



Original Research Paper

Integrated Water Quality and Habitat Assessment for Environmental Sustainability and Welfare in Aquatic Animal Production Systems

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Key Words

Nutrient accumulation, Sediment organic matter, Integrated monitoring, Semi-intensive aquaculture, Environmental management.

Abstract

The configurations of environmental sustainability and animal welfare in aquaculture are completely influenced by the intricate connections of water quality dynamics and habitat configuration. This paper defined a comprehensive environmental surveillance model that incorporates daily physicochemical evaluations and features of the habitat and animal welfare measures in semi-intensive freshwater fish farming systems. Regular records in the variations in time of dissolved oxygen, temperature, pH, conductivity, total suspended solids and nutrient levels were taken together with measurements of sediment organic matter, saprophyte cover and periphyton development. The fish welfare was rated through growth rate, ratio of fed to weight, condition of the gill, frequency of external lesion and reaction to behavioural stress. Multivariate processes revealed that the variability in dissolved oxygen, organic loading of sediment and nutrient accumulation were the principal environmental factors that can lead to the welfare diminishment and production inefficiency. When specific habitat management treatments, including sediment eradication, shore vegetation adjustment, and feeding optimization, were implemented, the oxygen processes, the accumulation of nutrients and the health, growth, and survival of fish were enhanced. On the whole, the results show the paramount role of combined, non-IoT-based water quality and habitat monitoring methods in advancing environment-friendly, welfare-oriented, and sustainable systems of aquaculture production.

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Introduction

This is because aquatic animal production systems are found in complicated ecological systems in which environmental sustainability, as well as animal welfare, is dictated by the interaction of water quality parameters and habitat structure. Variations in vital physicochemical indicators of dissolved oxygen (DO), temperature, pH, nutrients and suspended solids could cause metabolic stress, adverse feeding behavior, and increase disease susceptibility in cultured species. Past reports

have noted that the aquaculture systems are susceptible to abiotic stressors and that there is the need to have resilient models of production that would enable the management of ecological balance in changing conditions (Abisha et al., 2022; Arega et al., 2022; Bai et al., 2021). Small disturbances in the stability of nature within a semi-intensive system of pond culture, in which the functioning of natural productivity and additional feeding are parallel, can quickly spread throughout the system affecting fish growth, survival and long-term productivity.

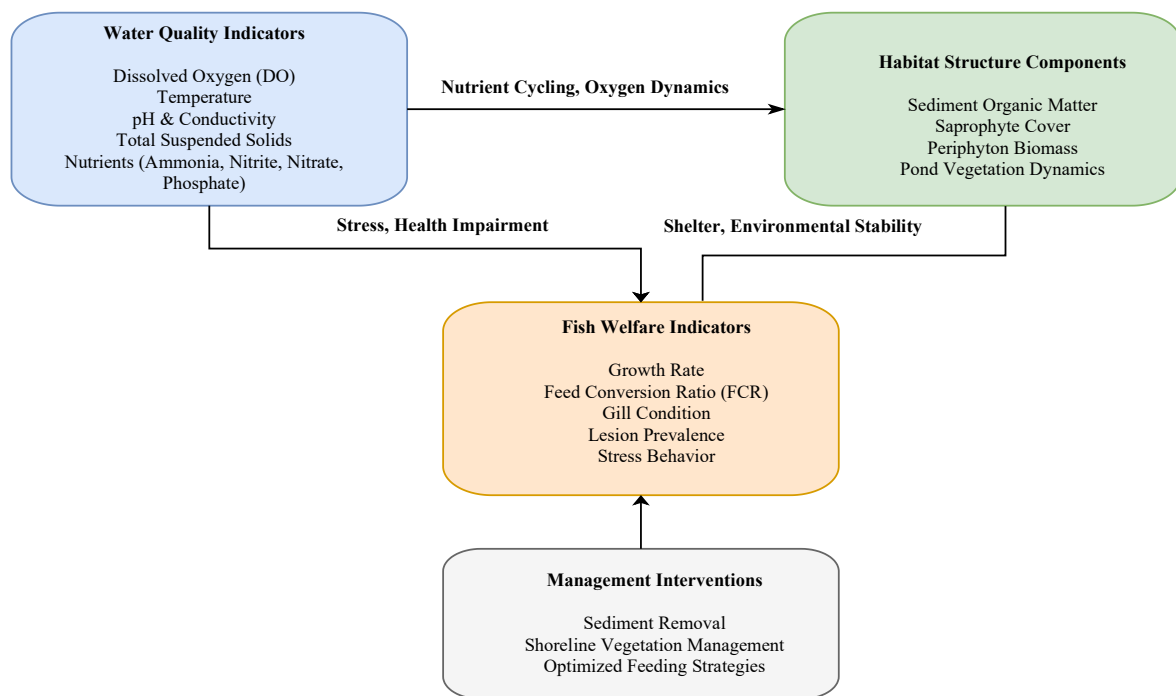


Figure 1: Conceptual Framework of Water Quality–Habitat–Welfare Interactions in Aquaculture

Although there are significant improvements in water quality monitoring, the conventional methods of monitoring usually provide a one-parameter picture, or a short-term profile of the relationship between various components of the environment in the long run. It has also been found that nutrient enrichment, organic loading of sediment, and vegetation structure have a great impact on oxygen processes, microbial activity,

and pond functioning (Addy et al., 2017; Bhatia et al., 2022; Chiquito-Contreras et al., 2022; da Silva Morales et al., 2022). However, most farms do not possess comprehensive monitoring systems that are able to combine physicochemical, habitat and welfare measurements into a single evaluation. New directions have embraced remote sensing, IoT-enabled sensing solutions, and more advanced

water quality modeling (Caballero & Navarro, 2021; Calone et al., 2019; Danh et al., 2020) that can be inhibited in limited resource and small-scale aquaculture settings due to its high costs and infrastructure demands. This leaves a loophole in the practical, yet non-IoT-based models which offer just as much, in terms of environmental diagnostics.

Simultaneously, the use of machine learning (ML) in aquaculture has grown fast and presented the use of new instruments that predict complicated biological and environmental reactions. Other models like hybrid DO forecasters, neural networks, optimization-based predictors have proven to be very accurate in the field of environmental modelling and fisheries analytics (Eze & Ajmal, 2020; Geetha & Thanushkodi, 2008; Nathiya et al., 2024; Kumar, 2024). Gradient Boosted Decision Trees (GBDT) are among them, and they are the most robust, interpretable, and can address non-linear interactions among several predictors. GBDT-based models may be able to readily detect threshold effects, determine importance of variables and observe the existence of subtle interactions that may be neglected by traditional statistical models. They have not been fully utilised in the environmental assessment of aquaculture, and this presents a choice to examine their predictive power in the integrated water-habitat-welfare monitoring frameworks. The conceptual organisation of these interconnected parts is shown in (Figure 1).

This research constructs and implements a compound tracking approach implementing a blend of regular water quality measurement,

setting requirements of the habitat condition, and an indicator of fish welfare to test semi-intensive aquaculture systems. The framework documents the dynamics of temporal variability of DO, nutrients, sediment organic matter, macrophyte cover, and periphyton relationship involving such relationship with growth performance, gill condition, lesion prevalence, and stress-related behaviours. Multivariate analysis and GBDT modelling were used to identify the key environmental factors causing impairment of welfare and low production efficiency. In addition, the intervention interventions at the habitat level (removal of sediments, shoreline vegetation control and implementation of optimum feeding measures) were undertaken to assess system responsiveness. Having proposed a feasible and low-cost, non-iot based monitoring and decision-support strategy, the current research helps in developing welfare-oriented and environmentally responsible approaches to the management of aquaculture.

Literature Review

Sustainable aquaculture centred on maintaining ideal water quality because the changes in the physicochemical system directly affect fish welfare, metabolic activity and entire system outputs. It has been established in a variety of studies that the lack of dissolved oxygen (DO), thermal stress, pH disproportion and nutrient loading can negatively affect physiological stability, feed performance and cause a higher mortality within cultured species (Abisha et al., 2022; Bai et al., 2021; Eze & Ajmal, 2020; Shanthi & Duraiswamy, 2008). Overload of total suspended solids (TSS) and

ammonia might lead to damages of the gill structures, osmoregulation, and increase vulnerability to infectious organisms. Water quality and fish welfare therefore have a multidimensional relationship and simultaneously are shaped by various parameters that determine the stability of the environment. The full Table 1 summarises these interactions based on key findings obtained by previous studies investigating the connexions linking water quality drivers and welfare outcomes.

In addition to chemistry of water, habitat structure is also a very important factor in the determination of the function of the aquatic ecosystem and its sustainability in production. The cover of the macrophytes, periphyton growth as well as the sediment organic matter control the nutrient cycling, oxygen supply, and microbial activity of aquaculture ponds (Addy et al., 2017; Bhatia et al., 2022; Chiquito-Contreras et al., 2022). Intravenous sediment deposition especially has been reported to augment the biological oxygen demand and raise the chances of periodic hypoxia. In the same manner, the excess growth of macrophytes may cause shading, oscillations of dial Oxygen and habitat fragmentation. The evaluation of the sustainability of aquaculture studies, generally tend to stress the importance of incorporating habitat variables into the environmental assessment models (Calone et al., 2019; da Silva Morales et al., 2022). Nonetheless, the bulk of commercial or field-level monitoring systems continue to consider water quality and habitat as separate parts of an ecosystem and not a system.

IoT-based and otherwise integrated methods of assessment, such as remote sensing applications, water quality monitoring systems, and automated data acquisition systems, have turned out to be relevant solutions to enhance environmental monitoring in aquaculture (Caballero & Navarro, 2021; Danh et al., 2020). Although these innovations improve the temporal resolution and predictability, they are both expensive, technologically challenging as well as unavailable to small/semi-intensive farm activities especially in developing economies. Such technological divide underscores that there is a need to have practical low cost non-IoT-based techniques that can still record the intricate relationship between water quality, habitat structure and fish welfare. Semi-manual monitoring can also serve as an option to farms that do not have advanced digital infrastructure when paired with powerful analytical models.

Developments in the recent data-driven analytics domain have brought about machine learning (ML) algorithms that have the potential to consider non-linear relationships, which are complex in nature, in the aquaculture setting. The hybrid DO forecast models, neural networks and optimization-based algorithms have displayed high predictive potentials on the water and environmental modelling (Eze & Ajmal, 2020; Geetha & Thanushkodi, 2008; Nathiya et al., 2024). Specifically, Gradient Boosted Decision Trees (GBDT) such as XGBoost, LightGBM and CatBoost have become more popular because of their effectiveness in case of heterogeneous data and resistance to noise and their capacity to generate understandable rankings of variable

importance. Although they are increasingly used in ecological and environmental studies, their application in the analysis of semi-intensive aquaculture systems in terms of the integrated welfare, water and habitat is very low. Filling this

research gap, the given research incorporates manual observations with GBDT modelling to summarise primary welfare determinants and estimate the ecological merits of the habitat-centred management intervention.

Table 1: Summary of Key Studies Linking Water Quality Parameters to Fish Welfare Outcomes

Study / Reference	Key Water Quality Parameters Investigated	Main Welfare Outcomes Assessed	Major Findings
Abisha et al., 2022	Dissolved oxygen, temperature, nutrient stress	Growth performance, stress resilience	Abiotic stressors significantly impair fish metabolism and reduce climate resilience in aquaculture systems.
Bai et al., 2021	DO, ammonia, suspended solids, contaminants	Health risk, tissue condition, safety index	Water quality deterioration increases physiological stress and elevates risk of toxic accumulation in fish.
Addy et al., 2017	Nutrients (N, P), turbidity, DO dynamics	Growth, feeding efficiency, system stability	Nutrient loading affects oxygen balance, influencing feeding behavior and survival in aquaponic systems.
Arega et al., 2022	DO, salinity, temperature (model evaluation)	Welfare risk, mortality prediction	Water quality variability is strongly correlated with welfare impairment in mariculture models.
Eze & Ajmal, 2020	DO forecasting and temporal fluctuations	Stress events, survival probability	Accurate prediction of DO fluctuations helps prevent hypoxic stress and associated welfare decline.

Methodology

The experiment was run in semi-intensive fresh water purchase system aquaculture ponds of standard commercial practices. The three ponds were stocked with similar species and stock levels of fish to provide uniformity of the experimental units. The observation was completed over several months to record diurnal and seasonal changes within the environment that generally affect the ecology of ponds. The time structure enabled the determination of two domains of variability both in the short term, including daily dissolved oxygen peaks, and in the long term including nutrient accumulation and sediment organic loads.

Water quality control concentrated on major physicochemical parameters that are recognised to determine the health of fish and eco-stability.

The handheld metres were used to measure the dissolved oxygen, temperature, pH, conductivity, and total suspended solids (TSS) at pre-defined locations and depths in each pond. The nutrient analysis of the nutrient concentration of ammonia, nitrite, nitrate and phosphates was done according to standard laboratory protocols aiming to determine the nutrient enrichment and estimate the possibility of eutrophication (Ekawati et al., 2021). The measurements were taken regularly in time, and thus the temporal profiles of each parameter could be made.

The indicators which were used in habitat assessment are indicators that reflect structural and ecological elements of pond environments. The loss-on-ignition technique was used to determine sediment organic matter, which offered information on benthic organic loading

and its effect on the demand of oxygen. Visual assessment of macrophyte cover was done through standardised grid-based processes to establish the degree of immersions and non-immersion vegetation. Periphyton biomass which plays a significant role in the nutrient cycling and oxygen regime was determined using scrape samples of artificial habitats which were put in the ponds. Through these habitat metrics, it was possible to characterise ecological processes that interact with water quality in order to determine fish health outcomes.

An assessment of fish welfare was done based on a mixture of the production based, health based and behavioural indices. The level of production efficiency was measured in terms of growth rate and feed conversion ratio (FCR) and the most important health indicators of the environmental stress were the gill condition scoring and external lesion prevalence. The observation of behaviour considered surface breathing, low feeding activity, and the unsteady movement, which give an early indication of poor welfare. The combination of these measures made it possible to determine the extent to which environmental conditions were converted into biological responses at the organismal level.

The data analysis was conducted using multivariate statistical tools as well as machine learning based modelling. The relationships between water quality and habitat variables with welfare indicators were then investigated with Principal Component Analysis (PCA) and correlation matrices which revealed the most prevalent gradient of the environment. Gradient Boosted Decision Trees (GBDT) was

subsequently used to measure the change in predictability of each of the predictor variables to fish welfare outcome. Every parameter of water quality and habitat was taken as inputs, whereas the growth rate, FCR, lesion prevalence, and a composite score of welfare risk were the result. Performance dependent model parameters were optimised including the depth of the tree being used and the learning rate and the number of estimators (Geetha & Thanushkodi, 2008). Model accuracy was assessed using R², RMSE and the rankings of variable importance. Furthermore, mid-study management interventions, which comprised sediment removal, control of shoreline vegetation, and optimization in feeding strategies were applied, and data on pre- and post-intervention were compared to measure the effects of the targeted intervention in raising the environmental and welfare conditions.

Results and Discussion

Time series analysis of water quality indicated the obvious oscillation that was in harmony with feeding intervals, seasonal variations in temperature conditions, and the natural stratification processes of ponds. The depressions on dissolved oxygen were intense in the early mornings, especially within ponds that had large amounts of sediment organic matter and heavy growth of periphyton. Elements such as ammonia and nitrate elevated intermittently after big feeding events and during warmer seasons which enhanced the rate at which microbes were being broken down. Agreement existed in high transparency of water levels and increased oxygen demand having a high level of

sediment organic matter. The type of habitat variables including macrophyte cover and periphyton biomass was also significantly different among ponds affecting nutrient uptake and playing a role in diel oxygen processes. Table 2 is the compilation of these observations that shows the time distribution of the key water quality and habitat parameters.

These environmental changes were well reflected in fish welfare. The growth rate and feed conversion ratio (FCR) were found to decrease during the nutrient loading periods and high levels of dissolved oxygen hence high metabolic stress. Gill condition score showed the presence of mucous as well as mild lamellar damage in ponds with frequent hypoxic crashes whereas external lesion prevalence grew with increase in suspended solids and turbulence of sediments. The close relationship between physicochemical instability and welfare impairment was confirmed by the fact that behavioural indicators, such as surface breathing, a decreased motivation to feed, and an unsystematic swimming.

There were further findings of multivariate analysis that attempted to explain the existing environmental gradients underlying welfare outcomes. Principal Component Analysis (PCA) identified three major axes that cover most of the variability (1) oxygen dynamics were due to variability in DO and temperature patterns, (2) nutrient enrichment was caused by concentrations of ammonia, nitrate, and phosphates, and (3) organic loading of sediment was promoted by benthic decomposition processes. These gradients were able to

distinguish between high- and low-risk groups of ponds to where welfare could deteriorate which demonstrates the importance of combinations of environmental pressures and not the individual parameters in determining a stable system. The results of the clustering showed that the welfare score was consistently lower in the ponds with the high content of the sediments organic matter and the high amount of nutrients as well.

Gradient Boosted Decision Trees (GBDT) model allowed gaining additional information on the relative weight of every environmental factor on the fish welfare outcomes. Variability of dissolved oxygen was the most significant predictor, which shows it is the core determinant of growth, FCR and health indices. Ammonia concentration was next in order of importance followed by sediment organic matter that indicates that physiological stress increases with benthic processes and nutrient deposition. Secondary variables, such as the total suspended solids (TSS) and the biomass of periphyton, played a significant role in that it determined the turbidity, the gill loading, and oxygen utilisation. The use of the partial dependence plots showed clear threshold effects in that welfare measures dropped drastically when the DO fluctuation was greater than critical levels or ammonia levels crossed the sub-lethal stressful levels. These results support the relevance of GBDT modelling in determining the high-impact environmental drivers in the aquaculture systems.

Introduction of specific habitat management interventions resulted in definite positive changes in the state of the environment and fish welfare. The removal of sediment lowered the

benthic oxygen requirements and water circulation raised the water supply of mornings, whereas vegetation control at the shoreline raised the levels of organic debris and reduced its build-up. Optimised feeding approach minimised nutrient outbursts and enhanced feed conversion ratio. More consistent DO profiles, reduced ammonia and nitrate and major improvements of

gill conditions, lesion prevalence and behavioral welfare indicators were found after intervention monitoring. All in all, the interventions confirmed the integrated monitoring scheme and revealed the ways of specific environmental management that realise sustainability, welfare, and production efficiency in the semi-intensive aquaculture systems.

Table 2: Temporal Variation in Key Water Quality and Habitat Parameters

Parameter	Early Monitoring Phase	Mid Monitoring Phase	Late Monitoring Phase	Key Observations
Dissolved Oxygen (DO)	5.8–7.2 mg/L	3.9–6.1 mg/L	4.2–6.5 mg/L	DO dips observed during early mornings; lowest values coincided with warm periods and high organic load.
Ammonia (NH₃-N)	0.12–0.25 mg/L	0.30–0.48 mg/L	0.22–0.37 mg/L	Peaks followed feeding events and decomposition; mid-phase values highest.
Total Suspended Solids (TSS)	18–26 mg/L	24–35 mg/L	20–28 mg/L	Increased during periods of pond disturbance and sediment accumulation.
Sediment Organic Matter	4.5–5.8%	6.2–7.8%	7.0–8.1%	Progressive accumulation across months, indicating rising benthic oxygen demand.
Macrophyte Cover	10–18%	15–25%	8–16%	Mid-phase expansion influenced light penetration and nutrient uptake; late-phase reduction after management actions.

Future Research

In the future, the study should expand the time span of monitoring of the multi-season and multi-year data, which will allow understanding long-term environmental variations and how they have accumulated over time, affecting fish welfare. Temperature, hydrology, nutrient cycle, and sediments can cause considerable changes in the condition of ponds with season, and recording these longer intervals would give stronger results of welfare risks. The longitudinal data would also assist in separating both short-term changes and long-term environmental stressors in order to

implement more sustainable management measures.

The second direction that is worth pursuing is the combination of low-cost, based on the IoT, water quality sensors with the manual system of monitoring applied in the current study. Although the current solution focuses on practicality of resource-starved systems, the IoT can improve the resolution of data, detect fast environmental variations, and give real-time notifications when the welfare is critical. With periodic manual calibration, low-cost sensor networks would form hybrid monitoring systems, which would still be accessible and be more

accurate and early warning. These systems would facilitate proactive decisions and decrease chances of hypoxic or nutrition related welfare failures.

Also provided by advancements in the computational modelling, there are great opportunities in the improvement of welfare prediction. Time-dependent interactions can be better represented by deep learning models, namely Long Short-Term Memory (LSTM), Temporal Convolutional Networks, as well as hybrid ML frameworks, over time, in comparison with more static models. In combination with the GBDT technique explored in this paper, the models can offer a higher predictive value, allow detection of non-linear threshold effects, and adaptive management systems (Senthil et al., 2021). These models would also be improved by cross-validation of the results on multi-species, or the design of ponds, and on different climatic situations to increase their generalizability as well as to increase their applicability in a variety of aquaculture practises.

Lastly, new studies should be done on spatially explicit habitat analyses to supplement the water quality prediction models. Drones could be used to collect aerial images on periponic lentic systems, macrophyte distribution could be studied by GIS maps, heat-source signatures in sediment could be analysed, and various other tools might also be applicable in understanding spatial heterogeneity in ponds. Integrating these spatial datasets with either a GBDT or a deep learning could enhance the knowledge about localized welfare risks and ecological processes influenced by habitats.

These interdisciplinary measures will help in the establishment of comprehensive, data-based models that will advance the idea of environmental sustainability and welfare-driven management of aquaculture.

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Conclusion

This experiment illustrates that water quality, habitat structure as well as fish welfare as indicators offer an effective model that one can use to enhance sustainability in semi-intensive aquaculture systems. The findings indicate that the variability of the dissolved oxygen, sediment

organic loading, and the accumulation of nutrients are the core environmental factors of welfare impairment, which are validated using multivariate and Gradient Boosted Decision Trees (GBDT) models. Application of specific habitat treatments such as sediment removal, vegetation on the shore and optimal feeding strategies helped in quite a significant enhancement of oxygen dynamics, decrease in nutrient accumulation and an increase in fish health and growth performance. The above results highlight the practicality of inexpensive monitoring methods, which are unrelated to IoT, and the significance of both data-insightful and comprehensive management strategies to attain an environmentally responsible and welfare-focused aquatic animal production.

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