirect pathways of harm involve interference with metabolism, hormonal signalling, and the immune response, undermining the fish's overall health and resilience [2]. The ramifications of pollution-induced stress on fish populations are profound. Fish may experience stunted growth, decreased energy reserves, and reduced capacity to cope with environmental changes. Contaminants often meddle with the endocrine system, resulting in reduced fertility, increased developmental abnormalities in offspring, and long-term population decline [3]. Impaired immune function leaves fish vulnerable to disease and infection, further adding to the burden of a polluted environment. Worryingly, even the neurological systems of fish aren't safe from these effects, as pollutants can disrupt behaviours like feeding, predator avoidance, and social interaction, impacting their survival and altering the complex web of relationships within their ecosystem [4].

Faced with such far-reaching consequences, immediate action is essential. A successful approach demands a combination of proactive and reactive strategies. Proactively, stringent regulations for industries, a shift towards sustainable agriculture, and improved wastewater treatment systems are necessary to significantly reduce the flow of pollutants into aquatic environments [5]. Efforts must focus on the remediation of contaminated habitats, promoting fish population recovery, and supporting broader ecosystem restoration initiatives. Alongside these actions, continuous scientific research and monitoring are critical to pinpoint emerging pollutants, understand the severity of their impact on fish health, and ensure the effectiveness of chosen mitigation tactics.

The battle to protect fish health against the relentless onslaught of pollution is a crucial one. It necessitates a comprehensive understanding of the interplay between pollutants and fish biology, the extensive reach of these harmful effects, and the potential strategies for effective mitigation. Prioritizing the health of fish populations translates directly to safeguarding the vibrant and interconnected aquatic ecosystems on which we all depend.

2. EFFECTS OF POLLUTANTS ON FISH HEALTH

2.1 Chemical Pollutants (Heavy Metals, Pesticides, Industrial Chemicals)

Heavy metal contaminants such as cadmium, copper, mercury, and zinc are commonly found in rivers, reservoirs, and other aquatic environments. These metals are persistent pollutants that do not undergo biodegradation, leading to their accumulation in various components of aquatic ecosystems. Fish, oysters, mussels, sediments, and other aquatic organisms are known to bioaccumulate these heavy metals, posing significant risks to ecosystem health and human health through the consumption of contaminated seafood.

The presence of heavy metals in aquatic ecosystems can have detrimental effects on both aquatic organisms and humans. For example, cadmium exposure in fish has been linked to reproductive abnormalities, reduced growth, and impaired immune function [6].

Cadmium, a heavy metal pollutant found in industrial and agricultural waste, poses a significant threat to fish health. Exposure to cadmium disrupts vital physiological processes in fish, leading to various adverse effects. Studies have shown that cadmium can interfere with the endocrine system, disrupting hormonal pathways that regulate sexual development and reproduction [7]. Consequently, fish exposed to cadmium may experience reduced fertility, decreased sperm and egg quality, and developmental abnormalities in offspring [8]. Cadmium exposure has been implicated in growth impairment in fish. It can damage cellular processes involved in metabolism and energy production, ultimately limiting growth rates and overall body size [9]. This reduced growth not only weakens individual fish but can impact population dynamics and food web interactions within the ecosystem. Another harmful consequence of cadmium exposure is its detrimental impact on fish immune function [10]. It has been shown to suppress the immune response, making fish more susceptible to infections and diseases [11]. This weakened immune system further increases the vulnerability of fish populations to environmental stressors and contributes to higher rates of mortality.

Copper, though an essential element in trace amounts, poses a significant risk to fish health when present in excess concentrations. One major mechanism of copper toxicity is through the induction of oxidative stress. Excess copper can destabilize cellular processes, leading to the generation of harmful reactive oxygen species (ROS) that can damage proteins, lipids, and deoxyribonucleic acid (DNA) [12]. This oxidative damage is particularly severe in delicate gill tissues, which are directly exposed to waterborne copper. Consequently, impairment of gill function is a prime concern, hindering the fish's ability to efficiently extract oxygen from the water and maintain critical respiratory processes [12].

Mercury, primarily in its toxic methylmercury form, is a potent environmental contaminant with profound neurotoxic effects in fish and other organisms. Fish readily absorb methylmercury from the environment, where it accumulates in tissues, including the nervous system. Mercury acts by interfering with neurotransmitter function and disrupting vital processes within nerve cells [13]. The ensuing neurological damage has several negative repercussions for fish, including impaired sensory function, behavioural changes that limit feeding and predator avoidance, and developmental abnormalities in their offspring [13]. Importantly, due to biomagnification, the toxic effects of mercury can extend up the food chain to humans consuming contaminated fish.

Zinc is an essential trace element that plays a role in various physiological processes in many organisms, including fish. However, elevated zinc concentrations in the aquatic environment can have detrimental effects on these organisms. Excess zinc can interfere with critical cellular processes in fish, *disrupting* membrane function, enzymatic activity, and overall metabolic pathways [14]. This cellular dysfunction can have cascading impacts on fish health. A prominent concern with zinc toxicity in fish is the negative impact on the proper functioning of their gills. Gills serve the vital role of facilitating oxygen uptake and waste removal and require precise regulation of ion balance to sustain these functions. Excessive zinc can cause disruptions in gill ion regulation, affecting respiration and the proper balance of electrolytes in the fish [14]. Impairment of gill function can significantly restrict the fish's ability to thrive in their environment. Its toxicity can lead to reduced growth rates and developmental issues in fish populations. Zinc's ability to disrupt enzymatic activity can limit the proper use of essential nutrients needed for growth [15]. Similarly, impaired cellular metabolic processes caused by zinc toxicity can lead to stunted development and a range of physiological problems for the fish.

Heavy metals can have cascading effects throughout aquatic food webs, as predators accumulate higher concentrations of metals from their prey. This bioaccumulation and biomagnification process can lead to increased metal concentrations in apex predators, posing greater risks to organisms higher up the food chain, including humans.

2.2 Microplastics

Plastic pollution has become one of the most pressing environmental concerns of our time. A crucial but often overlooked aspect of this pollution is the proliferation of microplastics. Microplastics are tiny plastic particles, typically less than 5 millimeters in size, originating from various sources. Some are intentionally manufactured for use in personal care products or industrial applications (primary microplastics), while others result from the breakdown of larger plastic items (secondary microplastics) [16].

Plastic pollution represents a rapidly growing challenge, with the proliferation of microplastics posing a particularly concerning threat. Microplastics, as the name suggests, are minuscule plastic particles (>5 mm). These particles originate from a variety of sources and now contaminate nearly every environment on the planet. Some microplastics, classified as primary microplastics, are intentionally designed for specific applications. Examples include the microbeads used as exfoliants in many personal care products or the plastic "nurdles" employed in industrial processes like sandblasting. A major contributor to primary microplastics is the release of synthetic microfibers released from textiles during the laundering process. Alternatively, secondary microplastics arise from the gradual breakdown of larger plastic items. Sunlight, wave action, and physical wear fragment everyday plastic objects such as bags, bottles, and fishing gear, generating countless microplastic particles [17].

Due to their tiny size and resemblance to food sources, microplastics are easily ingested by a wide range of aquatic organisms. This contamination extends beyond oceans, as microplastics pollute rivers, lakes, and even terrestrial soils. Ingested microplastics, along with any toxins they've absorbed, move up the food chain, affecting larger fish, marine mammals, and potentially humans who consume seafood. Research is ongoing to fully comprehend the health effects of microplastic exposure, but preliminary evidence points to worrying potential consequences for both ecosystem and human health. These minuscule plastic fragments permeate nearly every corner of the planet, including aquatic ecosystems, posing a substantial threat to their inhabitants. Microplastics can be ingested by fish and other wildlife, either directly or through the consumption of contaminated prey. The ingested microplastics can cause several problems, such as physical blockages in the digestive tract, reduced feeding, and altered metabolism [18].

Microplastics act as vectors for a wide range of hazardous chemicals. During manufacturing, plastics often incorporate additives like stabilizers or flame retardants that can pose environmental and health concerns [19]. They can adsorb toxins, like heavy metals and persistent organic pollutants (POPs), from the surrounding water [20]. Once ingested, these harmful chemicals bound to microplastics can transfer to the fish's tissues, accumulating through the food chain.

The effects of microplastic exposure in fish are cause for major concern. Studies indicate that plastics and their associated chemicals can interfere with endocrine signaling, impair immune function, and have the potential to cause neurological damage [20]. This disruption of physiological processes can lead to reproductive dysfunction, increased susceptibility to disease, and potential behavioural changes in fish populations.

2.3 Biomedical Wastes

The improper disposal of biomedical waste into water bodies poses a significant threat to fish health and broader aquatic ecosystems. Biomedical waste contains hazardous substances, including chemical residues, infectious agents, pharmaceutical waste, and sharps [21]. Direct leaching of chemicals from improperly managed biomedical waste dumps can introduce various toxins into the water [22]. Pharmaceuticals, particularly antibiotics and synthetic hormones, can interfere with various biological processes in fish, including growth, immune function, and reproduction [23]. Pathogens such as viruses and bacteria present in biomedical waste can directly infect fish populations and, if unchecked, cause disease and high mortality rates [24].

These wastes can contribute to the generation of antibiotic-resistant bacteria, another major threat to fish health [21]. The release of antibiotics and other antimicrobial agents into aquatic environments promotes the selection and development of drug-resistant bacteria strains [25]. This resistance can spread to fish populations and ultimately pose risks to human health via the food chain.

Poorly managed biomedical waste can also contribute to toxic algal blooms that significantly harm fish populations. Excess nutrients such as phosphorus and nitrogen can fuel explosive algal growth. The subsequent collapse of these blooms causes oxygen depletion, creating conditions known as "dead zones" unsuitable for aquatic life, including fish [26].

2.4 Organic Pollutants and Hydrocarbons

Organic pollutants and hydrocarbons, with their diverse origins and varied properties, present pervasive threats to aquatic ecosystems and the fish populations within them. Industrial discharges, agricultural runoff, and the complex by-products of fossil fuel use introduce these chemicals into waterways, where they adversely affect fish populations at multiple levels. The ways that organic pollutants and hydrocarbons disrupt fish health depend on the specific compound and its concentration. Many types of hydrocarbons, like polycyclic aromatic hydrocarbons (PAHs), are directly toxic to fish and aquatic organisms [27]. PAH exposure can damage cellular structures, including DNA, hindering crucial cell functions and increasing the risk of cancers. These pollutants can have complex interactions with a fish's endocrine system. Mimicking or blocking natural hormones, these pollutants can disrupt reproductive capacity, impair development in offspring, and create physiological imbalances that diminish overall resilience [28].

The immune system of fish is also a susceptible target. Certain organic pollutants and hydrocarbons suppress the immune response, leaving fish more vulnerable to diseases and infections, leading to heightened mortality rates within populations [11]. Even seemingly subtle physiological disruptions can cause repercussions as they ripple through an ecosystem. Impacts on a fish's sense of smell or neurological function can hinder behaviors critical for feeding, predator avoidance, or finding suitable spawning grounds [29]. The implications of these pollutants can even extend beyond fish populations to food webs. In areas with pollution, bioaccumulation concentrates pollutants up the food chain, potentially compromising the health of higher-level organisms and even humans who consume contaminated fish species.

2.5 Nutrient Pollution and Eutrophication

Nutrient pollution is one of the most widespread, costly, and challenging environmental problems, and is caused generally by excess nitrogen and phosphorus in water bodies. Aquatic plants and algae gradually fill in freshwater lakes and estuaries over time in a natural process called eutrophication. This process is controlled by concentrations of certain nutrients (like phosphate and nitrogen). However, due to anthropogenic actions, nitrogen and phosphorus concentrations in water bodies have increased. This has accelerated the process of eutrophication.

Nutrient pollution, driven by excessive nitrogen and phosphorus loading in water bodies, has become a major environmental crisis with dire consequences for fish populations and overall aquatic health. Eutrophication, the natural process of nutrient enrichment, typically progresses gradually. However, human activities, such as intensive agriculture and inefficient wastewater management, have dramatically accelerated this process, pushing ecosystems past their resilience threshold [30].

The effects of eutrophication on fish health are multi-faceted. Rampant algal blooms, fueled by abundant nutrients, block sunlight vital for submerged vegetation, upon which many fish rely for both habitat and food sources. More insidious yet is the process of decay following these blooms. These dying algae consume massive amounts of dissolved oxygen, creating hypoxic or even anoxic (no oxygen) conditions known as "dead zones." These oxygen-depleted areas deprive fish of their fundamental life support, triggering large-scale die-offs [31].

Nutrient pollution doesn't simply suffocate fish directly. Elevated phosphorus and nitrogen levels disrupt delicate nutrient balances within aquatic systems, altering the composition of zooplankton and other organisms lower on the food chain, and compromising the quality of food resources available to fish. Even seemingly subtle shifts in nutrient dynamics can undermine fish growth and increase disease susceptibility [32].

Beyond these indirect effects, some algal blooms fueled by nutrient pollution produce potent toxins. These toxins can cause direct harm to fish and invertebrates, bioaccumulate up the food chain, and endanger the health of larger animals (including humans) consuming contaminated seafood [33].

3. TOXIC STRESS CAUSED BY POLLUTANTS IN FISH

3.1 Oxidative Stress and Reactive Oxygen Species (ROS)

Reactive oxygen species (ROS), including radicals like superoxide anion (O^{2-}), hydrogen peroxide (H_2O_2), and non-radical species like hydroxyl radical (HO•), are produced during normal cellular metabolism as byproducts. However, when ROS levels surpass the cellular antioxidant defence mechanisms, oxidative stress arises. This imbalance can occur due to either an increase in ROS production or a decrease in the cellular antioxidant capacity [34].

Reactive oxygen species (ROS) represent a collection of chemically reactive molecules containing oxygen. Naturally occurring as by-products of essential cellular processes like aerobic respiration, ROS include radical species, like the superoxide anion (O_2^-) and the hydroxyl radical (HO•), as well as non-radical species, like hydrogen peroxide (H_2O_2) as shown Fig 1. At typical levels, ROS plays key signalling roles in various physiological functions [35]. However, a tipping point exists beyond which ROS causes harm. Under circumstances of environmental stress, toxin exposure, or disease, ROS production can rise dramatically. Concurrently, if a cell's antioxidant defense systems become weakened, a dangerous imbalance between ROS generation and the ability to counteract them emerges – resulting in oxidative stress [34].

When oxidative stress sets in, ROS wreaks havoc by reacting readily with vital molecules within the cell. They can directly damage proteins, lipids (fats) within cell membranes, and even the very blueprints of cellular function - DNA. This destructive interaction compromises essential cellular functions, disrupting metabolic pathways, hindering cell signaling, and even leading to outright cell death [34].

The far-reaching repercussions of oxidative stress manifest in many diseases and have far-reaching health consequences. Oxidative stress has been implicated in several conditions, including neurodegenerative diseases, inflammatory disorders, cancer, and accelerated aging [35]. The mechanisms are complex and often depend on specific molecules and tissues, but oxidative stress has the potential to drive disease formation at multiple levels.

Fortunately, organisms have evolved natural defence's against the ravages of oxidative stress. Various antioxidant systems, including both enzymatic and non-enzymatic components, exist to scavenge ROS and maintain normal balance. While powerful, these defence systems can become overwhelmed if oxidative stress is severe or chronic.

3.2 Immune Suppression and Immunotoxicity

The understanding of how environmental chemicals affect the immune system of fish is still relatively limited. However, one prominent mechanism that has been suggested is the modulation of receptors and signalling pathways within immune cells by these chemicals, leading to alterations or disruptions in immune cell functioning.

These receptors also play crucial roles in integrating the immune system with other physiological systems within the organism, such as the reproductive system or the growth axis. These receptors and pathways serve to coordinate immune responses with other biological processes, ensuring overall homeostasis and health. However, it's important to recognize that these immune system-based receptors can also serve as molecular entry sites through which environmental contaminants may interfere with fish immunity. Environmental chemicals can interact with these receptors, disrupting their normal function and leading to dysregulation of immune responses. This can result in a range of effects, from changes in immune cell proliferation and differentiation to modulation of cytokine production and immune response [36].

Understanding the specific ways that environmental pollutants modulate the immune system of fish remains an active area of research. One of the major proposed mechanisms involves how these chemicals can directly interact with and disrupt crucial receptors and signaling cascades within the various cells that make up the immune system. In doing this, they manipulate the cell's machinery responsible for coordinating effective immune responses [37].

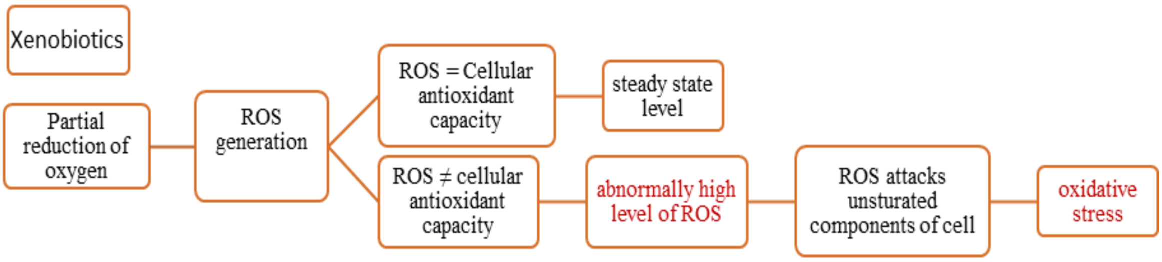

Fig. 1. Signaling pathway

It's vital to realize that receptors present on immune cells serve a purpose extending beyond immune defense itself. These complex signaling systems function as links between the immune system and other physiological systems, such as those controlling growth and reproduction. This integration across multiple interconnected systems allows the body to harmonize overall function and balance resources accordingly when a stressor such as an infection is present. But it also leaves this delicate balance vulnerable. Environmental chemicals have the potential to exploit these same critical receptors, using them as a gateway to alter and disrupt the finely-tuned function of the immune system [38].

The outcome of these chemical hijackings is variable but often harmful. Some pollutants trigger abnormal receptor activation, others mimic natural chemicals and send false signals, and some interfere with normal signaling processes directly. Disrupting receptor activity can, in turn, alter how immune cells develop, communicate with one another, and react to threats. Consequences encompass shifts in how fast specific defense cells proliferate, disturbances in the release of inflammatory signals (cytokines), and impairment of the overall ability to mount targeted immune responses against bacteria, viruses, and parasites [38].

The resulting compromised immunity increases a fish's vulnerability to a wider array of illnesses and infections and can reduce its capacity to recover when disease does strike. These effects on the immune system can hinder growth and development, leaving resources normally targeted for these needs diverted to combatting illness and its aftermath. Furthermore, researchers speculate that even modest disruption of the complex interplay between the immune system, reproduction, and growth could significantly affect fish populations over time by lessening reproductive success or slowing growth rates.

3.3 Endocrine Disruption and Reproductive Dysfunction

Endocrine disruptors represent a category of environmental contaminants that pose a significant threat to fish health and populations by interfering with the complex, interconnected processes of the endocrine system. Endocrine disruptors can interfere with the endocrine system by binding to steroid hormone receptors as agonists or antagonists. These receptors are present in cells of various systems, including the neuroendocrine and reproductive systems. The disruption caused by endocrine disruptors can lead to adverse effects on fish reproduction and sexual development.

One essential way they accomplish this disruption is by exploiting the presence of steroid hormone receptors within various target tissues throughout the body. These receptors, as their name implies, recognize and respond to specific steroid hormones such as estrogen, testosterone, and cortisol, mediating a myriad of essential processes, including development, growth, metabolism, and reproduction [39].

Endocrine disruptors can interfere with these critical signaling pathways by acting as either agonists or antagonists. Agonists mimic natural hormones, artificially activating receptors and potentially triggering responses at inappropriate times or with exaggerated intensity. In contrast, antagonists bind to receptors without activating them, blocking the binding sites needed by the genuine hormones and obstructing their function [40]. The effects of this manipulation are most acutely felt within the neuroendocrine and reproductive systems. Endocrine disruptors can cause abnormalities in sexual development, hinder reproductive capacity, and ultimately disrupt population dynamics through reduced fertility or the birth of less viable offspring [39].

Crucially, steroid hormone receptors are not restricted to the reproductive system. It's here that the insidious effects of endocrine disruptors often extend further, as they can infiltrate other biological systems. Numerous studies indicate that immune cells in fish also possess these receptors. This revelation means that chemicals capable of acting on specific steroid hormone receptors (like those mimicking estrogen or androgens) could disrupt the balance and proper functioning of the immune system while hindering reproduction [38].

It's worth noting that steroid hormone receptors are not limited to the reproductive system; they are also present in the immune cells of fish. Therefore, chemicals with estrogenic or androgenic activity have the potential to impact not only the reproductive system but also the immune system of fish.

3.4 Neurobehavioral Effects and Cognitive Impairment

Studies have demonstrated that both inorganic and organic pollutants can directly and indirectly, affect the behaviour of fish. For instance, pollutants such as pesticides and antidepressants have been linked to changes in activity levels, exploration, avoidance behaviour, and sociability in fish species [41]. Additionally, alterations in neurotransmitter levels, hormone regulation, and cholinesterase activity have been implicated in mediating these neurobehavioral effects. Furthermore, pollutants can influence fish cognitive performance, potentially leading to impaired learning and problem-solving abilities [42].

The neurobehavioral effects of pollutants on fish are multifaceted and may involve disruptions to neurofunction, neurotransmitter systems (serotonin), and hormonal regulation. For example, exposure to carbofuran pesticide has been shown to alter neurofunction and activity in sea bass, while fluoxetine antidepressant affects aggression, boldness, and learning in Siamese fighting fish by modulating the serotonin system. Additionally, changes in the energetic balance due to the costs of detoxification and stress responses may indirectly impact fish behaviour [42].

Pollutant-induced cognitive impairment in fish is characterized by difficulties in remembering things and solving problems, which can have detrimental effects on survival and reproductive success. Methylmercury, a common environmental pollutant, has been found to provoke oxidative damage and neural impairments in the brains of Nile tilapia. Moreover, dietary exposure to methylmercury has been associated with significant behavioural alterations and increased aggressive nature in fish [43, 44].

4. PHYSIOLOGICAL RESPONSES TO POLLUTION-INDUCED STRESS

4.1 Cellular Damage and Tissue Pathology

The gills of fish play a crucial role in respiration and serve as a primary interface for the exchange of gases and other substances with the surrounding water. However, they are also particularly susceptible to the harmful effects of waterborne pollutants due to their direct exposure to environmental contaminants [45]. Numerous studies have investigated the structural changes induced by toxicants and irritants in fish gills.

When toxic substances seep into waterways, gills often serve as the primary entry point and site of significant harm. Researchers have thoroughly documented the myriad of structural abnormalities and pathological changes that pollutants trigger within gill tissues. The specific nature of cellular damage depends on the pollutant, its concentration, and the duration of exposure. Common pathologies triggered by toxicants include swelling and thickening of the gill lamellae, which can drastically restrict the functional surface area available for respiration [45]. In some cases, pollutants induce changes in cell proliferation, causing the fusion of neighboring gill lamellae and further reducing the gill's vital gas exchange capacity. Direct damage to cells of the gill epithelium is another hallmark of toxicant exposure and can lead to cell death and a devastating impairment of function [46].

Beyond visible tissue damage, waterborne pollutants can also disrupt cellular machinery within the gills. Certain contaminants impair the function of ion pumps and transport channels responsible for a key function of gills: maintaining a fish's delicate internal electrolyte balance [47]. Disruption of these cellular mechanisms impedes proper gill function and hinders the fish's overall physiological condition. Moreover, toxic chemicals may elicit the production of excessive mucus within gill tissues, which creates a physical barrier obstructing efficient gas exchange and can lead to the proliferation of pathogenic bacteria.

The devastating effects of waterborne contaminants on fish gills have broad physiological consequences. As the main gas exchange organ, gills directly influence the capacity of a fish to extract vital oxygen from the aquatic environment. Impairment of gill functionality severely compromises the ability to power movement, digestion, reproduction, and every other facet of survival. Overwhelming gill damage often ends in suffocation and eventual death [43]. However, even seemingly sublethal changes on a cellular level can have lasting, adverse effects on a fish's overall health and energy, weakening them, affecting growth, and susceptibility to diseases and parasites.

4.2 Metabolic Changes and Energy Allocation

The stress induced by toxicants on organisms may result in the depletion of energy reserves, particularly over prolonged exposure [48]. Available energy, reserved energy, and consumed energy in an organism are affected by different factors. Of these, available energy is vital for sustaining fundamental physiological processes such as growth, tissue regeneration, reproduction, and basal metabolism [49]. Consequently, additional energy is necessary to cope with stress. Failure to provide this additional energy through diet may compromise growth, reproduction, and overall bodily functions (De Coen and Janssen, 2003b).

Cellular energy allocation (CEA) serves as a biomarker developed based on the "metabolic cost" hypothesis, positing that toxic stress induces metabolic alterations that may deplete energy reserves, leading to adverse effects on growth and reproduction [50]. CEA involves a biochemical comparison of an organism's energy consumption and available energy reserves for metabolism [51]. This method not only functions as an indicator of an organism's available energy content but also serves as a rapid and immediate means of measuring its energy status [52,53,54].

4.3 Behavioural Alterations and Predation Risk

Pollution-induced stress in fish can lead to a range of behavioural alterations, including sluggishness, impaired swimming ability, reduced feeding efficiency, and compromised territorial defence [55]. These changes in behaviour can disrupt important ecological interactions and ultimately affect the survival and reproductive success of fish populations. Moreover, exposure to neurotoxic substances in polluted environments can result in structural and functional impairments in the nervous system, further exacerbating behavioural abnormalities.

Pollution-induced behavioural alterations can significantly increase the predation risk for fish. Sluggishness and impaired swimming ability make fish more vulnerable to predation, as they are less able to evade predators or escape dangerous situations. Reduced feeding efficiency can lead to malnutrition and weakened conditions, further diminishing their ability to cope with predation pressure. Additionally, compromised territorial defence may result in the loss of valuable habitat and increased susceptibility to predation.

Pollution-induced changes in chemosensory behaviour can disrupt the ability of fish to detect predators or locate suitable food sources and mates. Altered chemotactic responses to pollutants may lead to shifts in spatial distribution and habitat use, exposing fish to different predation pressures and altering predator-prey dynamics within aquatic ecosystems [43].

4.4 Reproductive Impairment and Population Decline

Sex steroids stand as paramount heterocyclic compounds comprising androgens, estrogens, and progestogens which regulate the development and function of reproductive organs, gametogenesis, and sexual behaviour (Kumar & Mishra., 2023). Their pivotal role extends beyond mere fertility, permeating into broader aspects of physiology, metabolism, and even behaviour. Through signalling cascades and feedback loops, sex steroids coordinate the delicate balance necessary for successful reproduction, making them indispensable components of the reproductive toolkit across the animal kingdom.

A significant problem facing aquatic ecosystems is the negative impact of various pollutants on fish reproduction. Heavy metals, such as cadmium and mercury, are known to disrupt the endocrine systems of fish. These metals can mimic or interfere with natural hormones, causing issues with the development of reproductive organs, egg production, and sperm quality [56].

Pesticides and herbicides also play a harmful role. They can alter hormonal pathways, directly damage reproductive tissues, and reduce overall fish health, hindering successful reproduction [57]. Pharmaceuticals and personal care products, particularly synthetic estrogen compounds like 17α-ethinylestradiol (EE2), have been documented as influencing fish gene expression, reproductive behaviour, and overall fertility [57]. Moreover, persistent organic pollutants (POPs), due to their bioaccumulation in the food chain, can significantly disrupt hormone balance and gonad development, adversely affecting the timing and viability of fish reproduction [58].

The consequences of these disruptions to fish reproduction extend beyond individual organisms. Reproductive impairment can significantly reduce fish populations, destabilizing aquatic ecosystems and causing food web imbalances. Therefore, it is imperative to mitigate these pollution sources and promote cleaner water systems to protect the sensitive and complex reproductive cycles of fish populations.

5. BIOMARKERS OF POLLUTION-INDUCED STRESS IN FISH

5.1 Biochemical Biomarkers (Antioxidant Enzymes, Oxidative Stress Markers)

Antioxidant enzymes like superoxide dismutase (SOD), glutathione peroxidase (GPX), and catalase (CAT) are commonly used as markers of oxidative stress [59]. These enzymes play crucial roles in maintaining cellular balance for normal function. Heavy metals, particularly cadmium and mercury, severely compromise fish health by targeting their endocrine systems. The endocrine system is a complex network of glands and organs that produce and release hormones. These hormones are essential messengers that regulate vital functions like growth, development, metabolism, and reproduction [59]. Heavy metals can mimic or block natural hormones, causing a cascade of negative effects [56]. The disruption can occur at several levels, leading to issues like reduced gonad size, impaired egg and sperm development, and altered reproductive behaviours.

To combat the potential damage caused by heavy metals and other pollutants, fish rely on protective mechanisms. Oxidative stress arises when there's an imbalance between harmful reactive oxygen species (ROS) and the body's antioxidant defences.

Additionally, a well-known biomarker for neurotoxicity is the inhibition of acetylcholinesterase (AChE) activity. AChE is an enzyme vital for proper nerve function, breaking down the neurotransmitter acetylcholine. This breakdown process is essential for controlled signaling between nerves [60]. Monitoring AChE inhibition is commonly used in freshwater systems to assess exposure to these insecticides and their physiological effects on exposed animals [61]. Organophosphate and carbamate insecticides primarily work by inhibiting AChE, leading to the buildup of acetylcholine in synapses and resulting in overexcitation and severe toxicity symptoms. Measuring AChE activity in the brain or whole-body samples of exposed organisms provides a way to quantify the severity of this neurotoxic effect [60].

5.2 Mitigation Strategies and Management Approaches

A multifaceted approach is essential to protect fish populations and their aquatic habitats from the adverse effects of water pollution. Prioritizing prevention is key, focusing on source reduction strategies to minimize the entry of pollutants into waterways. Industrial facilities must implement advanced wastewater treatment technologies and adhere to strict regulations to significantly reduce or eliminate the release of heavy metals, toxic chemicals, and excessive nutrients [62]. Similarly, sustainable agricultural practices like buffer zones, cover cropping, and optimized waste management can minimize fertilizer and pesticide contamination that threaten aquatic ecosystems [63]. Cities can be redesigned with green infrastructure such as rain gardens and permeable pavements, which help treat polluted urban stormwater before it reaches sensitive waterways [62]. In cases where contamination is already present, the remediation of polluted sites through soil removal, sediment capping, or even natural bioremediation processes becomes necessary.

Regulations and enforceable standards play a critical role in mitigating water pollution. Governments often establish water quality standards that define the maximum allowable concentrations of pollutants to safeguard aquatic life, including fish [64]. Discharge permits mandate treatment requirements for facilities releasing wastewater, ensuring pollutants are within acceptable limits [62]. When water bodies fail to meet quality standards, a Total Maximum Daily Load (TMDL) plan lays out strategies to reduce pollution from various sources and bring the water body back into compliance [64]. International treaties, like the Stockholm Convention on Persistent Organic Pollutants, address a global effort to restrict the production and release of highly hazardous chemicals known to cause long-term harm to fish and their environments [65].

Effectively addressing water pollution demands continuous monitoring and assessment programs. Comprehensive data on water quality, fish health, and pollutant levels guide targeted control strategies and highlight areas for improvement. However, challenges persist, such as regulating diffuse non-point source pollution (often tied to agricultural runoff) which requires broader awareness campaigns and incentives for sustainable practices. Legacy pollutants continue to impair fish populations long after their introduction, emphasizing the need for remediation. Additionally, new and emerging contaminants like microplastics and pharmaceuticals call for constant research, risk assessment, and potential adjustment of regulatory standards. Rigorous enforcement of existing regulations is paramount to ensure accountability and promote cleaner, healthier waterways for fish and the ecosystems they support.

Habitat restoration and ecosystem-based management (EBM) are interconnected approaches vital for preserving and improving aquatic ecosystems, including those essential for fish populations. Habitat restoration encompasses activities aimed at re-establishing damaged or degraded habitat components. This can include efforts like removing dams to improve river connectivity, replanting native vegetation along shorelines, or restoring wetland areas that provide critical spawning and nursery grounds for fish [66]. Ecosystem-based management adopts a holistic perspective, aiming to manage entire ecosystems by considering the complex interactions between all their components, including human activities [67]. In aquatic environments, EBM promotes managing factors like fishing pressure, pollution, and land-use practices that collectively impact the health and function of entire watersheds or lake systems.

A fundamental principle of EBM is balancing ecological protection with the sustainable use of natural resources [68]. This approach involves setting science-based targets for ecosystem sustainability, often focusing on preserving key species like fish, which play critical roles in food webs and overall biodiversity [69]. Integrating socioeconomic considerations is also vital since aquatic ecosystems support fishing communities and diverse livelihoods dependent on healthy resources [70]. Therefore, EBM encourages stakeholder collaboration, incorporating the knowledge and needs of fishing communities, governments, and conservationists to find balanced solutions.

Habitat restoration and EBM often overlap in practical applications. Restoration activities contribute to broader EBM goals by re-establishing essential habitat components and supporting diverse fish populations. Conversely, an EBM framework can guide larger-scale restoration projects, prioritizing critical sites and employing a comprehensive strategy aligned with the overall health of the targeted ecosystem. EBM can even help mitigate the negative impacts of human activities and create a more favourable environment for restoration efforts.

Implementing effective habitat restoration and EBM programs requires long-term monitoring and adaptive management techniques [68]. Continuous data collection on fish populations, water quality, and overall ecosystem health provides feedback on the success of projects, allows for adjustments, and supports continuous learning processes.

Efforts to mitigate heavy metal contamination in aquatic ecosystems involve implementing pollution control measures, such as reducing industrial discharges and implementing wastewater treatment technologies. Additionally, monitoring programs are essential for assessing the extent of heavy metal contamination and implementing appropriate remediation strategies to protect ecosystem health and human well-being.

Integrated Water Quality Management (IWQM) adopts a holistic perspective, aiming to protect and improve water resources [65]. Unlike traditional approaches focused solely on treating pollutants at the end of the pipe, IWQM considers the entire watershed or catchment area. It recognizes that various factors within a watershed impact water quality, including land-use practices, industrial activities, urban runoff, and more [65]. IWQM prioritizes collaboration between diverse stakeholders like regulatory agencies, local communities, industries, and scientists, enabling a more balanced and comprehensive planning process [71].

Best Management Practices (BMPs) are specific tools or techniques employed to prevent or minimize water pollution. Within an IWQM framework, BMPs can be both structural and non-structural. Structural BMPs include engineered solutions like constructed wetlands, green infrastructure in urban areas, or advanced wastewater treatment technologies [62]. Non-structural BMPs often focus on behavior change such as promoting sustainable agricultural practices, responsible chemical use in industries, or public education efforts to reduce littering [62].

IWQM and BMPs are vital for safeguarding the aquatic ecosystems that fish populations depend upon. By managing pollution at its source and considering broader landscape elements, IWQM aims to maintain water quality suitable for diverse aquatic life [72]. Strategically employed BMPs address specific pollutant sources, helping to ensure healthy water for fish to thrive. Additionally, IWQM promotes stakeholder engagement, providing opportunities for local communities and fishermen to share knowledge and perspectives, ensuring that management strategies are well-suited to local conditions and needs.

A critical component of implementing IWQM and BMPs is continuous monitoring and data-driven decision-making. Collecting information on water quality, aquatic ecosystem health, and the effectiveness of BMPs assists in adaptive management, ensuring strategies evolve in response to on-the-ground outcomes [65].

Interdisciplinary approaches and collaborative research are becoming increasingly vital for addressing complex problems that defy narrow disciplinary boundaries. Environmental challenges, such as those impacting aquatic ecosystems and fish populations, necessitate this type of integrated thinking. Interdisciplinary research encourages experts from diverse fields, like biologists, chemists, social scientists, and engineers, to work together to more holistically understand these multifaceted issues [72]. Collaborative research builds on this principle, emphasizing open communication, shared goals, and collective problem-solving among team members to tackle complicated questions [73].

These interconnected approaches bring several key benefits to studying and managing aquatic ecosystems. Interdisciplinary teams often uncover new perspectives and identify novel solutions for addressing issues such as pollution, habitat degradation, and declining fish populations [72]. A biologist investigating fish reproductive impairments might collaborate with a chemist to better analyse pollutants, an engineer to design potential remediation systems, and a sociologist to understand community perspectives on pollution risks and solutions. Collaborative research promotes the free exchange of ideas, enhances learning among participants, and facilitates the development of more robust and impactful research results [74].

Importantly, the inclusion of stakeholders outside academia—government agencies, communities, and industries affected by environmental problems—provides vital knowledge and strengthens the potential for long-term successful outcomes. Integrating indigenous knowledge and perspectives can ensure solutions are better informed and respect local cultures and needs [75].

Challenges such as overcoming different disciplinary languages, balancing various research methodologies, and navigating logistical complexities often accompany interdisciplinary and collaborative approaches [76-81]. Still, the rewards of comprehensive solutions to complex environmental problems and innovative breakthroughs highlight the need to foster a scientific culture that encourages and supports these approaches [73].

6. CONCLUSION

This review emphasizes the severe and multifaceted impacts of pollution and toxic stress on fish health. Diverse pollutants, from heavy metals to emerging contaminants, can disrupt vital physiological functions like endocrine regulation, oxidative balance, and neurotransmission. Consequences range from individual-level health impairments such as altered reproductive capabilities to broader shifts in fish populations and aquatic ecosystem stability. To combat these escalating threats, a strategic, multi-pronged approach is required. Stricter pollution control measures, including source reduction and advanced remediation, must be prioritized alongside ecosystem-based management practices like habitat restoration. Regulatory frameworks for existing and emerging contaminants must be bolstered and consistently enforced. Interdisciplinary research remains crucial to elucidate complex toxicant interactions and provide science-backed solutions for mitigation and improved ecosystem health. Continuous monitoring and assessment programs will further enable adaptive management decisions to track ongoing threats and inform future strategies. The importance of raising public awareness and empowering community stakeholders in pollution prevention and management cannot be overstated. Ultimately, protecting aquatic ecosystems and the fish they support requires a collaborative effort combining proactive legislation, innovative technologies, scientific vigilance, and strong community engagement. Only through coordinated and sustained action can we ensure a future where clean waterways support healthy and resilient fish populations.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Hamilton PB, Cowx IG, Oleksiak MF, Griffiths AM, Grahn M, Stevens JR, et al. Population-level consequences for wild fish exposed to sublethal concentrations of chemicals–a critical review. Fish Fish. 2016;17(3):545-66.
2. Samuel PO, Edo GI, Oloni GO, Ugbune U, Ezekiel GO, Essaghah AEA, et al. Effects of chemical contaminants on the ecology and evolution of organisms a review. Chem Ecol. 2023;39(10):1071-1107.
3. Canosa LF, Bertucci JI. The effect of environmental stressors on growth in fish and its endocrine control. Front Endocrinol. 2023;14:1109461.
4. Kampezidou D. Behavior effects of a psychotropic pharmaceutical contaminant on Atlantic salmon (*Salmo salar*) juveniles: Atlantic salmon juveniles exposed to two different oxazepam concentrations.
5. Carey RO, Migliaccio KW. Contribution of wastewater treatment plant effluents to nutrient dynamics in aquatic systems: a review. Environ Manag. 2009;44:205-17. Available: https://doi.org/10.1007/s00267-009-9309-5
6. Lee JW, Jo AH, Lee DC, Choi CY, Kang JC, Kim JH. Review of cadmium toxicity effects on fish: Oxidative stress and immune responses. Environ Res. 2023;236:116600.
7. Jezierska B, Ługowska K, Witeska M. The effects of heavy metals on embryonic development of fish (a review). Fish Physiol Biochem. 2009;35(4):625-40. Available:https://doi.org/10.1007/s10695-008-9284-4
8. Siraj M, Uddin MJ. Cadmium accumulation in freshwater fish: effects and remediation strategies. Environ Sci Pollut Res; 2023.
9. McGeer JC, Szebedinszky C, McDonald DG, Wood CM. Effects of chronic sublethal exposure to waterborne Cu, Cd or Zn in rainbow trout 1: Iono-regulatory disturbance and metabolic costs. Aquat Toxicol. 2000;50(3):231-43.
10. Bly JE, Quiniou SM, Clem LW. Environmental effects c. Develop Biol Standard. 1997;90:33-43.
11. Zelikoff JT. Metal pollution-induced immunomodulation in fish. Annu Rev Fish Dis. 1993;3:305-25.
12. Grosell M. Copper. In: Wood CM, Farrell AP, Brauner CJ, editors. Homeostasis and toxicology of essential metals. Elsevier. 2012;53-133.
13. Scheuhammer AM, Meyer MW, Sandheinrich MB, Murray MW. Effects of environmental methylmercury on the health of wild birds, mammals, and fish. Ambio. 2007;36(1):12-9. Available: https://doi.org/10.1579/0044-7447
14. Hogstrand C. Zinc. In: Wood CM, Farrell AP, Brauner CJ, editors. Homeostasis and toxicology of essential metals. Elsevier. 2011;135-200. Available:https://doi.org/10.1016/j.chemosphere.2012.09.030
15. Spry DJ, Wood CM. Zinc influx across the isolated, perfused head preparation of the rainbow trout (*Salmo gairdneri*) in hard and soft water. Can J Fish Aquat Sci. 1985;42(12):2061-5.
16. Andrady AL. Microplastics in the marine environment. Mar Pollut Bull. 2011;62(8):1596-605. Available:https://doi.org/10.1016/j.marpolbul.2011.05.030
17. Borrelle SB, Ringma J, Law KL, Monnahan CC, Lebreton L, McGivern A, et al. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science. 2020;369(6510):1515-8. Available:https://doi.org/10.1126/science.aba3656
18. Wright SL, Thompson RC, Galloway TS. The physical impacts of microplastics on

marine organisms: a review. Environ Pollut. 2013;178:483-92. Available:https://doi.org/10.1016/j.envpol.2013.02.031

19. Rochman CM, Browne MA, Underwood AJ, van Franeker JA. The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. Ecology. 2013;94(2):300-12. Available:https://doi.org/10.1890/14-2070.1
20. Rochman CM, Hoh E, Kurobe T, Teh SJ. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci Rep. 2013;3(1):1-7. Available:https://doi.org/10.1038/srep03263
21. World Health Organization. Safe management of wastes from health-care activities. 2nd ed. World Health Organization; 2018.
22. Chakraborty S, Veeregowda B, Gowda L, Sannegowda SN, Tiwari R, Dhama K, et al. Biomedical waste management. Interaction. 2013;12-02.
23. Brodin T, Fick J, Jonsson M, Klaminder J. Dilute concentrations of a psychiatric drug alter behavior of fish from natural populations. Science. 2013;339(6121):814-5. Available:https://doi.org/10.1126/science.1226850
24. Osman AGM, Mekky TM, Dahab MF, Mahmoud UE. Aquaculture water pollution and diseases of cultured fish: Mini-review. Res J Pharm Technol. 2022;15(8):3997–4001.
25. Zhang QQ, Ying GG, Pan CG, Liu YS, Zhao JL. Comprehensive evaluation of antibiotics emission and fate in the river basins of China: Source analysis, multimedia modeling, and linkage to bacterial resistance. Environ Sci Technol. 2015;49(11):6772–6782. Available: https://doi.org/10.1021/acs.est.5b00729
26. Smith VH, Tilman GD, Nekola JC. Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environ Pollut. 1999;100(1–3):179–196.
27. Meador JP, Stein JE, Reichert WL, Varanasi U. Bioaccumulation of polycyclic aromatic hydrocarbons by marine organisms. Rev Environ Contam Toxicol. 1995;143:79-165.
28. Collier TK, Stein JE, Sanborn HR, Heintz R, et al. Field studies of reproductive success and bioindicators of maternal contaminant exposure in English sole (*Pleuronectes vetulus*). Sci Total Environ. 1998;214:91-114.
29. Sandahl JF, Baldwin DH, Jenkins JJ, Scholz NL. A sensory system at the interface between urban stormwater runoff and salmon survival. Environ Sci Technol. 2007;41(8):2998-3004.
30. Smith VH, Schindler DW. Eutrophication science: where do we go from here?. Trends Ecol Evol. 2009;24(4):201-207. Available:https://doi.org/10.1016/j.tree.2008.11.009
31. Diaz RJ, Rosenberg R. Spreading dead zones and consequences for marine ecosystems. Science. 2008;321 (5891):926-929. Available:https://doi.org/10.1126/science.1156401
32. Le Moal M, Gascuel-Odoux C, Ménesguen A, Souchon Y, Étrillard C, Levain A, et al. Eutrophication: A new wine in an old bottle? Sci Total Environ. 2019;651:1-11.
33. Anderson DM, Glibert PM, Burkholder JM. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries. 2002;25(4):704-726.
34. Ray PD, Huang BW, Tsuji Y. Reactive oxygen species (ROS) homeostasis and redox regulation in cellular signaling. Cell Signal. 2012;24(5):981-990. Available:https://doi.org/10.1016/j.cellsig.2012.01.008
35. Sies H, Berndt C, Jones DP. Oxidative stress. Annu Rev Biochem. 2017;86:715-748.
36. Segner H, Bailey C, Tafalla C, Bo J. Immunotoxicity of xenobiotics in fish: a role for the aryl hydrocarbon receptor (AhR)? Int J Mol Sci. 2021;22(17):9460.
37. Reynaud S, Deschaux P. The effects of polycyclic aromatic hydrocarbons on the immune system of fish: a review. Aquat Toxicol. 2006;77(2):229-238. Available:https://doi.org/10.1016/j.aquatox.2005.10.018
38. Segner H, Verburg-van Kemenade BL, Chadzinska M. Immunotoxic effects of environmental pollutants in fish. In: Secombes CJ, editor. Fish Physiology. 2017;36B:231-275.
39. Kausch U, Chairmand IO, Schmidt-Posthaus H. Effects of estrogenic substances in fish. In: Schrenk OD, editor. Fertility and sterility: hormonal

contraceptives today and tomorrow. Springer Nature. 2016;169-175.

40. Diamanti-Kandarakis E, Bourguignon JP, Giudice LC, Hauser R, Prins GS, Soto AM, et al. Endocrine-disrupting chemicals: an Endocrine Society scientific statement. Endocr Rev. 2009;30(4):293-342.
41. Zala SM, Penn DJ. Abnormal behaviours induced by chemical pollution: a review of the evidence and new challenges. Anim Behav. 2004;68(4):649-664. Available:https://doi.org/10.1016/j.anbehav.2004.01.005
42. Nabi M, Tabassum N. Role of environmental toxicants on neurodegenerative disorders. Front Toxicol. 2022;4:837579.
43. Grue CE, Gardner SC, Gibert PL. On the significance of pollutant-induced alterations in the behaviour of fish and wildlife. Behav Ecotoxicol; 2002.
44. Crump KL, Trudeau VL. Mercury-induced reproductive impairment in fish. Environ Toxicol Chem. 2009;28(5):895-907.
45. Mallatt J. Fish gill structural changes induced by toxicants and other irritants: a statistical review. Can J Fish Aquat Sci. 1985;42(4):630-648. Available: https://doi.org/10.1139/f85-083
46. Fernandes MN, Mazon AF. Environmental pollution and fish gill morphology. In: Val AL, Kapoor BG, eds. Fish Adaptations. Science Publishers. 2003;203-231.
47. Wendelaar Bonga SE, Lock RAC. Toxicants and osmoregulation in fish. Neth J Zool. 1992;42(2-3):478-493.
48. Ferreira NG, Morgado R, Santos MJ, Soares AM, Loureiro S. Biomarkers and energy reserves in the isopod Porcellionides pruinosus: the effects of long-term exposure to dimethoate. Sci Total Environ. 2015;502:91-102. Available:https://doi.org/10.1016/j.scitotenv.2014.08.062
49. Gourley ME, Kennedy CJ. Energy allocations to xenobiotic transport and biotransformation reactions in rainbow trout (*Oncorhynchus mykiss*) during energy intake restriction. Comp Biochem Physiol C Toxicol Pharmacol. 2009;150(2):270-278. Available:https://doi.org/10.1016/j.cbpc.2009.05.003
50. Gomes SI, Soares AM, Amorim MJ. Changes in cellular energy allocation in Enchytraeus crypticus exposed to copper and silver—linkage to effects at higher level (reproduction). Environ Sci Pollut Res. 2015;22:14241-14247. Available: https://doi.org/10.1007/s11356-015-4630-4
51. Novais SC, Soares AM, De Coen W, Amorim MJ. Exposure of Enchytraeus albidus to Cd and Zn–Changes in cellular energy allocation (CEA) and linkage to transcriptional, enzymatic and reproductive effects. Chemosphere. 2013;90(3):1305-1309.
52. Verslycke T, Roast SD, Widdows J, Jones MB, Janssen CR. Cellular energy allocation and scope for growth in the estuarine mysid *Neomysis integer* (Crustacea: Mysidacea) following chlorpyrifos exposure: a method comparison. J Exp Mar Biol Ecol. 2004;306(1):1-16. Available:https://doi.org/10.1016/j.jembe.2003.12.022
53. Smolders R, Bervoets L, De Coen W, Blust R. Cellular energy allocation in zebra mussels exposed along a pollution gradient: linking cellular effects to higher levels of biological organization. Environ Pollut. 2004;129(1):99-112. Available:https://doi.org/10.1016/j.envpol.2003.09.027
54. Damian EC, Innocent II, Obinwanne OC, Obinna EC. Cellular energy budget in tropical freshwater fish following exposure to sublethal concentrations of cadmium. J Toxicol Environ Health Sci. 2019;11(7):75-83. Available:https://doi.org/10.5897/JTEHS2019.0447
55. Srivastava P, Singh A, Pandey AK. Pesticides toxicity in fishes: biochemical, physiological and genotoxic aspects. Biochem Cell Arch. 2016;16(2):199-218.
56. Ji K, Seo J, Liu X, Lee J, Lee S, Lee W, et al. Endocrine-disrupting chemicals and male reproductive health. Front Public Health. 2014;2:55. Available:https://doi.org/10.3389/fpubh.2014.00055
57. Porte C, Janer G, Lorusso LC, Ortiz-Zarragoitia M, Cajaraville MP, Fossi MC, et al. Endocrine disruptors in marine organisms: Approaches and perspectives. Comp Biochem Physiol C Toxicol Pharmacol. 2006;143(3):303–315. Available:https://doi.org/10.1016/j.cbpc.2006.03.004
58. Chatonnet P, Boutou S, Planchenault N, Durrieu G. Biochar-based nanocomposites

for contaminant management. In: Lin Z, Khraisheh MAA, eds. Biochar-based Nanocomposites for Environmental Applications. Elsevier; 2014:35-62.

59. Gutteridge JMC. Lipid peroxidation in mammalian systems. Prog Lipid Res. 1995;34:141-187.
60. Küster E, Altenburger R. A cross-laboratory validation of an in vitro AChE inhibition assay. Altern Lab Anim. 2006;34:89-92.
61. Fulton MH, Key PB. Acetylcholinesterase inhibition in estuarine fish and invertebrates as an indicator of organophosphorus insecticide exposure and effects. Environ Toxicol Chem. 2001; 20(1):37–45.
62. United States Environmental Protection Agency (EPA). Best Management Practices (BMPs); 2023.
63. Toossi S, Jones JW. The food and nutrition assistance landscape: Fiscal year 2022 annual report. 2023. DOI: 10.22004/ag.econ.337564
64. Clean Water Act (CWA). (33 U.S.C. § 1251 et seq.); 1972. Available: https://www.epa.gov/laws-regulations/summary-clean-water-act: https://www.epa.gov/laws-regulations/summary-clean-water-act
65. UNEP. Progress on integrated water resources management. Global baseline for SDG 6 indicator 6.5.1: degree of IWRM implementation. United Nations Environment Programme; 2018. Available:https://www.unwater.org/publications/progress-on-integrated-water-resources-management-651/
66. Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, et al. Synthesizing U.S. river restoration efforts. Science. 2005;308(5722):636-637.
67. Long RD, Charles A, Stephenson RL. Key principles of marine ecosystem-based management. Mar Policy. 2015;57:53-60.
68. Arkema KK, Abramson SC, Dewsbury BM. Marine ecosystem-based management: from characterization to implementation. Front Ecol Environ. 2006;4(10):525-532.
69. Pikitch EK, Santora C, Babcock EA, Bakun A, Bonfil R, Conover DO, et al. Ecosystem-based fishery management. Science. 2004;305(5682):346-347.
70. Leslie HM, Basurto X, Nenadovic M, Sievanen L, Cavanaugh KC, Cota-Nieto JJ, et al. Operationalizing the social-ecological systems framework to assess sustainability. Proc Natl Acad Sci. 2015;112(19):5979-5984.
71. Pahl-Wostl C. The implications of complexity for integrated resources management. Environ Model Softw. 2007;22(5):561–569.
72. National Academies of Sciences, Engineering, and Medicine. Facilitating interdisciplinary research. The National Academies Press; 2005.
73. Aboelela SW, Larson E, Bakken S, Carrasquillo O, Formicola A, Glied SA, et al. Defining interdisciplinary research: Implications for teamwork, mentoring, and research training. Acad Med. 2007; 82(7):729-735.
74. Katz JS, Martin BR. What is research collaboration? Res Policy. 1997;26(1):1-18.
75. Tengö M, Brondizio ES, Elmqvist T, Malmer P, Spierenburg M. Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. AMBIO. 2014; 43:579–591.
76. Fitzgerald JA, Könemann S, Krümpelmann L, Županič A, Vom Berg C. Approaches to test the neurotoxicity of environmental contaminants in the zebrafish model: from behavior to molecular mechanisms. Environ Toxicol Chem. 2021;40(4):989-1006.
77. Jacquin L, Petitjean Q, Côte J, Laffaille P, Jean S. Effects of pollution on fish behavior, personality, and cognition: some research perspectives. Front Ecol Evol. 2020;86.
78. Köllner B, Wasserrab B, Zschiesche W, Triebskorn R. Effects of the nonsteroidal antiinflammatory drug diclofenac on the early life stages of the zebrafish (*Danio rerio*). Aquat Toxicol. 2002;58(1-2):121-130.
79. Lee JW, Kim JH, Lee DC, Lim HJ, Kang JC. Toxic effects on oxidative stress, neurotoxicity, stress, and immune responses in juvenile olive flounder, *Paralichthys olivaceus*, exposed to waterborne hexavalent chromium. Biology. 2022;11(5):766.
80. Lu M, Chang Z, Bae MJ, Oh SM, Chung KH, Park JS. Molecular characterization of the aryl hydrocarbon receptor (AhR)

pathway in goldfish (*Carassius auratus*) exposure to TCDD: The mRNA and protein levels. Fish Shellfish Immunol. 2013;35(2): 469-475.

81. Song C, Liu B, Ge X, Li H, Xu P. miR-34a/Notch1b mediated autophagy and apoptosis contributes to oxidative stress amelioration by emodin in the intestine of teleost Megalobrama amblycephala. Aquaculture. 2022;547: 737441. Available:https://doi.org/10.1016/j.aquaculture.2021.737441

Peer-review history:
The peer review history for this paper can be accessed here:
https://prh.mbimph.com/review-history/3284