Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Assessing The Ecological Implications Of Pollutants On Fish Health: Biomarkers And Beyond

Mangal Sitaram Kadam

Research and P.G. Department of Zoology, Yeshwant Mahavidyalaya, Nanded(M. S.) INDIA
Email: mskadam2006@rediffmail.com

Fish are integral to aquatic ecosystems, serving as bioindicators of environmental health and a key food source for humans. However, the increasing presence of pollutants in aquatic environments poses significant threats to fish physiology, with potential long-term ecological and human health implications. This paper examines the impacts of various pollutants, including agricultural pesticides, industrial chemicals, pharmaceuticals, personal care products, microplastics, and petrochemicals, on fish physiology. These pollutants can disrupt endocrine function, reproductive physiology, growth, development, and behaviour. The paper also explores how environmental factors such as temperature and water quality parameters modulate these effects. Biomarkers and assessment methods are discussed as tools for evaluating pollutant impacts on fish health. The study highlights the need for continued research into the ecological implications of pollutants on fish populations and aquatic ecosystems to develop effective mitigation strategies.

Keywords: Fish physiology, Aquatic ecosystems, Pollutants, Endocrine disruption, Biomarkers, Environmental health.

Introduction

Fish play a crucial role in aquatic ecosystems, serving as important indicators of environmental health and providing a vital food source for humans. However, the increasing presence of pollutants in aquatic environments has raised significant concerns about their impact on fish physiology. These pollutants can disrupt various biological processes, potentially leading to long-term ecological consequences and affecting human health through the food chain (Yancheva et al., 2022).

Common Pollutants Affecting Fish

Aquatic ecosystems are exposed to a wide range of pollutants that can adversely affect fish physiology. These contaminants can be broadly categorized into several groups:

Agricultural Pesticides

Pesticides, particularly insecticides, pose a significant threat to non-target aquatic organisms when they enter surface waters. For example, chlorpyrifos (CPF) and cypermethrin (CYP) have been shown to have negative effects on important aquaculture species such as common carp (Cyprinus carpio) (Yancheva et al., 2022). These pesticides can impact various

physiological processes, including oxidative stress responses, histological structure of organs, and behaviour (Yancheva et al., 2022).
Recent studies have highlighted the potential toxicity of pesticides and their transformation products to aquatic organisms, particularly fish. These contaminants can affect growth, reproduction, physiology, immunity, and cause histopathological changes in multiple fish tissues (Ghosh & Sarower, 2024). The bioaccumulation of pesticides in fish tissues also presents substantial health risks for human consumers (Ghosh & Sarower, 2024).

Industrial Chemicals
Industrial pollutants, such as polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDT), continue to be a concern in aquatic environments due to their persistence and ability to bioaccumulate in fish tissues (Impellitteri et al., 2023). These chemicals can have long-lasting effects on fish physiology, potentially impacting entire populations and ecosystems.

Pharmaceuticals and Personal Care Products
The increasing presence of pharmaceuticals and personal care products in aquatic environments is an emerging concern. Compounds such as triclosan and triclocarban, commonly found in personal care products, can have adverse effects on fish physiology (Impellitteri et al., 2023). These contaminants can disrupt endocrine function, alter behavior, and impact reproductive success in fish populations (Bieczynski et al., 2022).

Microplastics and Associated Contaminants
Microplastics have become one of the fastest-growing pollutants in aquatic environments, posing a substantial toxic effect on fish (Chen, et al.,2023). These small plastic particles ($1 \leq 1000$ μm in size) can cause physical harm through ingestion and serve as vectors for other pollutants (Hanslik, 2020). Microplastics can adsorb heavy metals and other contaminants, facilitating their transfer from the environment to organisms (Yancheva et al., 2022).

Studies have shown that microplastics can be found in various fish tissues, including the digestive tract and gills, with evidence suggesting potential translocation to other organs (Galafassi et al., 2021). The ingestion of microplastics has been documented in 257 species of freshwater fishes from 32 countries, highlighting the widespread nature of this issue (Galafassi et al., 2021) (Romersi, & Nicklisch, 2022).

Oil and Petrochemicals
Oil spills and chronic releases of petrochemicals into aquatic environments can have severe impacts on fish physiology. These pollutants can cause acute toxicity, disrupt endocrine function, and lead to long-term population-level effects in fish communities.
In conclusion, the diverse array of pollutants affecting fish physiology presents a complex challenge for aquatic ecosystem health. The interactions between these contaminants and their combined effects on fish physiology require further research to fully understand the ecological implications and develop effective mitigation strategies (Impellitteri et al., 2023). As our understanding of these pollutants grows, it becomes increasingly important to implement

measures to reduce their input into aquatic environments and protect the health of fish populations and the ecosystems they inhabit.

Effects on Fish Physiology

The presence of pollutants in aquatic environments can have significant impacts on various aspects of fish physiology. These effects range from disruptions in endocrine function to alterations in growth, development, and behavior (Azaza et al., 2020). Understanding these physiological changes is crucial for assessing the overall health of fish populations and the potential long-term consequences for aquatic ecosystems.

Endocrine Disruption

One of the most significant concerns regarding pollutants in aquatic environments is their potential to act as endocrine-disrupting compounds (EDCs). These substances can interfere with the normal functioning of the endocrine system, which plays a critical role in regulating various physiological processes in fish.

Antidepressants, which are increasingly detected in aquatic habitats due to municipal wastewater effluent release, have been identified as potential EDCs in fish. These pharmaceuticals target monoaminergic signaling in the human brain, but the monoaminergic systems are highly conserved across vertebrates and are involved in modulating numerous endocrine functions (Thompson & Vijayan, 2022). Studies have shown that exposure to antidepressants can affect reproduction, growth, and stress responses in fish.

For example, the tricyclic antidepressant amitriptyline (AMI) has been found to bioconcentrate in zebrafish (Danio rerio) and induce a pharmacological effect by downregulating the gene encoding the serotonin transporter (slc6a4a) at environmentally relevant concentrations as low as 0.03 µg/L (Gould et al., 2024). This finding suggests that even low levels of antidepressants in the environment can potentially disrupt the endocrine system of fish.

Reproductive Physiology

Endocrine disruption can have significant impacts on fish reproductive physiology. Pharmaceuticals and personal care products (PPCPs) have been shown to negatively affect fish fecundity, which is a crucial predictor of population-level effects (Overturf et al, 2015). These compounds can alter hormone levels, affect gonadal development, and disrupt reproductive behaviors (Nicklisch & Hamdoun, 2020).

Xenoestrogenic chemicals, which mimic or interfere with natural estrogen functions, are particularly concerning for fish reproduction. These compounds can lead to various reproductive abnormalities, such as:
- Male fish abnormally producing vitellogenin (a female-specific protein)
- Reduced sperm counts in males
- Decreased fecundity and egg hatchability in females (Badamasi et al, 2020)

Growth and Development

Pollutants can also affect the growth and development of fish. Exposure to certain contaminants during early life stages can have long-lasting effects on fish physiology. For instance, early-life exposure to antidepressants has been shown to potentially alter the developmental programming of the endocrine system, which could lead to long-term and multigenerational effects in teleosts (Thompson & Vijayan, 2022).

In the case of amitriptyline exposure, higher concentrations were found to accelerate the hatch rate in zebrafish, indicating a potential disruption of normal developmental processes (Gould et al., 2024).

Behavioral Changes

Pollutants can induce significant behavioral changes in fish, which can have cascading effects on their survival and ecological interactions. For example, a study using the "Peek-A-Boo" test demonstrated that exposure to diazepam, an anxiolytic drug, altered the behavior of medaka fish (Oryzias latipes) in response to a predator image. Fish exposed to diazepam approached the predator image more quickly and spent more time near it compared to the control group, suggesting a reduction in anxiety-like behaviors (Takai et al., 2023).

These behavioral changes can have serious implications for predator-prey interactions, mating behaviors, and overall survival strategies of fish populations.

Hybridization and Mate Selection

An emerging concern is the potential for pollutants, in combination with climate change, to disrupt mate selection processes and facilitate hybridization between fish species. Chemical pollutants can alter the sensory environment, affecting chemical and visual communication among fish. Additionally, various compounds may impair fish physiology, potentially affecting phenotypic traits relevant for mate selection, such as pheromone production, courtship behaviors, and coloration (Ramirez-Duarte et al., 2024).

This disruption of mate selection processes could lead to increased hybridization between species, potentially threatening biodiversity and species conservation in freshwater ecosystems.

In conclusion, the effects of pollutants on fish physiology are diverse and far-reaching, impacting crucial aspects of their life cycles from development to reproduction. The complex interactions between various pollutants and environmental factors underscore the need for continued research to fully understand and mitigate these impacts on fish populations and aquatic ecosystems as a whole.

Environmental Factors Modulating Pollutant Effects

The impact of pollutants on fish physiology is not solely determined by the concentration of the contaminants themselves. Various environmental factors can significantly modulate the effects of pollutants, either exacerbating or mitigating their impact on fish health. Understanding these interactions is crucial for accurately assessing the risks posed by pollutants in aquatic ecosystems.

Temperature Influences

Temperature is a critical environmental factor that can significantly influence the toxicity of pollutants to fish. As ectothermic organisms, fish are particularly susceptible to temperature fluctuations, which can affect their metabolic rates, enzyme activities, and overall physiological processes.

Research has shown that temperature can modulate the toxicity of various pollutants:
1. Increased toxicity at higher temperatures: In many cases, higher temperatures can increase the toxicity of pollutants. This is often due to increased metabolic rates in fish, leading to greater uptake and accumulation of contaminants(Nicklisch & Hamdoun, 2020). For example, a study on the effects of waterborne copper and silver on zebrafish (Danio rerio) embryos found that temperature significantly influenced the toxicity of these metals (Mohammadbakir, 2016).

2. Altered detoxification processes: Temperature changes can affect the activity of enzymes involved in detoxification processes. This can lead to changes in the fish's ability to metabolize and excrete pollutants, potentially increasing their toxic effects(Meirelles et al., 2022).
3. Synergistic effects with other stressors: Temperature stress can make fish more susceptible to the effects of pollutants. For instance, hypoxia (low oxygen levels) often occurs in conjunction with elevated temperatures in aquatic environments, and this combination can exacerbate the toxic effects of pollutants (Heath, 2018).

Interaction with Other Stressors
Aquatic ecosystems are often subject to multiple stressors simultaneously, and the interaction between these stressors and pollutants can have complex effects on fish physiology:
1. Hypoxia and pollutants: Low oxygen levels can interact with pollutants in various ways. For example, hypoxia can alter the uptake and distribution of contaminants in fish tissues. Additionally, some pollutants can impair the fish's ability to cope with low oxygen conditions by damaging gill tissue or affecting hemoglobin function (Heath, 2018).
2. pH and metal toxicity: The pH of water can significantly influence the bioavailability and toxicity of metals. In general, lower pH (more acidic conditions) tends to increase the solubility and bioavailability of many metals, potentially increasing their toxic effects on fish.
3. Salinity and osmoregulation: Changes in salinity can affect the osmoregulatory capacity of fish, which in turn can influence their susceptibility to pollutants. A study on Oreochromis mossambicus exposed to manganese demonstrated that sublethal concentrations of this metal could disrupt osmoregulation, with effects becoming apparent even at lower exposure concentrations (Barnhoorn & Van Vuuren, 2001).

Water Quality Parameters
Various water quality parameters can modulate the effects of pollutants on fish physiology:
1. Dissolved organic matter: The presence of dissolved organic matter in water can bind to some pollutants, reducing their bioavailability and potential toxicity to fish(Biasato et al., 2023).

2. Hardness: Water hardness, particularly the concentration of calcium and magnesium ions, can affect the toxicity of certain metals. Generally, higher water hardness tends to reduce metal toxicity by competing with metal ions for binding sites on fish gills.
3. Suspended solids: High levels of suspended solids in water can interact with pollutants and affect their bioavailability. Additionally, suspended solids can directly impact fish health by damaging gill tissue, which may increase susceptibility to other pollutants (Dunn et al., 2011).

Seasonal Variations

Seasonal changes can influence the effects of pollutants on fish through various mechanisms:
1. Reproductive cycles: Many fish species have seasonal reproductive cycles, during which they may be more susceptible to the effects of pollutants. For example, endocrine-disrupting compounds may have more pronounced effects during spawning periods (Bieczynski et al., 2022).
2. Seasonal temperature fluctuations: As mentioned earlier, temperature changes can significantly modulate pollutant effects. Seasonal temperature variations can therefore lead to fluctuations in pollutant toxicity throughout the year.
3. Seasonal variations in pollutant inputs: In some cases, the input of pollutants into aquatic ecosystems may vary seasonally (e.g., due to agricultural runoff or seasonal industrial activities), leading to temporal variations in exposure and effects on fish.
In conclusion, the effects of pollutants on fish physiology are complex and can be significantly modulated by various environmental factors. Temperature, interactions with other stressors, water quality parameters, and seasonal variations all play crucial roles in determining the ultimate impact of pollutants on fish health. Understanding these interactions is essential for accurately assessing and managing the risks posed by pollutants in aquatic ecosystems. Future research should focus on elucidating the mechanisms underlying these interactions and developing more comprehensive models to predict pollutant effects under varying environmental conditions.

Biomarkers and Assessment Methods

The use of biomarkers and various assessment methods has become increasingly important in evaluating the impact of pollutants on fish physiology and overall aquatic ecosystem health. These tools provide valuable insights into the sublethal effects of contaminants and can serve as early warning indicators of environmental stress(Solé, et al., 2010).

Physiological and Biochemical Markers

Physiological and biochemical markers are widely used to assess the effects of pollutants on fish health. These markers can provide sensitive and specific indications of exposure to various contaminants:
1. Oxidative Stress Biomarkers: Antioxidant enzyme activities are commonly used as bioindicators of water pollution in fish. A study on Cyprinus carpio L. in the Sitnica River, Kosovo, examined the activities of three antioxidant defense enzymes: catalase (CAT), superoxide dismutase (SOD), and glutathione-S-transferase (GST) in fish blood. The results showed significantly higher levels of these enzymes in fish from polluted sites compared to less contaminated areas, indicating their sensitivity as biochemical bioindicators of chemical pollution (Valon et al., 2013).

2. Liver Enzymes: Serum levels of enzymes such as alkaline phosphatase (ALP), alanine transaminase (ALT), and aspartate transaminase (AST) can serve as indicators of liver function and overall fish health. A study on Nile tilapia in Egyptian watercourses found significantly higher activities of these enzymes in fish collected from highly polluted unlined sites compared to those from less polluted lined sites (Ismail & Mohamed, 2017).
3. Metallothioneins: These proteins play a crucial role in metal homeostasis and detoxification. Increased metallothionein levels in fish tissues can indicate exposure to heavy metals and serve as a biomarker of metal pollution (Teles et al., 2016).

Histopathological Approaches

Histopathological analysis of fish tissues provides valuable information about the structural changes induced by pollutants:
1. Gill Histopathology: Gills are often the first organ to be affected by water pollutants due to their direct contact with the aquatic environment. A study on fish gills in Situ Cikaret and Situ Cilodong, West Java, revealed various histopathological changes, including hyperplasia, leucocyte proliferation, secondary lamella fusion, vasodilatation, oedema, necrosis, and hypertrophy of mucus and chloride cells. These changes were observed even when water quality parameters (temperature, pH, and dissolved oxygen) were within normal ranges, indicating the sensitivity of gill histopathology as a biomarker of pollution (Phadmacanty et al., 2023).
2. Liver Histopathology: The liver plays a crucial role in detoxification and is often used for histopathological assessment. Common liver alterations observed in polluted environments include cytoplasmic vacuolation of hepatocytes, pyknosis of nuclei, and necrosis (Ismail & Mohamed, 2017).
3. Gonadal Histopathology: Histological analysis of gonads can reveal the effects of endocrine-disrupting compounds. A study on Sarotherodon melanotheron in Lake Nokoué, Benin, found testis-ova in males and follicular atretic oocytes in females, indicating estrogenic effects from pollutants (Prudencio et al., 2023).

Ecologically Relevant Biomarkers

Some researchers have proposed using ecologically relevant biomarkers that directly relate to fish survival and fitness in their natural environment:
1. Hypoxia Tolerance: The ability of fish to tolerate low oxygen conditions can be affected by pollutant exposure. However, a study on European sea bass (Dicentrarchus labrax) exposed to dispersant-treated oil found no significant effect on hypoxia tolerance at 1 and 11 months post-exposure (Mauduit et al., 2019).
2. Temperature Susceptibility: Fish sensitivity to temperature changes can be an indicator of overall health and stress tolerance. The same study on European sea bass also examined temperature susceptibility but found no significant effects from dispersant-treated oil exposure (Mauduit et al., 2019).

Integrated Assessment Approaches

To provide a comprehensive evaluation of pollutant effects, researchers often combine multiple biomarkers and assessment methods:
1. Multi-tissue Analysis: Examining multiple tissues (e.g., gills, liver, gonads) can provide a more complete picture of pollutant effects on fish physiology (Skouras et al., 2003).
2. Biomarker Indices: Some researchers have developed indices that combine multiple biomarkers to provide an overall assessment of fish health. For example, the study on the effects of monocrotophos on Etroplus maculatus used a histological index based on observed lesions to determine No Observable Effect Concentration (NOEC) and Least Observable Effect Concentration (LOEC) (Sulekha & Anna, 2022).
3. Field and Laboratory Studies: Combining field observations with controlled laboratory experiments can help validate the relevance of biomarkers in real-world scenarios.
In conclusion, the use of biomarkers and various assessment methods provides a powerful toolset for evaluating the effects of pollutants on fish physiology. These approaches offer sensitive and specific indicators of exposure and effects, allowing for early detection of environmental stress. However, it's important to note that the interpretation of biomarker responses requires a comprehensive understanding of the factors that can influence them, including natural variability and environmental conditions. Future research should focus on developing and validating new biomarkers, particularly those with ecological relevance, and on integrating multiple biomarkers to provide a more holistic assessment of fish health in polluted environments (Soengas et al., 2018).

Ecological Implications
The effects of pollutants on fish physiology extend beyond individual organisms, potentially impacting entire populations and ecosystems. Understanding these broader ecological implications is crucial for assessing the long-term consequences of pollution in aquatic environments.

Population-level Effects
Pollutants can have significant impacts on fish populations through various mechanisms:
1. Reproductive Impairment: Endocrine-disrupting compounds can affect reproductive success, potentially leading to reduced population growth rates. For example, high ammonia concentrations in mangrove wetlands of Tai O, Hong Kong, were found to exceed limits set by various water quality standards, including the U.S. EPA criterion for fish reproduction (2). Such high ammonia levels could adversely affect fish populations in these ecosystems.
2. Altered Population Dynamics: Pollutants can affect survival rates at different life stages, potentially altering the age structure and dynamics of fish populations. This can have cascading effects on ecosystem functioning and food web interactions.
3. Genetic Effects: Long-term exposure to pollutants may lead to genetic adaptations or reduced genetic diversity within populations, potentially affecting their resilience to other environmental stressors.

Ecosystem Consequences
The impacts of pollutants on fish can have far-reaching consequences for aquatic ecosystems:
1. Trophic Cascades: Changes in fish populations due to pollution can lead to trophic cascades, affecting the abundance and distribution of other species in the ecosystem. For instance, a

decline in predatory fish due to pollution could lead to an increase in their prey species, potentially altering ecosystem balance.
2. Bioaccumulation and Biomagnification: Many pollutants, particularly heavy metals and persistent organic pollutants, can bioaccumulate in fish tissues and biomagnify up the food chain. A study on the Spanish Mediterranean coast found that while most metal concentrations in sediments did not pose a significant risk to aquatic organisms, mercury levels in some areas could have low-level effects (5). This highlights the potential for pollutants to impact not only fish but also higher trophic levels, including humans who consume fish.
3. Ecosystem Services: Pollution-induced changes in fish populations can affect ecosystem services provided by aquatic environments, such as fisheries productivity and water purification.

Future Research Directions

As our understanding of the impacts of pollutants on fish physiology and aquatic ecosystems grows, several key areas emerge as priorities for future research:

Emerging Contaminants of Concern

1. Microplastics and Nanoplastics: While the presence of microplastics in aquatic environments is well-documented, more research is needed on their long-term effects on fish physiology and ecosystem functioning. Additionally, the potential impacts of nanoplastics, which can potentially cross biological barriers more easily, require further investigation.
2. Pharmaceutical Residues: The increasing presence of pharmaceutical compounds in aquatic environments necessitates more comprehensive studies on their effects on fish physiology, particularly at environmentally relevant concentrations and in mixture scenarios.

Long-term and Multigenerational Studies

1. Chronic Exposure Effects: More long-term studies are needed to understand the effects of chronic, low-level exposure to pollutants on fish physiology and population dynamics. This is particularly important for assessing the impacts of persistent pollutants that may accumulate in the environment over time.
2. Transgenerational Effects: Research into potential transgenerational effects of pollutant exposure, including epigenetic changes, could provide insights into the long-term evolutionary consequences of pollution on fish populations.

Combined Effects of Multiple Stressors

1. Pollutant Mixtures: Most aquatic environments contain complex mixtures of pollutants. Future research should focus on understanding the combined effects of these mixtures, as they may interact in ways that are not predictable from single-compound studies.
2. Climate Change Interactions: The interaction between pollutants and climate change-related stressors (e.g., increased temperature, ocean acidification) is an important area for future research. For instance, a study on the Kłodnica River found a relationship between high salinity and the response of exposed bioindicators (3), highlighting the need to consider multiple environmental factors when assessing pollutant impacts.

Improved Assessment Methods
1. Ecologically Relevant Biomarkers: Developing and validating biomarkers that are directly linked to ecological outcomes, such as population growth rates or ecosystem functioning, could improve our ability to predict and manage the impacts of pollution on aquatic ecosystems.
2. Integrated Monitoring Approaches: Combining traditional physicochemical analyses with ecotoxicological assessments and ecological surveys could provide a more comprehensive understanding of pollutant impacts. For example, a study on industrial discharge in the Kłodnica River demonstrated the value of combining physicochemical analyses with bioassays for a more complete assessment of water quality (3).
3. Advanced Modeling Techniques: Developing more sophisticated models that can integrate multiple lines of evidence and predict ecosystem-level responses to pollution could enhance our ability to manage and protect aquatic environments.

In conclusion, while significant progress has been made in understanding the impacts of pollutants on fish physiology and aquatic ecosystems, there remain many important questions to be addressed. Future research should focus on emerging contaminants, long-term and multigenerational effects, the combined impacts of multiple stressors, and the development of more integrated and ecologically relevant assessment methods. By addressing these research priorities, we can improve our ability to predict, manage, and mitigate the impacts of pollution on aquatic ecosystems.

References:

1. Azaza, M. S., Khiari, N., Dhraief, M. N., Aloui, N., Kraïem, M. M., & Elfeki, A. (2020). Growth performance, oxidative stress indices and hepatic carbohydrate metabolic enzymes activities of juvenile Nile tilapia, Oreochromis niloticus L., in response to dietary starch to protein ratios. Aquaculture Research, 51(5), 2333-2342.
2. Badamasi, I., Odong, R., & Masembe, C. (2020). Threats posed by xenoestrogenic chemicals to the aquatic ecosystem, fish reproduction and humans: a review. African Journal of Aquatic Science, 45(3), 243-258.
3. Barnhoorn, I., & Van Vuuren, J. H. J. (2001). Sublethal effects of manganese on the haematology and osmoregulation of Oreochromis mossambicus after acute exposure. Southern African Journal of Aquatic Sciences, 26(1), 1-7.
4. Biasato, I., Ferrocino, I., Biasibetti, E., Grego, E., Dabbou, S., Sereno, A., & Gai, F. (2023). Nutritional Physiology of Aquacultured species. Frontiers in Physiology, 14, 1131057.
5. Bieczynski, F., Romersi, R. F., & Luquet, C. M. (2022). Editorial: Cellular transport and metabolism of nutrients, natural toxins, pollutants, and drugs in the digestive system of fish and aquatic invertebrates. Frontiers in Physiology, 13, 1048333.
6. Chen, Q., Zhao, H., Liu, Y., Jin, L., & Peng, R. (2023). Factors affecting the adsorption of heavy metals by microplastics and their toxic effects on fish. Toxics, 11(6), 490.
7. Dunn, J. M., Rong, J., McKubre-Jordens, M., Henderson, B., Goudey, R., & Anderssen, R. (2011). Setting water quality objectives for the health of freshwater fish. ANZIAM Journal, 53, M62-M103.
8. Galafassi, S., Campanale, C., Massarelli, C., Uricchio, V. F., & Volta, P. (2021). Do freshwater fish eat microplastics? A review with a focus on effects on fish health and predictive traits of MPs ingestion. Water, 13(16), 2214.

9. Ghosh, A. K., & Sarower, M. G. (2024). Potential toxicity of pesticides and its transformation products to aquatic organisms. Khulna University Studies, 21-32.
10. Gould, S. L., Winter, M. J., Trznadel, M., Lange, A., Hamilton, C. M., Boreham, R. J., ... & Tyler, C. R. (2024). Exposure Effects of Environmentally Relevant Concentrations of the Tricyclic Antidepressant Amitriptyline in Early Life Stage Zebrafish. Environmental Science & Technology.
11. Hanslik, L. (2020). Microplastics in Limnic Ecosystems-Investigation of Biological Fate and Effects of Microplastic Particles and Associated Contaminants in Zebrafish (Danio rerio)-(Doctoral dissertation).
12. Heath, A. G. (2018). Water pollution and fish physiology. CRC press.
13. Impellitteri, F., Multisanti, C. R., Rusanova, P., Piccione, G., Falco, F., & Faggio, C. (2023). Exploring the impact of contaminants of emerging concern on fish and invertebrates physiology in the Mediterranean Sea. Biology, 12(6), 767.
14. Ismail, N. M., Ali, S. E., & Mohamed, I. K. (2017). Biochemical and histological biomarker approaches in the assessment of the water pollution in some lined and unlined watercourses of Egypt. International Journal of Fisheries and Aquatic Studies, 5(3), 288-296.
15. Mauduit, F., Farrell, A. P., Domenici, P., Lacroix, C., Le Floch, S., Lemaire, P., ... & Claireaux, G. (2019). Assessing the long-term effect of exposure to dispersant-treated oil on fish health using hypoxia tolerance and temperature susceptibility as ecologically relevant biomarkers. Environmental toxicology and chemistry, 38(1), 210-221.
16. Meirelles, P. M., Gomes, A. S., Melo, E. T., Amado, L. L., Moreira, R. G., & Baldisserotto, B. (2022). Growth hormone overexpression increases intestinal absorption capacity in zebrafish (Danio rerio). Frontiers in Physiology, 13, 869719.
17. Mohammadbakir, S. (2016). Impacts of waterborne copper and silver on the early life stage (ELS) of zebrafish (Danio rerio): physiological, biochemical and molecular responses (Doctoral dissertation, Plymouth University).
18. Nicklisch, S. C., & Hamdoun, A. (2020). Disruption of small intestinal β-carotene absorption by synthetic food colorants. Nature Communications, 11(1), 1-13.
19. Overturf, M. D., Anderson, J. C., Pandelides, Z., Beyger, L., & Holdway, D. A. (2015). Pharmaceuticals and personal care products: A critical review of the impacts on fish reproduction. Critical reviews in toxicology, 45(6), 469-491.
20. Phadmacanty, N.L., Yulianto, Dina, R., Wahyudewantoro, G., Aisyah, S., & Prawira, A.Y. (2023). Histopathological Study of Fish Gills in Situ Cikaret and Situ Cilodong, West Java. IOP Conference Series: Earth and Environmental Science, 1191.
21. Prudencio, A., Chabi, O., Edéya Orobiyi Rodrigue, P., Dzorgbe Agbeko Precious, M., Nicresse Léa, G., Ibrahim, I. T., & Antoine, C. (2023). Assessment of the health status of Lake Nokoué (Benin, West Africa) exposed to multiple pollutants during flood season. Chemistry and Ecology, 39(7), 726-752.
22. Ramirez-Duarte, W. F., Moran, B. M., Powell, D. L., Bank, C., Sousa, V. C., Rosenthal, G. G., ... & Rochman, C. M. (2024). Hybridization in the Anthropocene–how pollution and climate change disrupt mate selection in freshwater fish. Biological Reviews.
23. Romersi, R. F., & Nicklisch, S. C. (2022). Membrane transporters in the digestive system of fish and aquatic invertebrates: A review. Frontiers in Physiology, 13, 869719.
24. Skouras, A., Broeg, K., Dizer, H., von Westernhagen, H., Hansen, P. D., & Steinhagen, D. (2003). The use of innate immune responses as biomarkers in a programme of integrated biological effects monitoring on flounder (Platichthys flesus) from the southern North Sea. Helgoland Marine Research, 57(3), 190-198.
25. Soengas, J. L., Cerdá-Reverter, J. M., & Delgado, M. J. (2018). Central regulation of food intake in fish: an evolutionary perspective. Journal of Molecular Endocrinology, 60(4), R171-R199.

26. Solé, M., Antó, M., Baena, M., Carrasson, M., Cartes, J. E., & Maynou, F. (2010). Hepatic biomarkers of xenobiotic metabolism in eighteen marine fish from NW Mediterranean shelf and slope waters in relation to some of their biological and ecological variables. Marine Environmental Research, 70(2), 181-188.
27. Sulekha, B.T., & Anna Mercy, T. (2022). Fish Gills as a Tool for the Assessment of Sublethal Effects of Monocrotophos on a Freshwater Fish, Etroplus maculatus. Ecology, Environment and Conservation.
28. Takai, Y., Izumi, M., Motoyama, Y., Shimasaki, Y., Oshima, Y., & Kang, I. J. (2023). Peek-A-Boo Test: A Simple Test for Assessing the Effect of Anxiolytics on Fish Behavior. Environmental Toxicology and Chemistry, 42(11), 2358-2363.
29. Teles, M., Fierro-Castro, C., Na-Phatthalung, P., Tvarijonaviciute, A., Trindade, T., Soares, A. M., & Oliveira, M. (2016). Assessment of gold nanoparticle effects in a marine teleost (Sparus aurata) using molecular and biochemical biomarkers. Aquatic Toxicology, 177, 125-135.
30. Thompson, W. A., & Vijayan, M. M. (2022). Antidepressants as endocrine disrupting compounds in fish. Frontiers in Endocrinology, 13, 895064.
31. Valon, M., Valbona, A., Fahri, G., Qenan, M., Dhurat, K., & Fatmir, C. (2013). Evaluating Environmental Pollution by Applying Oxidative Stress Biomarkers as Bioindicators of Water Pollution in Fish. Polish Journal of Environmental Studies, 22(5).
32. Yancheva, V., Georgieva, E., Velcheva, I., Iliev, I., Stoyanova, S., Vasileva, T., ... & Nyeste, K. (2022). Assessment of the exposure of two pesticides on common carp (Cyprinus carpio Linnaeus, 1758): Are the prolonged biomarker responses adaptive or destructive?. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 261, 109446.