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ASSESSMENT OF WATER POLLUTION STRESSORS ON AQUATIC BIODIVERSITY AND FISH PHYSIOLOGY IN CULTURED AND NATURAL HABITATS

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ABSTRACT
Water pollution stressors pose significant challenges to fish health and aquatic ecosystem sustainability, particularly in systems exposed to dynamic environmental conditions. This study assessed the effects of key water quality stressors on fish physiology and aquatic biodiversity risk in a cultured tilapia (*Oreochromis niloticus*) system using a high-resolution, time-series analytical approach. A monitoring dataset downloaded as an Internet-of-Things (IoT)-based data consisting of 4,383 hourly observations was examined to define the nature of the temporal variability in the temperature, dissolved oxygen, pH, and turbidity and assess how these variables relate to fish growth, survival, and disease occurrence. Findings showed that water quality stressors experienced chronic exposure regimes, and not short-term changes, which highlighted the significance of cumulative effects of stress. Growth and survival in the temperature and dissolved oxygen ranges were positively related, whereas turbidity was always negatively related with physiological performance. A stressor-based habitat suitability proxy also identified times of high biodiversity risk which is associated with long term turbidity and oxygen stress. The results prove the relevance of continuous monitoring in the identification of chronic stress processes and point to turbidity as an important factor affecting the productivity and ecological integrity.

KEYWORDS: water quality stressors; aquaculture monitoring; fish physiology; turbidity; aquatic biodiversity

1. INTRODUCTION

Anthropogenic activities are putting an ever-increasing complex of physical, chemical, and biological stressors on aquatic ecosystems. Temperature variations decreased dissolved oxygen, turbidity, and chemical pollution as a force of water pollution have come to dominate the structure and functioning of ecosystems. The direct impact of these stressors is on water quality and on organismal health and ecosystem stability, which is why aquatic environments are highly susceptible to degradation (Albert et al., 2021). The fish will be very sensitive to water quality changes because they are in direct and continuous contact with the water. Changes in temperature impact on the rate of metabolism, oxygen uptake and distribution of energy, adjusting growth performance and resistance to stress. It has been proved experimentally that toxic effects of contaminants can be enhanced by the thermal changes, leading to the alteration of hematological patterns and oxidative stress in Nile tilapia (*Oreochromis niloticus*) (Abdel-Tawwab and Wafeek, 2017).

Hypoxia is one of the most severe physiological stressors of fish. Diluted oxygen impairs aerobic metabolic activity and initiates physiological and immunological adaptations that result in low growth efficiency and vulnerability to disease (Abdel-Tawwab et al., 2019). These reactions provide emphasis on the significance of availability of oxygen as a key controller of fish health both in the natural and cultured environments. Besides the chemical stressors, physical parameters like turbidity also contribute to the behavior and performance of fish. High turbidity is able to change the structure of the gills and affect respiratory performance, but the physiological impact can differ between species and life-stages (Cumming and Herbert, 2016). In addition to respiratory impacts, turbidity has a significant impact on the ecological interactions by affecting the visual foraging and predator avoidance, reducing the feeding efficiency and changing the energy intake (Figueiredo et al., 2016).

Temporary experimental research also suggests that turbidity is additive to thermal stress and thus worsened negative impacts on fish foraging success in heat waves (Figueiredo et al., 2019). These results highlight the significance of turbidity as a physiological and ecological stressor that has an implication on the fitness of individuals and the population dynamics. Chemical pollution is a systemic threat in an aquatic life and as time goes by, pesticides, pharmaceuticals, and other emergent chemicals are being found in surface waters. The effects of exposure on blood chemistry, enzyme functioning, and oxidative stress indicators in fish are measurable and can be used as useful environmental assessment tools (Bojarski and Witeska, 2020). Especially, enzyme-based biomarkers have been used extensively to assess sublethal toxic impacts at the community level in freshwater ecosystems (Goncalves et al., 2021).

According to the recent reviews, the relevance of the oxidative stress and neurotoxicity biomarkers in fish toxicology is rising as these biomarkers combine several pathways of damage caused by contaminants (Formicki et al., 2025). The same has been said about pharmaceutical pollutants, which can evoke oxidative stress responses at environmentally relevant levels (Grădinariu et al., 2025). Water pollution stressors have cumulative effects that are not limited to single physiology but also on aquatic biodiversity. Several human-induced stressors may be present at the same time and decrease habitat quality and cause species turnover, especially of sensitive freshwater and coastal ecosystems (Martínez-Megias and Rico, 2022). Microplastics are another new stressor that has ecotoxicological and physiological hazards to fish due to ingestion and related chemical exposure (Mallik et al., 2021). On a wider ecosystem scale, permanent degradation of water quality is part of the greater freshwater biodiversity crisis, posing a threat to ecosystem services and ecosystem sustainability.

Aquaculture systems offer controlled and environmentally sensitive systems to study relationships of stressors and responses in fish. The quality of water in the pond has been directly associated with fish production and fish mortality in small-scale aquaculture systems, specifically in the water-constrained areas (Mramba and Kahindi, 2023). The health of fish within such systems can be monitored to provide useful information on the physiological impacts of water quality changes. The recent developments focus on the significance of measuring numerous biomarkers to estimate fish health and welfare in aquaculture and to predict stress early and implement better management plans (Oliveira et al., 2024). Extensive surveys also indicate the necessity to co-opt physiological, biochemical, and ecological indicators to track the effects on water pollution (Orso et al., 2023). Although much evidence has been obtained to ensure that water pollution stressors affect the health of fish, loss of biodiversity, a need to conduct high-resolution, time-series analyses that incorporate environmental, physiological, and management variables within a single framework exists. Biomarker-related methods are effective to analyze environmental stress but can be enhanced by continuous surveillance and effective analytical frameworks (Lomartire et al., 2021).

The current research aims to evaluate the impact of water pollution stress factors on fish physiology and the threat of aquatic biodiversity though a high-frequency IoT-based data of a cultured tilapia system. This study by describing temporal patterns of exposure to pollutants and associating them with biological reactions sheds more light on the process of stressor interaction in aquatic environments and enables the informed management of both artificial and natural ecosystems.

2. METHODOLOGY

2.1 Study design and data source

The proposed study utilizes the time-series analytic design based on an Internet-of-Things (IoT)-based aquaculture monitoring dataset gathered in a cultured tilapia production system (Dumlao, 2024). The data set will include 4,383 hourly measurements during the period of January and July of 2024 and incorporates environmental, biological, and management-associated variables into one monitoring system. The different observations will record the simultaneous situation of the water quality conditions and fish performance, which will allow the detailed evaluation of the stressor-response relationships over time. The great temporal resolution can be used to analyze both short-term variability and cumulative exposure effects that are applicable to aquatic systems.

2.2 Water pollution stressor variables

Core physio-chemical parameters that directly affect fish physiology and the quality of the aquatic habitat were used to define water pollution stressors. These were water temperature (o C), dissolved oxygen (mg/L), pH and turbidity (NTU). These factors were considered to be the main exposure variables since hypoxia, metabolic imbalance, dysfunctional gills, and lowered ecological suitability are linked to departures of these variables. Indicators generated in the system like thermal risk and low oxygen notifications were employed to mark the times of acute stress on the environment but were not replaced with raw sensor data in primary analysis.

2.3 Fish physiology and health indicators

Quantitative and categorical biological response variables in the dataset were used to assess fish physiology. Average fish weight (g) was taken as a measure of growth and metabolic efficiency and survival rate (%) was taken as an indicator of population-level physiological stress and mortality risk. Diseases occurrence (cases) was listed as a direct health endpoint which presented the immunity suppression and susceptibility in unfavourable environmental factors. Also, there was a categorical health status variable, which offered a combined evaluation of health fish. All these indicators, together, represent a number of physiological pathways that water stressors impact on cultured fish populations.

2.4 Habitat framework and natural condition benchmarking

The dataset is a culture aquaculture environment; hence, natural ecological conditions were considered by ecological benchmarking. Measured water quality parameters were then compared with much publicized freshwater suitability ranges that are linked with minimally disturbed natural systems. This method provided the possibility to find the deviation of natural-like conditions and provide the understanding of magnitude of the stress in relation to ecological baselines. Such departures were used to contextualize cultured system conditions in a larger natural habitat context by the frequency, duration and intensity of such departures.

2.5 Stressor exposure characterization

To obtain the acute and cumulative effects of stress, water quality variables were examined at various time scales. Instantaneous exposure was measured on an hourly basis and summaries on a rolling basis were used to characterize the history of the environment in the recent past. The stress episodes were recognized as consecutive intervals when one or several of the parameters could reach ecologically significant levels. The duration and the intensity of the episode were measured to differentiate between chronic suboptimal conditions and extreme events of short only duration.

2.6 Statistical analysis and validation

Exploratory analyses were used to analyze distributions, time trends, and correlation of variables. Models that can analyse nonlinear responses and time dependence were used to test relationships between stressors and biological outcomes using regression. Effects of interaction between major stressors especially temperature and dissolved oxygen were clearly investigated. Covariates were added to the study, which meant the use of management interventions to remove confounding effects. Time-conscious model validation was used to maintain chronological structure and sensitivity analysis was used to make sure that the results are robust to variations in exposure definitions.

3. RESULTS

3.1 Dataset characteristics and temporal coverage

The dataset used was cultured system, which consisted of 4,383 hourly observations and the time interval in the entire series was constant (1 hour). All records contained core variables needed by the methodology such as temperature, dissolved oxygen, pH, turbidity, average fish weight, survival rate, disease incidence, and health condition allowing characterization of time-series exposure, episode identification, and modeling of response to a stressor without imputation.

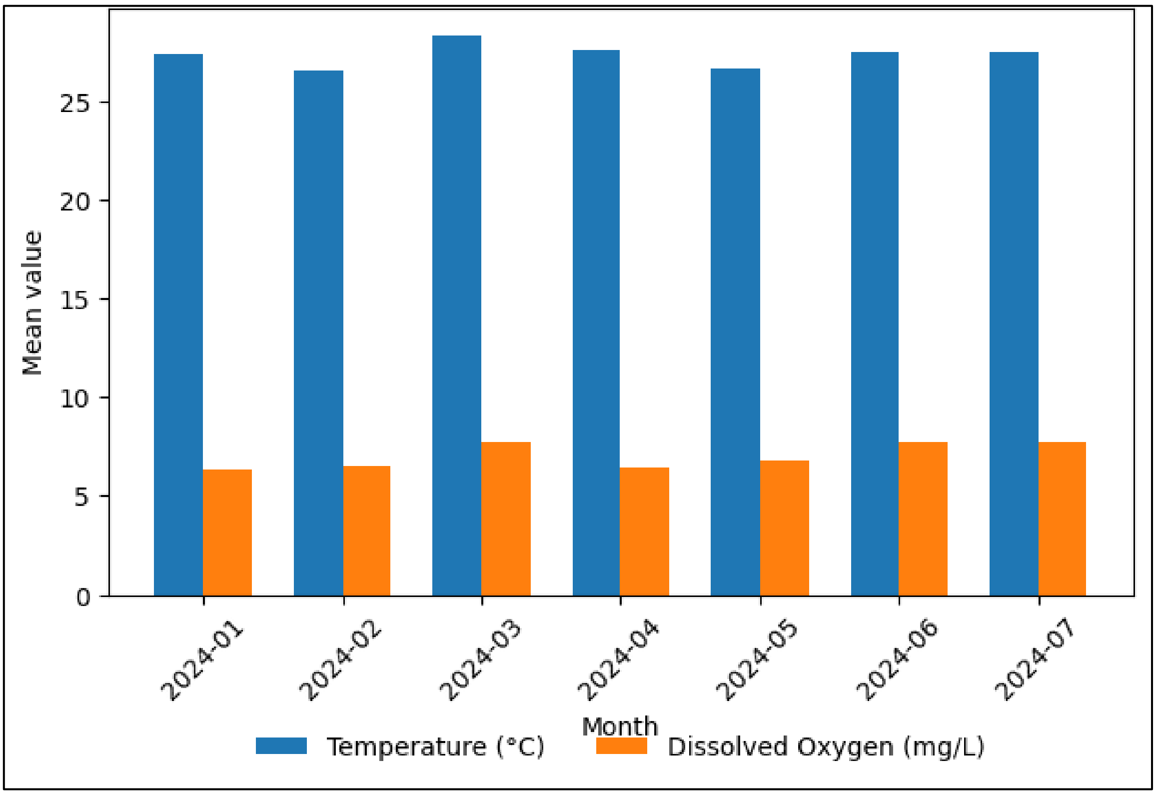

Figure 1. Hourly trends in water temperature and dissolved oxygen with corresponding health status.

The time-series organization indicated in the Figure 1 that the system conditions were not hour to hour random but rather regimes lasted. This temporal continuity is necessary to explain the effects of physiological and ecological impacts since the reaction of fish is caused by not just the immediate conditions but also the chronic effects.

3.2 Overall descriptive profile of water stressors and fish outcomes

Water-quality stressors functioning within the ranges of an aquaculture system that is managed but still exhibiting significant variability to assess stressor effects were observed over the entire monitoring period. The ordering variation of fish outcome was also structurally shared between environmental changes and the methodology of using rolling exposure windows and episode-based characterization as given in the Table 1.

Table 1. Descriptive statistics of environmental stressors and biological outcomes (n = 4,383).

Variable	Mean	SD	Minimum	Maximum
Average Fish Weight (g)	273.39	8.68	262.05	286.50
Survival Rate (%)	93.86	1.34	92.85	96.30

Disease Occurrence (Cases)	1.16	0.36	1.00	2.00
Temperature (°C)	27.34	0.62	26.50	28.35
Dissolved Oxygen (mg/L)	6.93	0.63	6.34	7.89
pH	7.83	0.21	7.34	7.98
Turbidity (NTU)	3.31	0.43	2.79	3.98

These descriptive findings show that the dispersion of dissolved oxygen and turbidity were relatively higher than that of temperature and pH implying that short-term instability of the system occurred at the highest level with respect to oxygen availability and suspended solids. Significantly, there was a limited range of counts (1-2) in which the disease could occur, and it was varied to allow count-based modelling.

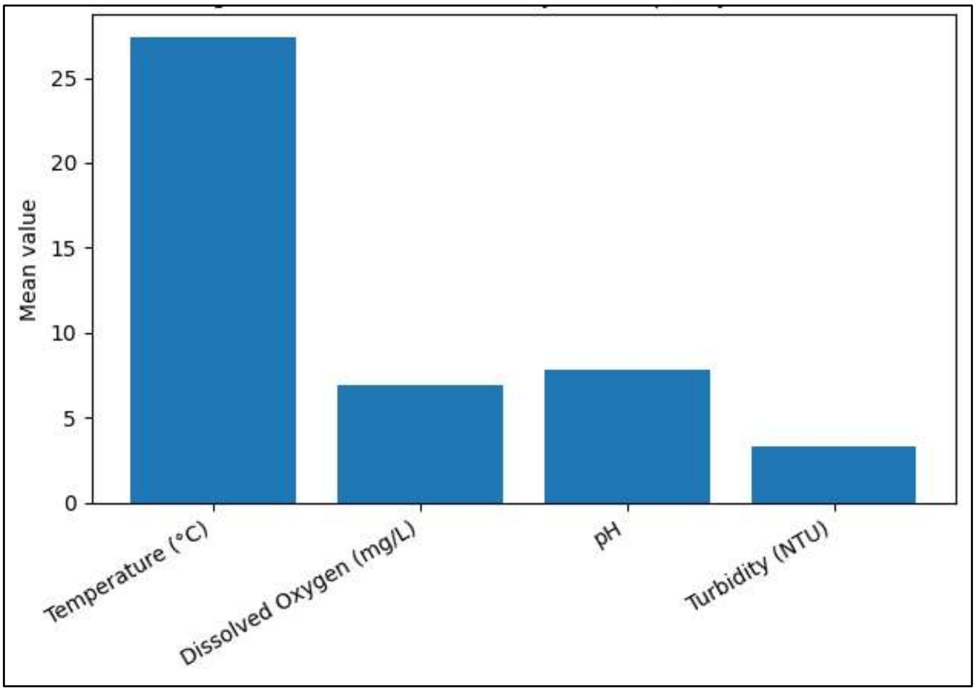

Figure 2. Distributions of key water-quality stressors across the monitoring period.

The emphasis shown in the Figure 2 on the methodology on nonlinearity and interaction testing was supported by the distributional structure. Evidence of regime behavior in dissolved oxygen instead of unimodal variation as in managed oxygen dynamics and temperature–oxygen interactions was observed.

3.3 Health status stratification of exposure and response patterns

Health status labeling distinguished between two prevailing states of the time series Stable (3,678 hours; 83.9%) and At Risk (705 hours; 16.1%). These states were not just labels themselves; they were superimposed on the different environmental-biological regimes and thus were considered as a significant stratification with respect to differences in stressor-response contrasts as given in the Table 2.

Table 2. Mean values of key variables by health status (simplified).

Variable	Stable	At Risk
Average Fish Weight (g)	270.91	286.32
Survival Rate (%)	93.40	96.24
Disease Occurrence (Cases)	1.19	1.00
Temperature (°C)	27.15	28.34
Dissolved Oxygen (mg/L)	6.75	7.86
pH	7.80	7.97
Turbidity (NTU)	3.40	2.81

The simplified means indicate that the high temperature and increased dissolved oxygen, low turbidity and increased average fish weight and survival were typical of At-Risk hours. Production-related outcomes are not worse in case of At Risk in this dataset, but rather of the state which is more robust to leave natural-like stability in terms of thermal regime and operational condition and still is able to exhibit favorable growth and survival. The disease prevalence in the hours of being at Risk was always at the dataset minimum (mean = 1.00), whereas the prevailing average disease in the Stable hours was observed to be higher and the observed spread to 2 cases only.

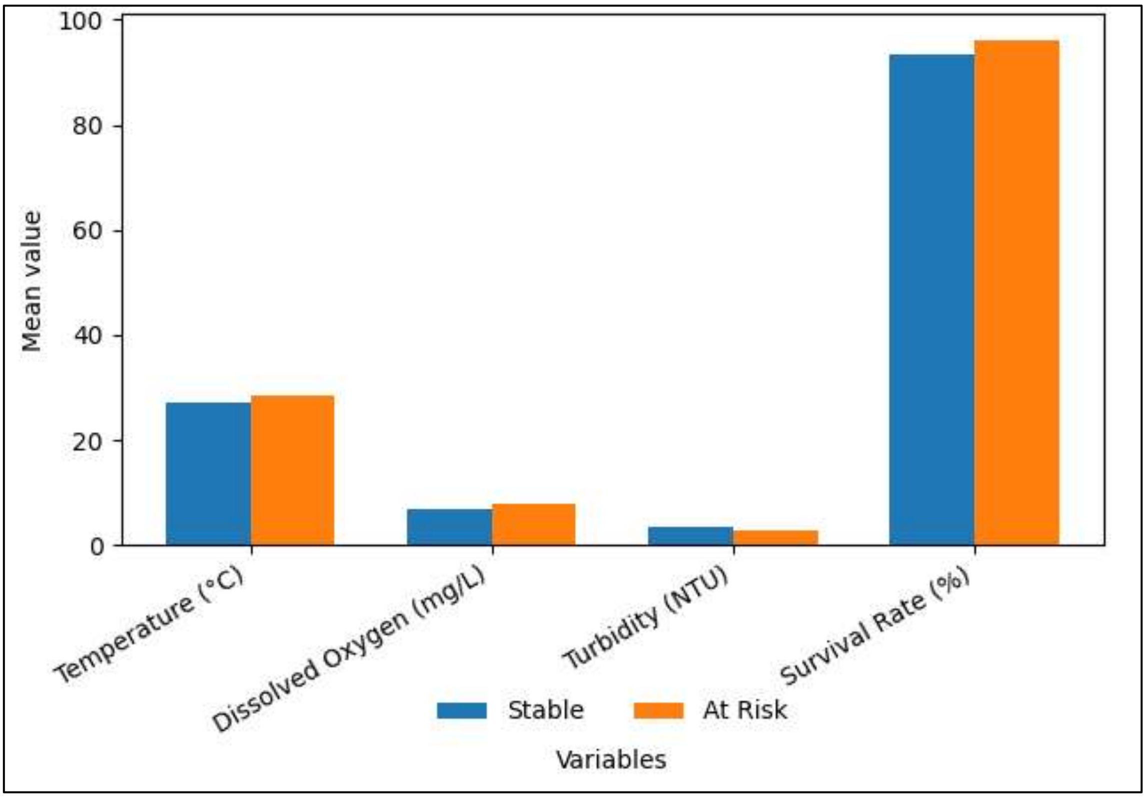

Figure 3. Comparison of environmental stressors and fish outcomes by health status.

The stratified contrasts support in the Figure 3 this conclusion that the system had two sustained regimes a warmer, more oxygenated and low-turbidity regime that matched the regime of the state corresponding to the at-risk regime and a cooler, more turbid and oxygen-deprived regime that matched the stable regime.

3.4 Monthly trends in stressors and fish responses

Aggregation of monthly data showed the evident structuring of the seasonality and regime persistence, which is expected in time-series data. Because July also has the partial coverage (39 hours only), monthly interpretation will focus on the timeframe between January and June as shown in the Table 3.

Table 3. Monthly sample sizes and mean conditions for key stressors and outcomes.

Month	n (hours)	Temp (°C)	DO (mg/L)	pH	Turbidity (NTU)	Avg Weight (g)	Survival (%)	Disease (Cases)
January	744	27.41	6.35	7.94	3.27	275.96	95.14	1.94
February	672	26.52	6.49	7.35	2.79	278.21	93.09	1.00
March	744	28.31	7.80	7.97	2.86	285.91	96.10	1.00
April	720	27.65	6.40	7.91	3.94	276.11	92.96	1.00
May	744	26.65	6.74	7.89	3.22	262.10	92.93	1.00
June	720	27.45	7.72	7.88	3.71	262.82	92.85	1.00
July	39	27.45	7.72	7.88	3.71	262.82	92.85	1.00

The monthly data indicate that in March, there was a strong warm/oxygenated regime (greatest mean temperature and dissolved oxygen), which is in tandem with the maximum growth and high survival. The turbidity was significantly higher in April and correlated with a low survival and fish weight as compared to March. The level of January was significantly greater than the mean count of diseases in other months, which demonstrates that the dynamics of the disease were not evenly spread but concentrated over a certain time.

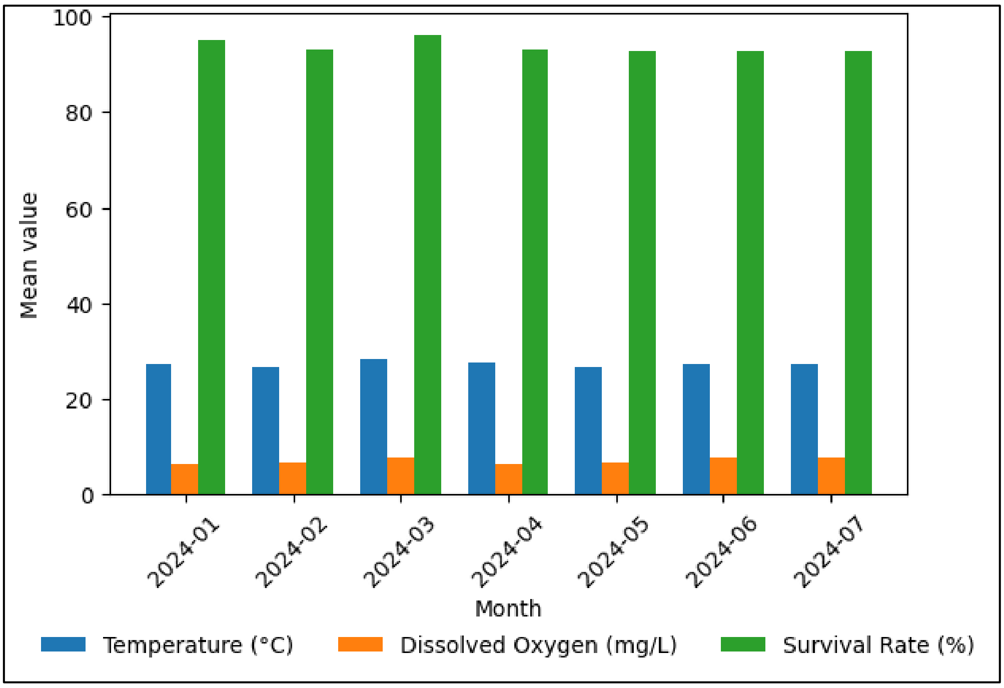

Figure 4. Monthly variation in water stressors and fish performance indicators.

The monthly patterns shown in the figure 4 help to underline that turbidity change was not insignificant: the peak in turbidity in April was the most unsuccessful combination of decreased survival and decreased growth in relation to the previous month. This trend is beneficial to the negative influence of turbidity in the multivariate models and gives time supports to stress characterization by episode.

3.5 Stress episode structure and persistence of unfavorable conditions

Stress episodes were defined as consecutive periods of threshold surpassing of the main stressors (temperature > 28C, dissolved oxygen < 7mg/L, pH < 7.5, turbidity> 3.5 NTU). This methodology can involve sustained exposure states which are more biologically significant than solitary hourly spikes as given in the table 4.

Table 4. Stress episode summary based on threshold exceedances.

Stress definition	Episodes	Total hours	Mean duration (h)	Max duration (h)
Temperature > 28°C	1	705	705.0	705
Dissolved Oxygen < 7 mg/L	2	2,843	1421.5	1,438
pH < 7.5	1	680	680.0	680
Turbidity > 3.5 NTU	2	1,525	762.5	795

The episode format does shown in the Figure 5 that exposure was characterized by long regimes as opposed to repetitive short events. Below 7 mg/L dissolved oxygen was present almost two-thirds of the hours in two extended episodes which demonstrate the presence of permanent oxygen limitation compared to the selected ecological reference point. There was also turbidity excess, which consisted of persistent episodes, just like the monthly peak in April.

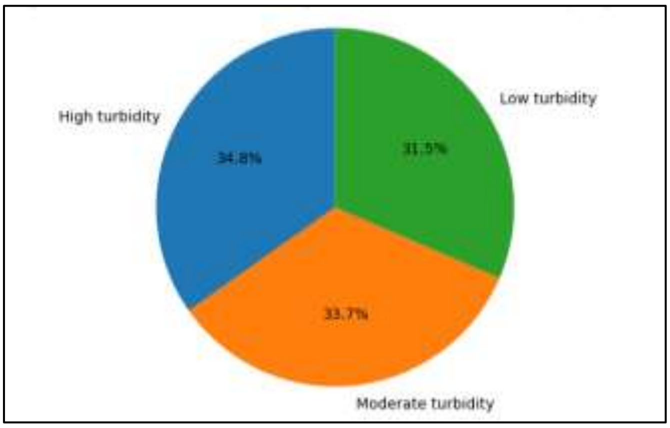

Figure 5. Proportion of monitoring time under different turbidity regimes

The episode times suggest that stressors were not independent of each other but overlapped in the time windows, which is the reason behind the interaction and joint-stressor evaluation in the multivariate models. The continued existence of exceedance conditions justifies the interpretations of the results as a cumulative exposure effect instead of an extreme.

3.6 Interrelationships among stressors and outcomes

Co-variation was measured in the environmental drivers and responses of the biological response by correlation analysis. These relations are meant to do two functions: they can be used as an ecological interpretation (e.g. temperatureoxygen coupling), and can be used as a guide to model specification (e.g. by identifying variables that are likely to interact or confound one another) as given in the Table 5.

Table 5. Pearson correlation matrix for key stressors and outcomes.

	Weight	Survival	Disease	Temp	DO	pH	Turbidity
Weight	1.00	0.71	0.13	0.53	0.01	-0.10	-0.44
Survival	0.71	1.00	0.45	0.67	0.31	0.40	-0.50
Disease	0.13	0.45	1.00	0.07	-0.41	0.28	-0.02
Temp	0.53	0.67	0.07	1.00	0.55	0.66	0.17
DO	0.01	0.31	-0.41	0.55	1.00	0.30	-0.12
pH	-0.10	0.40	0.28	0.66	0.30	1.00	0.43
Turbidity	-0.44	-0.50	-0.02	0.17	-0.12	0.43	1.00

The correlations bring out three patterns. To begin with, there was a positive correlation between temperature and survival as well as weight in the studied range which agrees with the fact that the closer thermal conditions are to an operational optimum, the better the growth conditions. Second, the turbidity exhibited the most negative correlations with weight and survival, which suggests suspended solids as the always negative stressful factor. Third, there was a distinct negative relationship between dissolved oxygen and the number of diseases, implying that the less oxygen the more disease burden or susceptibility.

3.7 Multivariate stressor–response modeling aligned with rolling exposure history

In order to fit the exposure-history format of the methodology, models were developed on 24 hour rolling averages of temperature, dissolved oxygen, pH and turbidity where predictors were standardized and time was modeled as an hourly trend term. This specification approximates the relationship between cumulative exposure in the near future and growth, survival and disease burden as given in the Table 6.

Table 6. Multivariate models using 24-hour rolling means (standardized predictors).

Outcome	Predictor (24h rolling)	Effect estimate	Interpretation metric	p-value
Fish Weight (g)	Temperature	+13.07	Δ grams per 1 SD ↑ temp	<0.001
Fish Weight (g)	Dissolved Oxygen	−6.95	Δ grams per 1 SD ↑ DO	<0.001
Fish Weight (g)	pH	−5.50	Δ grams per 1 SD ↑ pH	<0.001
Fish Weight (g)	Turbidity	−5.57	Δ grams per 1 SD ↑ turbidity	<0.001
Fish Weight (g)	Time (hours)	+1.81	Δ grams per study progression	<0.001
Survival (%)	Temperature	+0.44	Δ % points per 1 SD ↑ temp	<0.001
Survival (%)	Dissolved Oxygen	+0.26	Δ % points per 1 SD ↑ DO	<0.001
Survival (%)	pH	+0.60	Δ % points per 1 SD ↑ pH	<0.001
Survival (%)	Turbidity	−0.61	Δ % points per 1 SD ↑ turbidity	<0.001
Survival (%)	Time (hours)	−0.71	Δ % points per study progression	<0.001

The multivariate models validate the fact that turbidity had a strong negative influence on growth and survival despite other stressors and time. Within the observed temperature range, temperature had growth and survival relationships, a performance advantage in the warmer climate in this cultured system. The dissolved oxygen was found to enhance survival but negatively correlated with weight in the joint model, which was in line with the regime structure of the dataset (high oxygen being associated with certain time windows and management states as opposed to pure physiological monotonic effects). To establish the health and biodiversity aspects of the methodology, two further analyses were performed (i) a disease count model, based on a negative binomial framework and (ii) an ecologically-sound biodiversity pressure proxy (Biodiversity Stressor Index; BSI) based on the intensity of a threshold exceedance across stressors.

4. DISCUSSION

The water quality stressors have heavy and persistent effects on fish physiological performance in cultivated aquatic environments. The changes in temperature, dissolved oxygen and turbidity proved to organize growth, survival, and disease incidence throughout the period of the monitoring study and the sensitivity of fish to environmental factors. The results are in line with larger evidence that fish physiology is highly dynamic to water quality gradients, and it has implications on energy distribution and fitness (Tumwesigye et al., 2022). Temperature was a major driver of growth and existence in the system under observation, and a high temperature facilitated a better performance in the observed range. An analogous effect of the temperature on growth and muscle structure has been observed in young tilapia that had to be

subjected to a stress environment that is realistic and is influenced by the metabolic significance of thermal regimes (Zhang et al., 2024).
The assessed stressors exhibited the largest negative correlation with fish growth and fish survival, with turbidity being the most consistent. The results of this study indicate that the increased turbidity was lasting and chronic, and not a singular event. Empirical and meta-analytical data show that turbidity hinders the movement of fish and their foraging performance and disturbs behavioral patterns, which limits energy consumption and growth capacity (Rodrigues et al., 2023). Behavioral analyses also show that turbidity alters risk-taking and feeding behavioral choices in Nile tilapia, with the potential to expose it to ecological stress despite physiological factors seeming to be satisfactory (Wing et al., 2021). The negative impacts of turbidity in the current experiment are thus presumably a result of a compound of physiological stress coupled with behavioral limitation, which supports the fact that turbidity is a key determinant of performance reduction in the cultured and natural ecosystems.
Exposure history and time dynamics were found to strongly organize disease occurrence in the monitored system which allowed the use of disease counts as integrative measures of sublethal stress. The same trends have been reported in fish living in agro-contaminated waters in which exposure to contaminants results in bioaccumulation, oxidative stress, and neurotoxicity undermining immune systems (Rossi et al., 2020). The current findings indicate that despite low mortality, long-term water quality stress may be produced in the form of susceptibility to disease. It highlights the significance of sustained surveillance strategies that can help identify the warning signs early enough before it is too late and the effects have been severely felt on the population levels.
Even though there were no measurements of direct biodiversity measures, the stressor-based habitat suitability index does give some insight into the possible threat of biodiversity loss related to long-term water quality loss. A prolonged high turbidity and low oxygen levels may reduce the suitability of the habitat to sensitive taxa resulting in changes in the composition of the community with time. These processes will add to the general trends of freshwater biodiversity loss observed in a variety of regions (Reis et al., 2016). The existing literature on diet studies also shows that turbidity slows down the feeding efficiency in early life stages of fish, which may influence the recruitment success and long-term population stability (Trochime et al., 2022). The patterns of biodiversity stress, which are concluded in this paper, are thus consistent with the known ecological mechanisms of environmental degradation, which relate degraded water quality to the decreased ecosystem resilience.
The findings also point to the necessity to consider several stressors at the same time and not individually. There was also a high degree of temporal coupling between temperature, dissolved oxygen and turbidity which resulted in combined exposure regimes that modulated physiological and ecological responses. This observation is in line with the conceptual frameworks, which stress the cumulative and interactive effects of stressors over time and space (Segurado et al., 2021). Changes in catchment processes associated with land-use have been reported to affect the input of sediments and nutrients, which increases turbidity and oxygen stress to downstream water bodies (Tahiru et al., 2020). The extended stress events that were experienced in this study might thus be indicators of larger landscape-wide stressors as opposed to localized management problems on their own.
The management implications are that, as far as management is concerned the results reveal that turbidity and oxygen should be maintained at desirable levels, to keep the fish healthy and productive. The importance of effective water quality management practices including real-time monitoring and adaptive interventions is increasingly being considered an important part of sustainable aquaculture (Yusoff et al., 2024). High-frequency IoT-based method applied in the current research indicates the ease with which timely decision-making may be facilitated based on continuous data flows which allow managers to predict stress-induced events and alleviate their effects before productivity decreases or diseases break out.
The relationships between water quality stressors, fish physiology, and inferred biodiversity risk observed can be added to the increasing amount of evidence of a relationship between environmental degradation and ecosystem-level effects. There are several anthropogenic forces that are simultaneously taking their toll on biodiversity in aquatic environments on the global scale. To enhance the cause-and-effect relationship and enhance ecosystem-based management strategies, future studies should combine direct biodiversity measures with high-resolution physiological patterns with direct biodiversity measurements. These integrative strategies are necessary in dealing with the current conservation issues in freshwater ecosystems that are experiencing ever-growing environmental change.

5. CONCLUSION

An integrated evaluation of the effect of the water pollution stressors on fish physiology and aquatic biodiversity risk in a cultured tilapia system by time-series monitoring at high-resolution. The results indicate that differences in essential water quality parameters, especially temperature, dissolved oxygen, and turbidity are critical determinants of growth performance, survival and occurrence of diseases. Turbidity was the most consistent and stable of these stressors, and it had a negative influence on the physiological performance and suitability of a habitat. The combination of sustained monitoring based on IoT with analysis of stressor-response underlines the significance of time resolution in the dynamics of chronic exposure that are neglected in snapshot analysis. Despite higher temperature and oxygen favoring better growth and survival of the observed range, extended deviations of natural-like conditions show that there are possible ecological trade-offs especially to biodiversity conservation. This study demonstrates the significance of preventive management of water quality in aquaculture systems by associating the level of environmental variability with biological performance. The stressor-based biodiversity measure is also a good example of how cultured systems can be good sentinels of the risks of the entire aquatic ecosystem.

REFERENCES

1. Abdel-Tawwab, M., & Wafeek, M. (2017). Fluctuations in water temperature affected waterborne cadmium toxicity: hematology, anaerobic glucose pathway, and oxidative stress status of Nile tilapia, Oreochromis niloticus (L.). *Aquaculture*, *477*, 106-111.
2. Abdel-Tawwab, M., Monier, M. N., Hoseinifar, S. H., & Faggio, C. (2019). Fish response to hypoxia stress: growth, physiological, and immunological biomarkers. *Fish physiology and biochemistry*, *45*(3), 997-1013.
3. Albert, J. S., Destouni, G., Duke-Sylvester, S. M., Magurran, A. E., Oberdorff, T., Reis, R. E., ... & Ripple, W. J. (2021). Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio*, *50*(1), 85-94.
4. Bojarski, B., & Witeska, M. (2020). Blood biomarkers of herbicide, insecticide, and fungicide toxicity to fish—a review. *Environmental Science and Pollution Research*, *27*(16), 19236-19250.
5. Cumming, H., & Herbert, N. A. (2016). Gill structural change in response to turbidity has no effect on the oxygen uptake of a juvenile sparid fish. *Conservation Physiology*, *4*(1), cow033.
6. Dumlao, J. (2024). *IoT monitoring of water quality and tilapia* (Version 1.0) [Dataset]. Kaggle. https://www.kaggle.com/datasets/jocelyndumlao/iot-monitoring-of-water-quality-and-tilapia
7. Figueiredo, B. R., Calvo, C., López-Rodríguez, A., Mormul, R. P., Teixeira-de Mello, F., Benedito, E., & Meerhoff, M. (2019). Short-term interactive effects of experimental heat waves and turbidity pulses on the foraging success of a subtropical invertivorous fish. *Water*, *11*(10), 2109.
8. Figueiredo, B. R., Mormul, R. P., Chapman, B. B., Lolis, L. A., Fiori, L. F., & Benedito, E. (2016). Turbidity amplifies the non-lethal effects of predation and affects the foraging success of characid fish shoals. *Freshwater Biology*, *61*(3), 293-300.
9. Formicki, G., Goc, Z., Bojarski, B., & Witeska, M. (2025). Oxidative stress and neurotoxicity biomarkers in fish toxicology. *Antioxidants*, *14*(8), 939.
10. Goncalves, A. M., Rocha, C. P., Marques, J. C., & Gonçalves, F. J. (2021). Enzymes as useful biomarkers to assess the response of freshwater communities to pesticide exposure–A review. *Ecological Indicators*, *122*, 107303.
11. Grădinariu, L., Crețu, M., Vizireanu, C., & Dediu, L. (2025). Oxidative Stress Biomarkers in Fish Exposed to Environmental Concentrations of Pharmaceutical Pollutants: A Review. *Biology*, *14*(5), 472.
12. Lomartire, S., Marques, J. C., & Gonçalves, A. M. (2021). Biomarkers based tools to assess environmental and chemical stressors in aquatic systems. *Ecological Indicators*, *122*, 107207.
13. Mallik, A., Xavier, K. M., Naidu, B. C., & Nayak, B. B. (2021). Ecotoxicological and physiological risks of microplastics on fish and their possible mitigation measures. *Science of the Total Environment*, *779*, 146433.
14. Martínez-Megías, C., & Rico, A. (2022). Biodiversity impacts by multiple anthropogenic stressors in Mediterranean coastal wetlands. *Science of the Total Environment*, *818*, 151712.
15. Mramba, R. P., & Kahindi, E. J. (2023). Pond water quality and its relation to fish yield and disease occurrence in small-scale aquaculture in arid areas. *Heliyon*, *9*(6).
16. Oliveira, J., Oliva-Teles, A., & Couto, A. (2024). Tracking Biomarkers for the Health and Welfare of Aquaculture Fish. *Fishes (MDPI AG)*, *9*(7).
17. Orso, G., Imperatore, R., Coccia, E., Rinaldi, G., Cicchella, D., & Paolucci, M. (2023). A deep survey of fish health for the recognition of useful biomarkers to monitor water pollution. *Environments*, *10*(12), 219.
18. Reis, R. E., Albert, J. S., Di Dario, F., Mincarone, M. M., Petry, P., & Rocha, L. A. (2016). Fish biodiversity and conservation in South America. *Journal of fish biology*, *89*(1), 12-47.
19. Rodrigues, J. N., Ortega, J. C., Petsch, D. K., Padial, A. A., Moi, D. A., & Figueiredo, B. R. (2023). A meta-analytical review of turbidity effects on fish mobility. *Reviews in Fish Biology and Fisheries*, *33*(4), 1113-1127.
20. Rossi, A. S., Fantón, N., Michlig, M. P., Repetti, M. R., & Cazenave, J. (2020). Fish inhabiting rice fields: Bioaccumulation, oxidative stress and neurotoxic effects after pesticides application. *Ecological Indicators*, *113*, 106186.
21. Segurado, P., Ferreira, T., & Branco, P. (2021). Assessing the effects of multiple stressors on aquatic systems across temporal and spatial scales: From measurement to management. *Water*, *13*(24), 3549.
22. Tahiru, A. A., Doke, D. A., & Baatuuwie, B. N. (2020). Effect of land use and land cover changes on water quality in the Nawuni Catchment of the White Volta Basin, Northern Region, Ghana. *Applied Water Science*, *10*(8), 1-14.
23. Tumwesigye, Z., Tumwesigye, W., Opio, F., Kemigabo, C., & Mujuni, B. (2022). The effect of water quality on aquaculture productivity in Ibanda District, Uganda. *Aquaculture Journal*, *2*(1), 23-36.
24. Wing, J. D., Champneys, T. S., & Ioannou, C. C. (2021). The impact of turbidity on foraging and risk taking in the invasive Nile tilapia (Oreochromis niloticus) and a threatened native cichlid (Oreochromis amphimelas). *Behavioral Ecology and Sociobiology*, *75*(3), 49.
25. Yusoff, F. M., Umi, W. A., Ramli, N. M., & Harun, R. (2024). Water quality management in aquaculture. *Cambridge Prisms: Water*, *2*, e8.
26. Zhang, Q., Xie, Y., Qin, R., Huang, E., Zhang, Z., Zhou, J., ... & Tong, T. (2024). Effects of cadmium on the growth, muscle composition, digestion, gene expression of antioxidant and lipid metabolism in juvenile tilapia (Oreochromis niloticus). *Frontiers in Marine Science*, *11*, 1443484.