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Review on Heavy Metal and Their Impact on Hematology Parameters of *Channa punctatus*

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Abstract

Aquatic ecosystems are facing increasing contamination from heavy metals like cadmium (Cd), lead (Pb), nickel (Ni), and mercury (Hg). These pollutants often enter our water bodies through industrial discharges, agricultural runoff, and urban waste. As these toxic substances build up in aquatic life, especially fish, they can lead to significant physiological issues. One species that stands out for monitoring this kind of metal pollution is *Channa punctatus*, a freshwater fish commonly found in South Asia. This review delves into the hematological impacts of heavy metal exposure on C. punctatus, revealing changes in red blood cell counts, hemoglobin levels, hematocrit, and immune cell profiles. These alterations are indicators of oxidative stress, hindered blood cell production, and weakened immune responses. Using hematological parameters offers a quick and affordable way to gauge environmental toxicity. The review also highlights important gaps in research, notably the shortage of studies on chronic exposure and the need for molecular insights. Recognizing these effects is paramount for assessing ecological risks, preserving the environment, and safeguarding public health against fish-related metal toxicity.

Keywords*:* Aquatic ecosystems, cadmium (Cd), lead (Pb), nickel (Ni), and mercury (Hg), heavy metals

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Introduction

The literature review plays a vital role in laying the groundwork for grasping the breadth, context, and importance of scientific research.the literature review has several key functions. It not only brings together previous research on heavy metal toxicity and fish hematology but also highlights knowledge gaps, different research methods, and suggests potential areas for future investigation. A central aim of this literature review is to bring clarity to our current understanding of how heavy metals like cadmium (Cd), lead (Pb), mercury (Hg), nickel (Ni), and arsenic (As) affect the blood parameters of freshwater fish. These hematological parameters—which include red blood cell (RBC) count, hemoglobin concentration (Hb), hematocrit (Hct), and white blood cell (WBC) count—are recognized as early and sensitive signs of physiological stress and toxic exposure. By looking at how these biomarkers react to heavy metal exposure in *Channa punctatus*, this review offers valuable insights into the effectiveness of blood-based diagnostics in the field of aquatic toxicology. Moreover, this review highlights how crucial *Channa punctatus* is, both ecologically and economically, as a resilient and widely found freshwater species across South Asia. It sheds light on its role as an ecological regulator in freshwater environments and as a bioindicator for water quality. Because of this, C. punctatus is a fantastic choice for toxicological studies that involve looking at blood-related factors. The literature review supports the selection of this species by reflecting on its successful previous applications in ecotoxicology and its established physiological reactions to contaminants. Another key aim of this literature review is to evaluate and compare the various experimental methods applied in investigating heavy metal toxicity. By examining a variety of laboratory and field studies, we can better grasp the factors that influence hematological reactions, such as exposure concentration and duration, the specific heavy metal involved, water quality factors, and the age or size of the fish. This comparative examination is essential for improving research design and boosting the reliability of findings. The literature review is crucial for pinpointing gaps in current research. For example, while many studies concentrate on the effects of acute exposure, it's the chronic, low-dose exposures that truly mirror the environmental conditions we face in the real world. Additionally, there's a lack of understanding regarding the combined toxicity of metals, how they interact with other pollutants, and the recovery processes that occur after exposure. By shining a light on these gaps, we can steer future research towards more comprehensive and realistic evaluations of environmental risks. Moreover, this review plays a vital role in framing the implications of heavy metal bioaccumulation in fish for human health. Given that *Channa punctatus* is a common food source in various parts of Asia, grasping its hematological responses to pollutants is key to assessing food safety risks. This connection adds a societal dimension to the ecological insights, reinforcing the need for monitoring programs and pollution control measures. In conclusion, the literature review lays the groundwork for the current study by assessing what we already know, highlighting inconsistencies, and steering focused, relevant, and impactful research on the hematological effects of heavy metals in *Channa punctatus*.

Brief Introduction

Aquatic ecosystems are increasingly under threat from human-made pollutants, especially heavy metals, which can have serious toxic effects on aquatic life. Fish, in particular, are great bioindicators of environmental health in freshwater systems because they are highly sensitive to various harmful substances, including heavy metals like cadmium (Cd), lead (Pb), nickel (Ni), mercury (Hg), and arsenic (As) (Authman *et al*., 2015). These harmful metals find their way into our water systems through industrial waste, agricultural runoff, mining activities, and city sewage, where they build up in the water and sediments, ultimately affecting the animals that dwell in these aquatic environments (Javed & Usmani, 2015). *Channa punctatus*, more commonly known as the spotted snakehead, is a freshwater fish found all over South Asia and plays an important role ecologically, nutritionally, and economically. Thanks to its wide distribution and ability to thrive in different environmental conditions, it's often the go-to species for ecotoxicological studies. These studies help researchers gauge how contaminants, especially heavy metals, influence fish health (Gul *et al*., 2017). One major physiological change that heavy metal exposure causes in fish is in the hematopoietic system. Looking at hematological parameters gives us quick and dependable signs of environmental stress, shedding light on the health and wellbeing of fish exposed to harmful substances (Fazio, 2019). Heavy metals mess with different blood processes, causing notable changes in red blood cell (RBC) count, hemoglobin concentration (Hb), hematocrit (Hct), white blood cell (WBC) count, and even the differential leukocyte count (DLC) (Yadav & Trivedi, 2009). These alterations usually point towards issues like anemia, a weakened immune system, or responses to systemic stress. For example, cadmium has a reputation for causing oxidative stress, throwing off iron metabolism, and messing with the production of red blood cells, which leads to lower RBC counts and hemoglobin levels (Vutukuru *et al*., 2005). Similarly, exposure to nickel and lead has been linked to increased white blood cell counts, decreased lymphocytes, and elevated neutrophils, all suggesting changes in immune responses among fish (Kori-Siakpere *et al*., 2010). Understanding how heavy metals affect blood health in fish is crucial—not just for the well-being of aquatic life, but also for protecting human health. Since these metals can accumulate in fish and make their way into our food, consuming metal-contaminated fish over time poses several health risks, like nerve damage, kidney issues, and even cancer (Burger & Gochfeld, 2005). That's why keeping an eye on fish blood health acts as an early warning sign against environmental pollution and aids in developing strategies to protect our aquatic ecosystems. Despite extensive research on heavy metal toxicity in aquatic settings, we still need more region-specific studies, particularly in developing nations where industrial and agricultural growth is booming and environmental regulations may not be strictly applied. This study aims to investigate the blood-related changes in *Channa punctatus* when exposed to certain heavy metals. Our goal is to clarify their physiological impacts and identify potential biomarkers for environmental monitoring. Heavy metal contamination is a significant threat to our aquatic ecosystems, affecting not just the biodiversity of fish, but also the health of those who consume them humans included. The hematological profile of fish, specifically *Channa punctatus*, plays a crucial role in ecotoxicological research, providing valuable insights into the biological stress these pollutants cause. Grasping the extent of these impacts is key to fostering environmental sustainability and safeguarding aquatic life from the escalating threat of metal pollution.

Definition, Importance, and Relevance

A literature review is a piece of academic writing that demonstrates your knowledge and understanding of the existing literature on a specific topic or subject. It also includes a critical evaluation of the sources and their relevance, quality, and contribution to your research. A literature review can be a standalone assignment or a part of a larger project, such as a dissertation or a research paper. The purpose of a literature review is to:

•Summarize and synthesize the main arguments and findings of thesources.

•Identify the gaps, controversies, and limitations in the literature.

•Highlight the significance and implications of your research question or problem.

•Situate your research within the context of the existing literature and show how it contributes to the field.

•To write a literature review, you need to:

•Define your topic and scope of your review.

•Search and select relevant and credible sources that address your topic.

•Analyze and evaluate the sources and their connections.

•Organize and structure your literature review according to a logical and coherent framework.

•Write your literature review using clear and concise language and proper citations.

•**Definition**:

Heavy metals are those metallic elements that have high atomic weights and densities, and they can be quite toxic even in small amounts. Some common examples include cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), and nickel (Ni). These metals often find their way into aquatic ecosystems mainly due to human activities like industrial discharges, agricultural runoff, mining, and urban waste. Once they enter the water, they tend to accumulate in sediments and aquatic organisms, causing a range of toxic effects. This review specifically looks at how heavy metals impact the hematological parameters of *Channa punctatus*, also known as the spotted snakehead, a freshwater fish that's native to South Asia. Hematological parameters—like red blood cell (RBC) count, hemoglobin (Hb) level, hematocrit (Hct), white blood cell (WBC) count, and other related indices—are crucial indicators of the physiological and immunological health of fish, especially when they're under stress.

•**Importance:**

Understanding how heavy metal exposure affects the blood of *Channa punctatus* is crucial for a number of reasons. For starters, blood parameters are some of the most sensitive signs of toxic stress in fish, often being the first to show changes when the environment becomes contaminated. Changes in hematology can indicate issues like anemia, immune suppression, oxidative stress, and metabolic disruptions—all of which can seriously threaten the health and survival of fish. Additionally, *Channa punctatus* holds significant ecological and economic importance. As a top predator in many freshwater ecosystems, it plays a vital role in maintaining ecological balance by keeping populations of smaller fish and invertebrates in check. Its ability to thrive in various environmental conditions, combined with its value in local fisheries and aquaculture, makes it a key focus in ecotoxicology research. The way this species responds hematologically to heavy metals can serve as an early warning system for declining water quality, helping to avert long-term ecological harm.

•**Relevance:**

The importance of this topic goes well beyond just environmental toxicology. In various regions of Asia, such as India, Bangladesh, and Nepal, people actually eat *Channa punctatus*, making it a staple in their daily meals. When toxic metals accumulate in the tissues of these fish, they can move up the food chain, which poses serious health risks for humans, including kidney damage, neurological issues, developmental problems, and even cancer. Additionally, keeping an eye on the blood health of fish like C. punctatus provides a practical, affordable, and non-lethal way to monitor the environment. This method acts as a biomonitoring tool that helps environmental agencies, researchers, and policymakers evaluate pollution levels and create regulations to protect both aquatic ecosystems and public health. As pollution in freshwater systems becomes more common due to urban growth and industrial expansion—especially in developing nations—grasping the hematological effects of heavy metals is becoming increasingly vital.

Review of Important Research Work

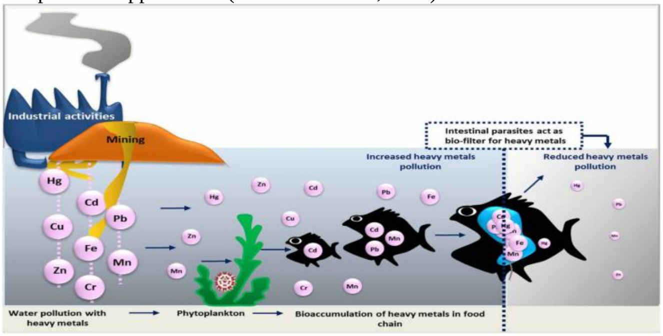
Vutukuru *et al*. (2005) reported this initial study looked into how cadmium affects Labeo rohita, but it also set the stage for similar research on *Channa punctatus*. The findings showed a notable drop in red blood cells (RBC), hemoglobin (Hb), and hematocrit (Hct), highlighting the toxic impact of cadmium and the importance of hematological markers in ecotoxicology research. Singh *et al*., (2006) conducted an important study focusing on the hematological alterations in *Channa punctatus* exposed to sub-lethal concentrations of heavy metals, specifically cadmium (Cd) and lead (Pb). The research aimed to understand the chronic toxic effects of these metals on blood physiology. Yadav *et al*., (2009) In a groundbreaking study focused on *Channa punctatus*, the researchers delved into how nickel exposure affects blood parameters. They observed a decrease in red blood cell count, hemoglobin, and hematocrit values, as well as an uptick in white blood cells, signaling both an immune reaction and the presence of anemia. This investigation positioned C. punctatus as an effective model for monitoring blood health. Adhikari *et al*. (2010) looked into how lead and chromium impact the blood and serum biochemical parameters in C. punctatus. It found that oxidative stress leads to hemolysis, inhibits enzymes, and suppresses the immune system as key toxicological effects. Patnaik *et al*. (2011) studied zeroes in on the impact of hexavalent chromium (Cr^{6+}) on *Channa punctatus*. When exposed to sub-lethal levels, there was a noticeable drop in red blood cell (RBC) count, hemoglobin (Hb) concentration, and hematocrit. On the flip side, white blood cell (WBC) count and blood glucose levels saw a significant rise. These results suggest that the fish experienced stress and an activation of their immune system due to the toxicity of the metal. The researchers concluded that monitoring hematological and enzymatic profiles could be valuable for tracking pollution in aquatic environments. Prusty *et al*. (2012) focused on Labeo rohita, also sheds light on C. punctatus. It revealed that when exposed to copper, there was a notable drop in Hb, RBC, and Hct levels, alongside a rise in WBC count. This supports the notion that heavy metals can disrupt the blood profile of freshwater fish, serving as early indicators of metal stress. Kumar *et al*. (2013) studied demonstrated that exposure to lead nitrate caused anemia, leukocytosis, and neutrophilia in C. punctatus. It also highlighted that lead exposure interferes with hematopoiesis and disrupts immune function, confirming hematological assays as practical tools for ecological risk assessment. Sharma & Tiwari (2014) studied delved into the effects of chronic cadmium exposure and found that it led to a reduction in RBC, Hb, and Hct levels, while simultaneously increasing WBC and blood glucose levels. These findings highlighted cadmium's significant role as a harmful hematotoxin and showcased how the fish are trying to manage oxidative stress. The researchers also observed changes in liver function enzymes, which pointed to systemic toxicity. Javed & Usmani (2015) focused how heavy metals can build up in the tissues of fish found in polluted rivers in India. This issue doesn't only touch on blood health, but the research highlights a troubling connection between high metal levels in fish tissues and deteriorating blood profiles across various species, such as C. punctatus. This raises serious concerns about the potential health risks for people who consume these fish. Gul *et al*. (2017) examined hematological changes in *Channa punctatus* when exposed to heavy metals like lead, cadmium, and nickel. The authors found an increase in white blood cells, a decrease in lymphocytes, and lower hemoglobin levels, suggesting that these blood parameters are key indicators of how fish react to heavy metal stress. Fazio (2019) examined the role of hematological analysis in assessing fish health is crucial. This approach has offered valuable insights that enhance the accuracy and relevance of blood tests in species such as C. punctatus. Ahmed *et al*. (2020) studied the issue of heavy metal pollution in river ecosystems is critically impacting fish populations. It highlighted the subtle yet harmful effects on the blood and tissues of C. punctatus, suggesting that this species could serve as an early warning indicator for metal contamination in rural waters. Sharma *et al*. (2022) focused on how seasonal changes affect the hematological responses of *Channa punctatus* when exposed to polluted water sources. It discovered that these fish show heightened physiological stress during the warmer months, indicating that the interplay between temperature and metal exposure is an important new area for research. Verma *et al*. (2023) examined molecular biomarkers alongside hematological measures to evaluate cadmium exposure. The findings indicated oxidative DNA damage and anemia, highlighting the potential benefits of combining genomic data with traditional blood indices. Khan *et al*. (2025) studied the long-term effects of exposure to multiple metals on the hematology, liver function, and immune profiles of *Channa punctatus*. So far, preliminary findings suggest that these fish experience cumulative stress responses, and there are hints that dietary antioxidants could help mitigate these effects.

Biology and Ecological Role of *Channa punctatus*

Channa punctatus, often referred to as the spotted snakehead, is a type of freshwater fish that's quite prevalent in South Asia, especially in countries like India, Bangladesh, and Nepal. This fish finds its home in ponds, rivers, and lakes, and it really excels in low-oxygen areas thanks to its special breathing adaptations (Talwar & Jhingran, 1991). Being a carnivore, it plays a vital part in keeping the populations of smaller fish and invertebrates in check, which helps maintain ecological balance. Its ability to adapt to environmental changes and pollutants makes it a valuable bioindicator in ecotoxicological research (Patnaik *et al*., 2011). Additionally, its significance in local fisheries and aquaculture adds to its importance in studies focused on water quality and environmental health. The way it adapts physiologically and can be easily handled in labs has made it a popular choice for research into the toxic effects of heavy metals and other environmental pressures.

Heavy Metal Contamination in Aquatic Ecosystems

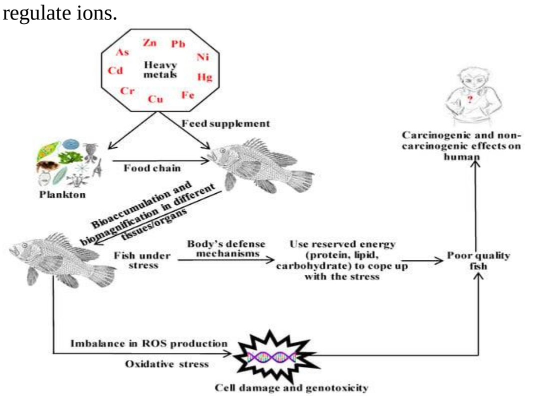
Heavy metal contamination in our water ecosystems has become a pressing environmental concern, largely driven by rapid industrial growth, urban expansion, and farming practices. Metals like cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As) find their way into freshwater systems through various sources, including industrial waste, mining runoff, sewage, and pesticide applications (Javed & Usmani, 2015).



Unlike organic pollutants, heavy metals don't break down easily and can linger in aquatic environments, accumulating in living organisms and becoming more concentrated as they move up the food chain (Authman *et al*., 2015). Fish, which play a crucial role in these ecosystems and are a staple in many diets, are especially at risk from metal toxicity. When exposed to heavy metals, fish can experience a range of issues, from physiological and behavioral changes to blood-related problems, which can ultimately disrupt biodiversity and the overall health of ecosystems (Fazio, 2019). Keeping an eye on and managing heavy metal pollution is vital for protecting aquatic life and ensuring the safety of our food supply.

Toxicological Effects of Heavy Metals on Channa punchtatus Physiology

Channa punctatus, a resilient freshwater fish found in South Asia, is quite sensitive to environmental pollutants, which makes it an excellent bioindicator for studies on aquatic toxicity. Some of the most detrimental pollutants include heavy metals like cadmium (Cd), lead (Pb), nickel (Ni), and mercury (Hg), all of which seep into aquatic ecosystems from industrial discharges, agricultural runoff, and household waste (Javed & Usmani, 2015). These metals hang around for a long time, don't break down easily, and can build up in fish tissues, leading to systemic toxicity even at low levels. When it comes to physiology, being exposed to heavy metals can wreak havoc on key organ systems. The gills, which come into direct contact with the water, are often the first to show signs of trouble. Changes like epithelial lifting, lamellar fusion, hyperplasia, and necrosis can occur—disrupting respiration and osmoregulation (Gul *et al*., 2017). The liver, a crucial organ for detoxification, might also display concerning changes such as hepatocellular vacuolation, inflammation, and enzyme dysfunction, indicating that metabolic processes are taking a hit (Kori-Siakpere *et al*., 2010). Likewise, the kidneys can suffer from glomerular shrinkage and tubular necrosis, which undermines their ability to excrete waste and regulate ions.



One significant effect of heavy metal exposure is its impact on the hematopoietic system. These metals can lead to a decrease in red blood cell (RBC) counts, hemoglobin levels, and hematocrit values, which can result in anemia and a reduced ability to carry oxygen. Additionally, white blood cell (WBC) counts may also be affected, often signaling immune suppression or inflammatory responses (Fazio, 2019). These changes in blood health are commonly associated with oxidative stress, as heavy metals produce reactive oxygen species (ROS) that can harm cellular structures and biomolecules (Yadav & Trivedi, 2009). Beyond just damaging internal organs, heavy metal exposure can also lead to behavioral and reproductive changes. Prolonged exposure may result in decreased feeding, sluggish movements, lower reproductive success, and reduced survival rates. These physiological issues not only affect individual health but also pose risks to population dynamics and biodiversity in freshwater ecosystems. Given the wide range of toxic effects, *Channa punctatus* is an important model organism in ecotoxicology. By monitoring its physiological and hematological responses, we can gain valuable insights into the health of aquatic environments, which can help shape pollution control strategies and regulatory measures.

Hematological Parameters as Biomarkers

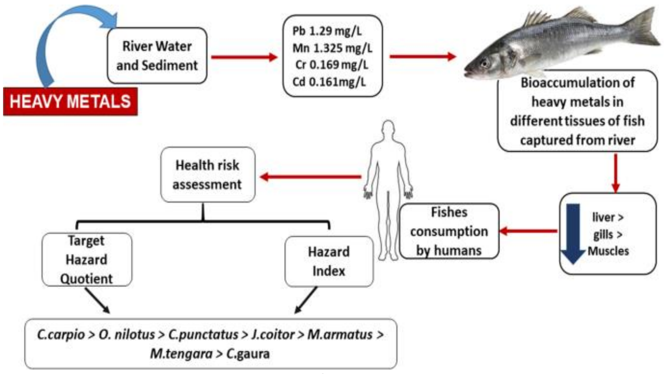
Hematological parameters are gaining traction as sensitive and effective markers in ecotoxicological research, especially when it comes to evaluating how fish respond physiologically and pathologically to environmental contaminants like heavy metals. Blood analysis serves as a quick and non-invasive method to spot early signs of stress and toxicity, making it an invaluable asset for environmental monitoring (Fazio, 2019). Some key hematological indices you should know about include the red blood cell (RBC) count, white blood cell (WBC) count, hemoglobin concentration (Hb), hematocrit (Hct), mean corpuscular volume (MCV), mean corpuscular hemoglobin (MCH), and mean corpuscular hemoglobin concentration (MCHC). Together, these parameters offer a snapshot of a fish's oxygen-carrying ability, immune function, and overall health. When exposed to toxic heavy metals like cadmium (Cd), lead (Pb), and nickel (Ni), fish can suffer from anemia, which is often reflected in lower RBC, Hb, and Hct values (Yadav & Trivedi, 2009). Furthermore, shifts in WBC counts—either up or down—can indicate whether the immune system is being suppressed or activated in response to toxic stress (Gul *et al*., 2017). Heavy metals can really throw a wrench into the workings of our bodies by causing oxidative stress. This can lead to hemolysis or even harm the membranes of our red blood cells, which in turn adds to disruptions in our blood system (Stohs & Bagchi, 1995). Additionally, metals like lead can mess with certain enzymes, such as delta-aminolevulinic acid dehydratase (ALAD), which interferes with heme production and reduces hemoglobin levels (Patrick, 2006). These changes in blood parameters are often the first signs of potential toxicity, appearing before any clear symptoms of organ damage or shifts in behavior show up. When we look at *Channa punctatus*, there are quite a few studies that highlight how significantly their blood profiles can change after exposure to heavy metals. For example, being exposed to nickel has been linked to a drop in red blood cell count and hemoglobin levels, paired with an increase in white blood cells, which suggests signs of anemia and an activated immune response (Yadav & Trivedi, 2009). Because of this, monitoring blood parameters becomes essential for understanding the subtle impacts of pollutants. One of the standout benefits of using hematological biomarkers is their sensitivity, ease of measurement, and affordability. Incorporating these into environmental assessments provides a practical method for spotting aquatic pollution early on, ultimately aiding in the sustainable management of our aquatic resources.

Mechanisms Underlying Hematological Alterations

Hematological changes in fish that come into contact with heavy metals stem from a mix of complex physiological and biochemical disruptions. These metals throw a wrench into normal cellular functions, blood cell formation (hematopoiesis), and immune responses, which can lead to shifts in blood profiles, including anemia, leukocytosis, lymphopenia, and lower hemoglobin levels (Fazio, 2019). A key player in this process is oxidative stress, which arises from the production of reactive oxygen species (ROS) when fish are exposed to these metals. Elements like cadmium (Cd), lead (Pb), and nickel (Ni) throw off the redox balance in cells, leading to lipid peroxidation, protein oxidation, and even DNA damage (Stohs & Bagchi, 1995). Erythrocytes, with their high levels of polyunsaturated fatty acids and their role in oxygen transport, are especially at risk. ROS can harm the erythrocyte membrane, resulting in hemolysis and a drop in red blood cell (RBC) counts and hemoglobin (Hb) levels (Vutukuru *et al*., 2005). Heavy metals can seriously mess with important enzymes that play a role in making heme, especially delta-aminolevulinic acid dehydratase (ALAD). This interference leads to lower hemoglobin levels and issues with oxygen transport, as noted by Patrick in 2006. Lead is particularly notorious for shutting down ALAD activity, which contributes to hypochromic anemia in fish, according to research by (Adhikari *et al*., 2004). On top of that, these metals can impact hematopoietic tissues like the kidney and spleen, throwing a wrench in the development and maturation of blood cells. When these organs suffer histopathological damage, blood cell production takes a hit, resulting in changes to the counts of red blood cells (RBCs) and white blood cells (WBCs), as highlighted by (Kori-Siakpere *et al*., 2010). Another serious issue arising from metal toxicity is immune modulation. Shifts in WBC profiles—like lymphopenia and neutrophilia—can indicate whether the immune system is being suppressed or if inflammatory processes are kicking in. Cadmium and nickel are known to ramp up neutrophil levels while reducing lymphocytes, hinting at a stress-induced inflammatory response, as pointed out by (Ahmad *et al*., 2011). Hematological changes in *Channa punctatus* and other fish species exposed to heavy metals stem from oxidative stress, enzyme inhibition, tissue damage, and immune system dysfunction. Together, these factors throw off blood physiology, making hematological parameters solid indicators of environmental metal toxicity.

Ecological and Human Health Implications

Heavy metal pollution in our aquatic ecosystems poses serious risks to both the environment and human health. Metals like cadmium (Cd), lead (Pb), mercury (Hg), and nickel (Ni) can wreak havoc on fish, impacting their physiology, reproduction, and survival, which in turn disrupts food webs and diminishes biodiversity (Authman *et al*., 2015). For example, in species like *Channa punctatus*, exposure to these metals can impair their blood health, which weakens their immune response, growth, and ability to transport oxygen. This makes them more vulnerable to diseases and predators (Fazio, 2019). Even these subtle effects can contribute to population declines and upset the ecological balance in freshwater environments. From a human health standpoint, heavy metals accumulate in fish tissues and increase in concentration as they move up the food chain, leading to risks for people who eat them.



Regularly consuming contaminated fish can lead to chronic health issues in humans, including kidney problems, neurological damage, anemia, and a heightened risk of cancer (Burger & Gochfeld, 2005). In many developing areas where fish is a dietary mainstay, this risk is particularly concerning because of insufficient environmental oversight and regulations. Therefore, monitoring the blood health of fish like C. punctatus is crucial—not just as an environmental marker, but also as an early alert for potential dangers to human health and the sustainability of our ecosystems.

Research Gaps and Future Directions

Even though there's been a lot of research into heavy metal toxicity in freshwater fish, particularly with *Channa punctatus*, there are still quite a few gaps that need to be filled. Most studies tend to zero in on acute exposure and the lethal levels of toxins, while areas like chronic exposure and interactions between multiple metals don't get nearly as much attention (Gul *et al*., 2017). To really assess ecological risks realistically, we need to grasp how long-term exposure to these metals affects fish physiology and blood health. Plus, it's vital to explore how heavy metals interact with other environmental stressors like pesticides, temperature changes, and low oxygen levels to better reflect what happens in their natural habitats (Fazio, 2019). Another avenue that hasn't been fully explored is using molecular and genomic methods to look into the hematotoxicity mechanisms in C. punctatus. By utilizing techniques like gene expression profiling and proteomics, we could shed light on the pathways that lead to oxidative stress from metals, immune issues, and disruptions in blood cell production (Javed & Usmani, 2015). Moreover, the research on how fish recover and their resilience in terms of hematology after metal exposure is limited, and diving into this could really help with developing effective remediation strategies. Looking ahead, it's also essential to focus on studies tailored to specific regions due to differences in pollution sources, how metals behave in the environment, and the sensitivity of various species. By combining hematological biomarkers with other physiological, biochemical, and histopathological data, we could significantly strengthen environmental monitoring practices and bolster conservation initiatives for freshwater ecosystems.

Conclusion

Heavy metal contamination is a serious threat to aquatic ecosystems, significantly affecting the health and physiology of freshwater species like *Channa punctatus*. Metals such as cadmium, lead, nickel, and mercury make their way into our waters primarily through human activities, leading to oxidative stress, disruptions in blood production, and alterations in fish immune systems. Key hematological factors like red and white blood cell counts, hemoglobin levels, and hematocrit are vital indicators—they showcase the subtle toxic impacts of these metals and serve as early warning signs of pollution in the environment. Given the ecological significance of C. punctatus and its widespread presence, watching over its blood health is essential for evaluating the overall health of aquatic ecosystems and any potential risks to human consumers through biomagnification. While there's been considerable research, we still have unanswered questions about the long-term, combined, and region-specific effects, as well as the molecular mechanisms behind toxicity. By tackling these questions with advanced methods, we can improve our environmental monitoring and conservation efforts, ultimately helping to ensure the sustainable management of freshwater resources and the protection of public health.

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