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Living Sensors: What Fish Physiology Tells Us About a Changing Ocean

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Abstract

Fish physiology has emerged as a valuable and sensitive tool for monitoring the health of marine ecosystems. As fish respond rapidly and measurably to environmental stressors such as pollution, ocean warming, acidification, and hypoxia, their physiological responses ranging from hormonal fluctuations to gill damage can serve as natural bioindicators of ocean health. This article explores how key physiological markers, including stress hormones, respiratory function, and reproductive health, provide early warnings of ecological disturbances. By integrating fish physiology into ocean monitoring programs, scientists gain a real-time, cost-effective method for detecting and understanding changes in marine environments. In the face of accelerating climate and human-driven pressures, fish are not only vital components of aquatic ecosystems but also act as sentinels alerting us to the declining state of the oceans.

1. Introduction

The world's oceans are facing unprecedented challenges. From climate change and ocean acidification to chemical pollution and habitat destruction, the stressors on marine ecosystems are intensifying rapidly. These changes not only affect biodiversity but also threaten the billions of people who rely on oceans for food, livelihood, and climate regulation. While satellites and water sensors offer valuable environmental data, they often fail to capture the biological impacts of these changes. The study of the biological mechanisms that allow organisms to exist and function is known as physiology. For a quicker and more accurate understanding of ecosystem stress, scientists are increasingly turning to a natural, responsive system of fish physiology. Fish are in constant contact with their environment, and their bodies react quickly to changes in water quality, temperature, oxygen levels, and pollutants. Alterations in physiological processes such as increased stress hormone levels, disrupted metabolism, impaired gill function, or reproductive failure serve as biomarkers of environmental health. Unlike static sensors, fish are living organisms that integrate multiple stressors

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over time. This makes them not just inhabitants of the marine world, but also biological sentinels, offering early warnings of ecological disturbance. As climate and human pressures continue to reshape the oceans, understanding fish physiology could play a crucial role in guiding conservation and marine management strategies. Fish can serve as real-time biological sensors, with their physiological changes mirroring environmental fluctuations (Kuklina et al., 2013). As ectotherms (cold-blooded), fish are especially sensitive to changes in water temperature, chemistry, and oxygen levels. These physiological responses, ranging from stress hormone production to altered gill function, can be measured to assess ocean health (Figure 1) with a high degree of sensitivity and specificity.

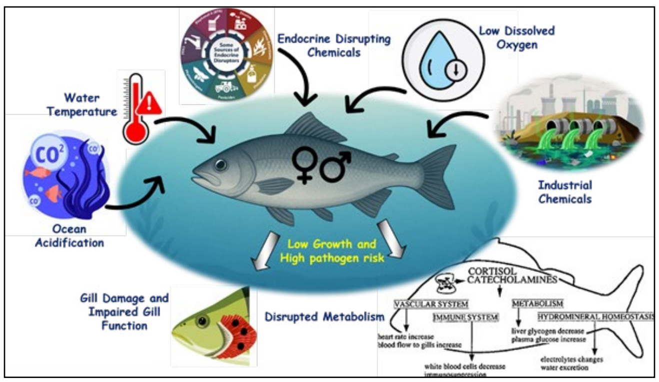

Figure 1: Responses of fish to various stressors in aquatic environments

2. Stress Hormones as Biological Alarms

In fish, the recognition of a stressor initiates a neuroendocrine cascade that results in the production and release of corticosteroid hormones, primarily cortisol and catecholamines, such as adrenaline and noradrenaline (also known as epinephrine and norepinephrine). The stress response in teleost fish occurs in two phases. Initially, there is a rapid spike in circulating catecholamines released from chromaffin cells in the kidney; this is followed by a slower-onset but more sustained increase in cortisol levels, synthesized by the interrenal tissue. When fish are exposed to environmental stressors like pollutants, low oxygen, or sudden temperature shifts, their bodies produce cortisol, a primary stress hormone. Elevated cortisol levels can suppress immune function, alter behaviour, and reduce growth and reproductive success. Monitoring cortisol levels in fish blood or mucus provides a non-lethal method for assessing environmental stress. In polluted estuaries, for example, fish have shown chronically high cortisol levels, indicating long-term exposure to harmful substances like heavy metals or endocrine-disrupting chemicals (Lemos et al., 2023). Goikoetxea et al. (2021) demonstrated that cortisol levels in the scales of European sea bass (*Dicentrarchus labrax*) can effectively serve as an indicator of long-term thermal stress. After four months, fish maintained at 21 °C exhibited ten times higher cortisol concentrations than those kept at 16 °C. Additionally, most teleost species show a measurable increase in plasma cortisol within 10 minutes following a stress event, suggesting that the activation timing of the hypothalamic-pituitary-interrenal (HPI) axis is largely unaffected by temperature (Pankhurst, 2011).

3. Gills as a Front Line of Environmental Interaction

Gills are one of the most sensitive and exposed organs in fish, compose half of the body surface area, responsible for gas exchange, ion regulation, and waste excretion (Wood and Soivio, 1991). As such, they are the first to react to changes in water quality. In hypoxic conditions where oxygen levels are dangerously low, fish gills often become inflamed or damaged. Structural changes in gill tissues can reduce oxygen uptake and overall fitness. Gill histopathology (microscopic tissue analysis) has been used to detect damage by the pollutants (Table 1) such as ammonia, pesticides, and oil derivatives, making gill condition a key physiological indicator in toxicological assessments (Evans, 1987).

4. Metabolism As a Potential Biomarker

Dramatic effects environmental fluctuations may have on the metabolic rates of fishes; Fish metabolism is directly influenced by water temperature. Warmer waters increase metabolic demand, leading to higher oxygen consumption. However, warmer oceans often hold less dissolved oxygen, especially in stratified layers, creating a dangerous mismatch between oxygen supply and demand. Various biochemical markers have been studied in Antarctic fish to assess their response to environmental changes. These include enzymes involved in energy metabolism (such as citrate synthase, malate dehydrogenase, phosphofructokinase, hexokinase, pyruvate kinase, isocitrate dehydrogenase, creatine kinase, Na^+/K^+-ATPase, cytochrome oxidase, β-hydroxybutyrate

Table 1: Different histopathological signs of gills due to the effect of pollutants

Pollutant Exposure	Histopathological condition	Key Identifications
Detergents, phenols, ammonia, acids, and metals like mercury	Epithelial lifting	Increase the intracellular spaces between the pillar system and the epithelial lining of secondary lamellae
Heavy metals and certain pesticides, doses of therapeutic hydrogen peroxide or formalin, red tides	Aneurysm	Blood leakage within the lamellae and by the pillar cell system's rupture, with subsequent dilation of blood vessels
Prolonged exposure to irritants, toxins, water suspensions	Necrosis	Eosinophilic cytoplasm and necrotic nuclei
Ammonia High copper sulfate concentrations	Lamellar blood congestion Lamellar epithelium hyperplasia	Microscopic damages and losses of double-concave cells (pillar cells), capillaries of the respiratory lamella fused and formed a uniform space filled with blood
Chronic effects caused by aluminium	Secondary lamellar fusion	Partial or total fusion of lamellar capillaries within a hyperplastic epithelial mass.

dehydrogenase, and glycogen phosphorylase), L-arginine metabolism (arginase and nitric oxide synthase), antioxidant defences (superoxide dismutase, catalase, glutathione peroxidase, and glutathione reductase), and xenobiotic metabolism (including EROD and glutathione S-transferase). Species like salmon, cod, and tuna are already showing reduced growth and survival rates in warmer, low-oxygen waters (Claireaux et al., 2000). Scientists use metabolic rate measurements to identify temperature thresholds beyond which fish can no longer maintain normal activity or reproduction.

5. Reproductive Disruption and Endocrine Impacts

Reproduction is one of the most sensitive processes in fish physiology. Contaminants such as pharmaceuticals, pesticides, and plastics can interfere with the endocrine system, leading to abnormal hormone levels, reduced egg production, and even intersex conditions in wild populations. Endocrine-disrupting chemicals (EDCs) are defined as external substances or mixtures that interfere with the normal functioning of the endocrine system, leading to harmful effects in whole organisms, their offspring, or even populations (Table 2). EDCs originate from both synthetic and natural sources. Synthetic EDCs include compounds found in plastics, pharmaceuticals (like oral contraceptives), detergents, cosmetics, flame retardants, herbicides, pesticides, and other industrial products, which can enter the environment via wastewater discharge, industrial runoff, or direct application. Naturally occurring EDCs consist of hormones from humans and animals, as well as plant- and fungus-derived estrogens (phytoestrogens and mycoestrogens), which may contaminate the environment through sewage, agricultural runoff, or their presence in food and animal feed, whether by design or accident. Endocrine-disrupting chemicals (EDCs) can affect organisms through several mechanisms: (1) acting as hormone agonists or antagonists, (2) interfering with the synthesis, transport, metabolism, or release of natural hormones, and (3) disrupting the formation or activity of hormone receptors. Their impact varies depending on how closely they mimic endogenous hormones, potentially leading to sex-specific effects on reproductive function. Documented consequences include impaired gametogenesis, the development of intersex gonads, changes in the gonadosomatic index, and reduced fertility. In males, EDC exposure has been associated with decreased sperm count, reduced motility, and impaired fertility across various wild species. Females may experience similar adverse effects, including inhibited oocyte growth and maturation, as well as the activation of apoptotic and autophagic pathways. In several studies, male fish exposed to wastewater effluents were found to produce egg yolk proteins (vitellogenin), a clear sign of hormonal disruption (Teta and Naik, 2017). Monitoring reproductive biomarkers like vitellogenin levels offers a powerful method for assessing chemical pollution in aquatic environments (Table 2).

6. Behaviour and Migration Patterns

Changes in physiology often lead to altered fish behaviour, such as reduced swimming performance, feeding, or migration. For example, oxygen-deprived

Table 2: Effects of various endocrine-disrupting chemical exposures in aquatic species

Chemical	Different Effects	Species
Tributyltin	masculinization of the female	Gastropods
4-nonylphenol (model xenoestrogen)	steroid metabolism disruptor, modulating estrogen receptor levels	Atlantic salmon (Salmo salar)
β-hexachlorocyclohexane	Induce the production of Vtg	Medaka (juvenile)
4-tert-pentylphenol (TPP)	Oviducts in all male fish	Genetic male carp
4-nonylphenol	Intersex condition	Medaka
Estradiol	phenotypic females, No testicular tissue	Male carp

fish may abandon their spawning grounds or delay migration entirely, which can disrupt entire food webs (Chen, 2022). By tagging and monitoring fish movement alongside physiological sampling, researchers can link environmental conditions to behavioural shifts. This approach is increasingly used in conservation biology and fisheries management. Fish behavior and migration patterns act as sensitive indicators of ocean health, offering real-time biological feedback on environmental changes. As climate change alters ocean conditions, such as temperature, salinity, acidity, and oxygen levels, fish respond by shifting their distributions, adjusting migration timing, and changing social behaviours. These changes are often among the earliest visible signs of ocean stress. For instance, the poleward and deeper migration of species like lobster, pollock, and sea bass reflects warming trends in the North Atlantic and Bering Sea. Similarly, the unexpected appearance of chum salmon in Arctic rivers signals that warming has reached even the planet's coldest marine ecosystems. Behavioural shifts, such as disrupted shoaling due to acidification, further highlight deteriorating ocean chemistry. When large predators like tiger sharks expand into new regions or remain in seasonal areas longer than usual, it points to significant and persistent changes in water temperature and prey availability. These biological responses act like living sensors, revealing the cumulative effects of multiple stressors on ocean systems. By monitoring fish movements and behaviour, scientists can track ocean health trends, assess the impacts of climate change, and guide adaptive management strategies to protect marine biodiversity and the people who depend on it.

7. A Non-Invasive and Scalable Tool

One of the advantages of using fish physiology as a monitoring tool in a non-invasive technique is its non-lethal nature. Mucus, scale, and fecal samples can be collected without harming the fish, allowing repeated monitoring across populations and time (Carbajal et al., 2019). This makes physiological sampling especially useful in endangered species or protected areas. Additionally, field kits are making physiological monitoring more accessible for conservation teams, especially in remote coastal regions.

8. Conclusion

Fish are more than just residents of aquatic ecosystems, they are also active participants and indicators of ocean health. Their physiological responses provide early, integrative signals of stress, long before mass die-offs or ecosystem collapse occur. In a rapidly changing climate, integrating fish physiology into environmental monitoring programs can help policymakers, scientists, and the public better understand and protect our marine environments.

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