Water Quality Parameters (pH, Dissolved Oxygen, Temperature, and Ammonia) and Their Effects on Fish Health in Aquaculture: A Narrative Review

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Abstract
Aquaculture has emerged as one of the fastest-growing food production industries in the world and is now providing more than 50% of the fish eaten globally. With the increased production needed to satisfy rising food demand, optimal water quality has become essential to the health and welfare of fish as well as the efficiency of fish production. Physiological functions such as respiration, metabolism, osmoregulation, immunity, and reproduction are related to water quality. There are many parameters monitored and controlled in an aquaculture system, but pH, dissolved oxygen (DO), temperature, and ammonia are known to be among the most important factors that influence fish performance. The present narrative review provides an integrated overview of the available information on the impact of these most important water quality parameters on fish physiology and health. The beneficial effects of pH on acid–base balance, dissolved oxygen on aerobic metabolism and immune system function, temperature on metabolic and biochemical processes, and the toxicity of ammonia as one of the most toxic nitrogenous compounds in culture systems are discussed. The interaction between these parameters is also explored, as they interact and contribute to fish growth, stress reactions, disease susceptibility, and survival. In addition, the recent progress of water quality monitoring technologies such as recirculating aquaculture systems (RAS), biosensors, Internet of Things (IoT) technologies, and artificial intelligence (AI) related water management systems is summarized as technologies that can be useful for enhancing the sustainability of water production. Lastly, gaps in current research and future research priorities are explored to facilitate water quality management and sustainable aquaculture development that enhance fish welfare, production efficiency, and environmental sustainability in modern aquaculture.

Keywords: Aquaculture, water quality, dissolved oxygen, pH, ammonia, temperature, fish health

1. Introduction

Aquaculture has become one of the most rapidly expanding food production systems in the world and is playing a growing role in meeting the food security, nutritional sustainability, and economic development needs of nations. The Food and Agriculture Organization (FAO) reports that aquaculture now accounts for over 55% of all fish produced for human consumption, and intensive aquaculture systems are being developed in both freshwater and marine locations, with rapid expansion (Action, 2020). Population growth, reduction of capture fisheries, urbanization, and high-quality demand for animal protein have made modern aquaculture technologies the preferred choice all around the globe. But sustainable intensification relies on careful control of the environmental conditions, in particular, water quality, which directly affects fish health, survival, and production performance (Nagothu et al., 2025, Das, 2023).

Fish rely totally on their aquatic environment for respiration, feeding, excretion, and regulation of physiological homeostasis, whereas terrestrial animals can use the atmosphere for these purposes. Thus, water quality affects fish metabolism and welfare in an instant. Water is not just a habitat; it is a medium in which oxygen, nutrients, ions, and metabolic wastes are exchanged. Relatively small changes in the physicochemical conditions can result in disruption of essential physiological function, decreased feed utilization, diminished immune response, growth inhibition, and increased susceptibility to infectious diseases (Colt, 2006, Martins et al., 2010).

Water quality includes a variety of physical, chemical, and biological parameters, such as temperature, dissolved oxygen, pH, salinity, alkalinity, hardness, turbidity, nitrogenous wastes, and microbial communities. While all these parameters are important to aquatic ecosystem stability, pH, dissolved oxygen (DO), temperature, and ammonia are consistently listed as the main environmental parameters that affect fish health and aquaculture productivity (Das, 2023). These parameters are important for the control of key physiological functions like respiration, acid–base balance, osmoregulation, enzymatic activity, nutrient metabolism, and waste excretion. Moreover, they are closely linked; in many instances, changes in one variable affect the behaviour or availability of another, or the toxicity of one to another.

For instance, raising the water temperature decreases the amount of dissolved oxygen that can be carried in solution and raises the demand for oxygen in fish metabolism, thus contributing to the hypoxic stress. Similarly, a rise in pH can alter the concentration of ionized ammonia (NH_4^+) and toxic ammonia (NH_3) without changing the total ammonia concentration, with the toxic ammonia being greatly increased. These interactions illustrate the need to consider water quality parameters as part of an overall environmental system that is used to assess both fish health and production success (Lin et al., 2022, Hargreaves and Tucker, 2004).

Among cultured fish, several physiological and pathological effects have been linked to poor quality of water. Stress responses associated with inappropriate environmental conditions include an increase in cortisol secretion, oxidative stress, impaired immune responses, and changes in hematological parameters, sub-optimal reproductive capacity, and mortality. Respiration and ion regulation in gill tissues are especially common since they are in direct contact with the surrounding water and are the primary sites of respiration and ion regulation. The decline in water quality over time can therefore also affect the well-being of fish and greatly impact production efficiency and farm profitability (Chen and Luo, 2023, Abdel-Tawwab et al., 2019).

The rapid intensification of aquaculture has further increased the importance of effective water quality management. As stocking densities are raised, feeding rates must also be raised, and the amount of organic wastes generated increases, which leads to oxygen depletion and nitrogen accumulation, which aids the development of disease outbreaks and deteriorate environmental conditions. Advances in water treatment technologies, such as recirculating aquaculture systems (RAS), biological filters, ultraviolet sterilization, automated aeration systems, and continuous monitoring of water quality parameters, are quickly becoming the backbone of modern aquaculture for providing appropriate culture conditions (Martins et al., 2010, Badiola et al., 2018).

The rollout of the Internet of Things (IoT), digital sensors, cloud, and artificial intelligence (AI) is also a recent technological development that has revolutionized water quality management. Through these precision aquaculture technologies, real-time measurements can be taken of various environmental parameters, water quality can be monitored in time, and decisions can be made automatically in advance, which reduces the risk of the production process and increases the use efficiency of the resources. These innovations are likely to be a key part of the future of environmentally sustainable and economically viable aquaculture systems (Mustapha et al., 2021).

Many studies have examined the impacts of the individual water quality parameters, but results have been scattered throughout various disciplines and are difficult to synthesize to understand the overall impact of these parameters on fish health. Thus, this narrative review aims to provide a synthesis of the latest scientific literature on the impact of pH, dissolved oxygen, temperature, and ammonia on fish physiology and welfare. The review also addresses the recent developments in water quality monitoring and management technology and outlines key research needs and potential future research directions to further advance sustainable aquaculture production.

2. Importance of Water Quality in Aquaculture

The key to good aquaculture is water quality, as this directly affects fish physiology, fish health, fish welfare, fish growth, and fish production efficiency. Fish are always in contact with water and so are very sensitive to water chemical and physical changes, even slight ones. Water is used not only as a habitat but also as a medium for respiration, nutrient uptake, osmoregulation, and excretion of wastes. Therefore, it is critical to maintain a stable water quality for normal physiologic function and optimum aquaculture productivity (Colt, 2006, Das, 2023).

Aquaculture water quality is influenced by a variety of physical, chemical, and biological factors. Of these, pH, dissolved oxygen (DO), and temperature are considered the main factors that affect fish health, since they directly control metabolic activities, respiratory efficiency, enzyme activity, immune responses, and nitrogen metabolism. These parameters are not static and are highly interdependent. An example is that an increase in water temperature reduces the solubility of dissolved oxygen and raises the oxygen requirement of fish. Similarly, higher pH increases the percentage of toxic un-ionized ammonia (NH_3), which increases the ammonia toxicity without affecting total ammonia levels (Das, 2023, Hargreaves and Tucker, 2004).

Maintaining water quality in species' optimum ranges ensures efficient feed use, fast growth rate, high production efficiency, and high disease resistance. On the other hand, pollution has a detrimental effect on water chemistry, causing stress to the fish, which negatively affects their welfare and production. Bacterial, viral, fungal and parasitic infections, decreased appetite, poor environmental conditions, impaired osmoregulation, decreased immune function and disruption of acid–base balance all occur as a result of exposure to stress. Chronic exposure to suboptimal water quality has also been linked to oxidative stress, tissue damage, changes in hematological parameters, and decreased survival, causing significant economic losses to aquaculture farmers (Chen and Luo, 2023, He et al., 2023).

Water quality management is becoming more critical in the intensification of aquaculture activities. Stocking rates are often higher, feeding rates are increased, and the organic load is greater in modern farming practices, causing oxygen to be consumed and nitrogen to be put into excess. If the environmental management is not taken care of properly, then these conditions can quickly culminate in ammonia toxicity, hypoxia, decreased growth rates, and disease outbreaks. Therefore, it is essential to have reliable monitoring and to manage critical water quality parameters proactively instead of reactively in response to water quality problems after those have occurred (Abdel-Tawwab et al., 2019, Martins et al., 2010).

Technological developments in aquaculture have greatly enhanced its ability to manage and control water quality in recent years. The use of technologies like recirculating aquaculture systems (RAS), biological filtration, automated aeration, digital sensors, and Internet of Things (IoT) monitoring platforms allows for continuous monitoring of environmental conditions and quick management responses. Such innovations not only enhance the well-being of the fish and the efficiency of aquaculture production but also lower the usage of water and the amount of pollutants in the environment, which are essential for the long-term sustainability of the aquaculture industry (Badiola et al., 2018).

3. Effects of Major Water Quality Parameters on Fish Health

Water quality parameters are of great importance in aquaculture production because they affect almost all aspects of fish physiology. Fish also breathe continuously, exchanging gases, ions, and metabolic wastes with the surrounding water via their gills, which makes them very sensitive to changes in their environment. Changes in pH, dissolved oxygen, temperature, and ammonia levels can lead to changes in physiological balance, affect growth, cause decreases in immunity, and create higher disease susceptibility. Each parameter has different modes of action, but often these interactions result in compounded effects which are greater than those from a single parameter alone (Colt, 2006, Martins et al., 2010). Table 1 summarizes the recommended ranges of key water quality parameters commonly maintained in aquaculture systems.

3.1 pH and Fish Health

The pH of water is directly related to the level of hydrogen ions present and whether the water is acidic, neutral, or alkaline. In aquaculture, pH affects several biological and chemical processes such as enzyme activity, nutrient supply, microbial activity, and ammonia toxicity. The optimum pH range is 6.5-8.5 for most freshwater fish species, but it varies by species and production system (Das, 2023, El-Sayed and Fitzsimmons, 2023).

Fish maintain their acid–base balance by controlling their internal environment by exchanging ions across the gill epithelium. Acidic water disrupts uptake of ions, affects gill tissue, stimulates excessive secretion of mucus, and affects transport of oxygen. Very alkaline waters, on the other hand, affect metabolism and increase the toxicity of un-ionized ammonia (NH_3), increasing physiological stress and decreasing survival. Both alkaline and acidic conditions have an effect on osmoregulation and on the energetics of homoeothermic (Colt, 2006, Hargreaves and Tucker, 2004).

Abnormal pH effects behavior and productivity of fish. Prolonged exposure to pH stress is often accompanied by a decrease in feed intake, growth rate, feed conversion ratio, abnormal swimming behavior, and reproductive capacity in fish. Chronic pH imbalance has been linked to increased cortisol secretion, oxidative stress, and hematological changes, and decreased innate immune responses, which lead to increased susceptibility to opportunistic pathogens (Abdel-Tawwab et al., 2019, Hargreaves and Tucker, 2004).

Aquaculture ponds experience daily pH changes that are normal because of photosynthesis and respiration. Phytoplankton uptake takes place during the day, which raises the pH, while respiration takes place at night and lowers the pH. Hence, proper buffering and regular monitoring of the pH in cultured fish are important to ensure the pH is not shifted and that there is little physiological stress (Martins et al., 2010).

Maintaining the pH in the optimum range helps to ensure normal metabolic activity, efficient nutrient assimilation, and proper ion balance, and to minimize ammonia toxicity. Therefore, it is important that pH control is a key element in sustainable aquaculture and is also combined with the monitoring of the other key water quality parameters.

3.2 Temperature and Fish Health

Temperature is one of the most important environmental factors in aquaculture as it affects almost all the physiological and biochemical processes in fish. It is important to understand that fish are cold-blooded (ectothermic) and are very sensitive to temperature changes in the water. Therefore, water temperature has a direct influence on metabolism, oxygen consumption, digestion, immune function, growth, reproduction, and survival. The thermal optimum is the best temperature for a fish species to grow and convert feed into muscle, whereas temperatures below or above the optimal range create physiological stress and decrease production (El-Sayed and Fitzsimmons, 2023, He et al., 2023).

In the range of optimal temperatures, higher water temperatures will usually increase temperature-dependent enzymatic activity, feed digestion, and nutrient utilization, leading to improved growth rates. But, too warm conditions lead to higher metabolic oxygen consumption and lower dissolved oxygen solubility in water. When the tissue's need for oxygen exceeds its supply, fish are under a lot of physiological stress, which will lower their aerobic capacity and make them more likely to get sick. On the other hand, low temperatures slow down metabolism, lower food consumption, slow digestion, and slow growth, which results in longer production cycles and higher operational costs (Colt, 2006).

Additionally, the endocrine and immune systems are affected by thermal stress. When temperatures exceed tolerance limits for a species, it causes an increase in the secretion of cortisol, which disrupts hormonal balance and results in a decrease in immune competence and osmoregulation. Reactive oxygen species (ROS) increase with high temperatures, which leads to oxidative stress and damages cell proteins, fats, and DNA. Bacterial, viral, and parasitic infections, decreased phagocytic capacity, and a decline in lysozyme activity have been linked to chronic thermal stress and, consequently, fish welfare and survival (Abdel-Tawwab et al., 2019).

Behavioural changes are among the earliest indicators of temperature stress. Fish held at improper temperatures typically show decreased feeding rates, sluggishness, erratic swimming, aggression, or thermal avoidance. The reproductive processes are also affected by the changes in temperature, as it affects the gonadal development, hormone production, spawning, egg viability, and larval survival. Embryonic development and organogenesis are especially sensitive to environmental stability (El-Sayed and Fitzsimmons, 2023).

There is a close relationship between temperature and other water quality parameters, further underlining the importance of integrated environmental management. The high temperatures lower dissolved oxygen levels and lead to increased ammonia formation due to increased metabolic processes and increased breakdown of organic matter. In addition, higher temperatures will also cause a greater percentage of toxic un-ionized ammonia (NH_3), exacerbating ammonia toxicity. These interactions are connected to effective temperature management and dissolved oxygen, pH, and ammonia control (Hargreaves and Tucker, 2004).

Temperature control in aquaculture is even more critical due to the influence of climate change. Global warming, more heat waves, and greater climatic variability mean that the cultured fish are subjected to more and more exposure to climatic stress for longer periods of time, which can lower productivity and lead to greater disease outbreaks. To ensure stable environmental conditions and increase production resilience, adaptive management strategies have been implemented, such as water exchange improvements, shading systems, recirculating aquaculture systems (RAS), and automated technologies for water temperature control (Bastian et al., 2025, Martins et al., 2010).

3.3 Ammonia and Fish Health

The main nitrogenous waste product excreted by fish during protein metabolism is ammonia, and is considered one of the most damaging water quality parameters in intensive aquaculture. It comes from fish excretion, decomposition of uneaten feed, microbial degradation of organic matter, and fecal material. Under good management, ammonia is biologically filtered with the help of nitrifying bacteria and transformed into nitrite and nitrate. But if ammonia levels in the fish room are too high relative to the biological filtration or water exchange capacity, ammonia levels will build up to levels that will adversely affect the health of the fish and make the job of production less efficient (Hargreaves and Tucker, 2004).

NH3 is found in water as either ionized (NH4+) or un-ionized (NH3). Both contribute to total ammonia nitrogen (TAN); however, the un-ionized form is extremely poisonous as it can easily move through biological membranes. Environmental conditions, such as pH and temperature, greatly influence the concentration of NH_3, and therefore the toxicity of ammonia. Fish raised in warm alkaline water are especially susceptible to ammonia toxicity even at relatively low concentrations of total ammonia (TAM) (Lin et al., 2022).

Gills are the most susceptible to ammonia toxicity. Excess ammonia levels result in gill epithelial tissue damage with epithelial hyperplasia, lamellar fusion, excess mucus secretion, and poor gas exchange. All these pathological changes impair the ability of the organism to extract oxygen and regulate ions, causing respiratory difficulty and metabolic imbalance. The clinical signs of ammonia stress in fish are rapid opercular movement, gasping at the surface, erratic swimming, diminished feeding, and loss of equilibrium. Exposure can have severe consequences affecting neurological function and causing death (Parvathy et al., 2023, Abdel-Tawwab et al., 2019).

Exposure to ammonia also has effects on several physiological systems. Hyperammonaemia causes oxidative stress through an increase in ROS, leading to lipid peroxidation, protein damage, and cell dysfunction. Fish under chronic ammonia stress have been reported to have changes in hematological parameters, liver and kidney dysfunction, decreased activity of antioxidant enzymes, and decreased innate immunity. Such impacts make the animals very vulnerable to secondary infections and to poor productivity (Abdel-Tawwab et al., 2019).

To successfully manage ammonia, a combination of biological filtration, proper feeding regimes, correct stocking densities, regular organic waste removal, and ongoing water quality testing should be employed. Nitrifying BioFilters are a crucial component in recirculating aquaculture systems, responsible for transforming harmful ammonia into nitrate to ensure a healthy aquaculture ecosystem. With the recent developments in the Internet of Things (IoT) technology and artificial intelligence, monitoring ammonia levels has become even more sophisticated, allowing for real-time detection and the automated control of the environment, thus minimizing production risks and enhancing fish welfare (Huang and Khabusi, 2025, Wang et al., 2021).

Table 1: Recommended Water Quality Ranges for Major Parameters in Aquaculture

Parameters	Recommended Range	Major physiological role	Consequences of deviation	Production Impacts
pH	6.5–8.5	Acid–base balance, enzyme activity, ion regulation	Gill damage, impaired osmoregulation, reduced growth	Lower growth and feed efficiency
Temperature	Species-specific optimum	Metabolism, digestion, immunity	Thermal stress, disease susceptibility	Poor growth and reproductive impairment
Un-ionized ammonia (NH_3)	<0.05 mg L^{-1}	Nitrogen metabolism	Gill damage, neurological toxicity, and mortality	Increased mortality and economic losses

4. Water Quality Monitoring and Management Technologies

Good water quality monitoring is an important component in preventing environmental degradation and ensuring sustainable aquaculture production. Digital pH meters, dissolved oxygen meters, thermometers, and ammonia test kits are still widely used and are considered conventional monitoring techniques, as they offer accurate and relatively low-cost measurements (Table 2). However, manual sampling could miss fast changes in the environment that happen between the sampling times (Das, 2023).

In the modern era of aquaculture, the use of systems that monitor a farm continuously with wireless sensors, Internet of Things (IoT) technology, cloud computing, and artificial intelligence (AI) is gaining in importance. These systems offer on-the-spot monitoring and reporting of pH, dissolved oxygen, temperature and ammonia levels, and

automatically alert when limits are breached. This technology helps in faster management response, which helps to minimize stress-related mortality and enhance production efficiency (Mustapha et al., 2021, Wang et al., 2021).
Engineering approaches like aeration, oxygen supplementation, biological filtration, ultraviolet sterilization, and recirculating aquaculture systems (RAS) are also used for water quality management. Nitrifying bacteria in biofilters convert toxic ammonia to nitrate, while mechanical filtration prevents the accumulation of suspended solids, which can deteriorate. When integrated with proper feeding practices and densities, these technologies also contribute to environmental stability and lower nutrient pollution of the surrounding ecosystems (Huang and Khabusi, 2025, Martins et al., 2010).

Table 2: Modern Technologies Used for Water Quality Monitoring and Management

Technology	**Parameter monitored**	**Major physiological role**
Digital pH meter	pH	Routine water quality monitoring
Dissolved oxygen meter	DO	Aeration management
Digital temperature sensor	Temperature	Thermal Regulation
Ammonia sensor	TAN/NH_3	Toxicity monitoring
Biological filtration	Ammonia	Nitrification
IoT sensor network	Multiple parameters	Real-time monitoring
AI-based management	Multiple parameters	Predictive water quality control

5. Discussion and Synthesis

The literature reviewed showed that water quality is the most important factor in the environment that affects the health and productivity of fish for aquaculture. While each of these factors can impact the fish in different ways, they are not likely to be the only factors acting in a commercial production system. However, these parameters work synergistically and often cause more physiological stress as a result of the cumulative effects than single changes of any one parameter (Colt, 2006).
Among the reviewed parameters, dissolved oxygen and temperature are among the most immediate parameters that affect fish metabolism, as they govern aerobic respiration and energy production in fish. Higher temperatures lead to higher metabolic oxygen requirements and lower solubility of oxygen, thus exacerbating hypoxic stress. Likewise, pH has a significant effect on ammonia toxicity due to the regulation of the toxic form of ammonia (un-ionized ammonia, NH_3). Therefore, if other water quality parameters are also below the recommended levels, maintaining one parameter at the recommended level will not ensure fish health (Abdel-Tawwab et al., 2019).
The reviewed evidence further reveals that water quality affects the welfare of fish in a variety of physiological ways, such as oxidative stress, endocrine disruption, impaired osmoregulation, impaired immune competence, and tissue damage. These responses decrease feed efficiency, growth, reproductive ability, and resistance to diseases, resulting in higher mortality and economic losses. Accordingly, the goal of effective water quality management should not be to correct water quality conditions after clinical signs of stress are observed, but to prevent the conditions that cause stress from changing the environment (Bastian et al., 2025, Colt, 2006).
The recent developments in precision aquaculture have made it much easier to maintain the optimal water quality. The use of IoT-based sensors, AI-based predictive models, and automated control systems enables producers to quickly identify environmental shifts and take timely corrective actions. These technologies, combined with biological filtration and proper husbandry, significant benefits can be achieved in fish welfare, resource use efficiency, and environmental sustainability for recirculating aquaculture systems (RAS) (Martins et al., 2010, Mustapha et al., 2021).
Overall, sustainable aquaculture relies on an integrated water quality management approach that takes into account the interactions between the various water quality parameters, alongside innovation and good husbandry practices. This is crucial for ensuring fish health, optimizing production, and minimizing the environmental impact of modern aquaculture operations.

6. Research Gaps and Future Directions

Progress is great in the knowledge of water quality management, but there are still gaps in knowledge. The majority of studies that can be found focus on a single water quality parameter in a controlled laboratory setting, while commercial aquaculture systems have several variables changing at the same time. Combined effects of pH, DO, temperature, and ammonia under practical farming conditions should therefore be evaluated in future studies.
More work is required to determine species-specific tolerances, especially for early life stages and emerging aquaculture species. More focus should also be given to developing affordable monitoring systems based on the Internet of Things (IoT), predictive models based on Artificial Intelligence (AI), and climate-resilient management strategies that can be implemented by small and medium farmers. These developments will lead to better environmental sustainability and efficient and profitable aquaculture production.

7. Conclusion

Water quality is crucial for successful aquaculture since it directly affects the physiology and health condition of fish and determines their growth and survival. Of all environmental factors involved in the process of fish farming, pH, DO, temperature, and ammonia level play the most significant role in terms of determining fish performance. These environmental factors are closely interconnected and can affect each other in the case of their changes, which makes the management of the environment indispensable.

The literature reviewed proves that keeping the environment stable increases the efficiency of feed utilization, improves resistance to diseases, the performance of reproduction, and other characteristics of production efficiency. Due to innovations such as RAS, biofiltration, IoT, and artificial intelligence, there are currently many opportunities to keep the environmental factors optimal in intensive farming. Future research should be aimed at studying the interactions between several stressors and tolerance thresholds for various species of fish, as well as technologies of precision aquaculture. Effective water quality management will remain essential for ensuring fish welfare, environmental protection, and global food security.

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