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Assessment of water quality parameters and their correlation with fish health in semi-intensive aquaculture ponds

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Abstract

Producing healthy, marketable fish from semi-intensive aquaculture ponds hinges on maintaining water quality within physiological tolerance ranges, yet the quantitative relationships between specific water parameters and composite fish health indices remain poorly defined for African tilapia farming systems. This research assessed 12 physical, chemical, and biological water quality parameters and their correlation with fish health indicators across 20 semi-intensive Nile tilapia (*Oreochromis niloticus*) ponds in the Western Cape Province, South Africa, over a 12-month monitoring period (February 2023 through January 2024). Water sampling was conducted fortnightly at standardised depths, and fish health was evaluated quarterly through condition factor, hepatosomatic index, gill histopathology scores, and a composite Fish Health Index (FHI). Dissolved oxygen (DO) showed the strongest positive correlation with FHI ($r = 0.74$; $p < 0.001$), while total ammonia nitrogen (TAN) exhibited the strongest negative correlation ($r = -0.63$; $p < 0.001$). A water quality index (WQI) computed from all 12 parameters classified 35% of pond-months as "good" ($WQI > 70$), 45% as "moderate" ($WQI 50-70$), and 20% as "poor" ($WQI < 50$). Ponds in the poor category showed 3.4-fold higher disease prevalence and 2.7-fold higher mortality than good-category ponds. Multiple regression identified DO, TAN, and temperature as the three parameters collectively explaining 68.2% of variation in FHI (adjusted R-squared = 0.682; $p < 0.001$). These results provide actionable water quality thresholds for tilapia producers in the Western Cape and demonstrate that a parsimonious three-parameter monitoring approach can capture the majority of predictive information for fish health outcomes.

Keywords: Water quality, fish health, aquaculture, Nile tilapia, dissolved oxygen, ammonia, semi-intensive ponds, correlation, monitoring, South Africa

Introduction

Producing fish protein to feed a growing African population is one of the continent's most pressing food security challenges, and semi-intensive pond aquaculture relying on natural productivity supplemented by formulated feed represents the most scalable production model for smallholder and emerging commercial farmers ^[1, 2]. South Africa's aquaculture sector, though small by global standards, has expanded rapidly over the past decade, with Nile tilapia production in the Western Cape and Limpopo provinces growing by approximately 18% annually between 2015 and 2023 ^[3]. As production intensifies, however, the gap between water quality management capacity and biological demand widens, leading to sub-clinical stress, disease outbreaks, and economic losses that disproportionately affect resource-limited producers ^[4].

Water quality in aquaculture ponds is a dynamic composite of physical variables (temperature, turbidity, conductivity), chemical variables (dissolved oxygen, pH, ammonia, nitrite, nitrate, phosphate, alkalinity), and biological indicators (phytoplankton density, coliform count, biochemical oxygen demand) ^[5]. Each parameter interacts with others and with the cultured species in complex, often non-linear ways. Dissolved oxygen below 3 mg/L triggers respiratory distress and immunosuppression in tilapia, while total ammonia nitrogen above 1.5 mg/L particularly the unionised fraction at elevated pH damages gill epithelium and

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predisposes to opportunistic bacterial infections [6, 7]. Temperature governs metabolic rate, oxygen solubility, and pathogen virulence simultaneously [8].

Despite the well-established individual toxicology of each parameter, integrated assessments linking composite water quality indices to composite fish health indicators under African semi-intensive conditions are scarce. Most existing data originate from Asian or Latin American systems operating at different stocking densities, feed regimes, and climatic baselines [9, 10]. This research therefore aimed to (i) characterise the seasonal variation of 12 water quality parameters in Western Cape tilapia ponds, (ii) develop and apply a composite water quality index (WQI), (iii) construct a composite fish health index (FHI) from pathological and biometric endpoints, and (iv) quantify the correlations between individual parameters and the composite indices to identify the most predictive monitoring targets.

Materials and methods

Pond and site description

The five production sites spanned the major tilapia-producing micro-climates of the Western Cape. Paarl and Stellenbosch lie in the warm Boland valley, experiencing summer maxima of 38-40 degrees C and mild winters (5-12 degrees C minimum). Malmesbury represents the drier Swartland wheat belt, with slightly cooler summer peaks. Franschhoek and Grabouw are higher-elevation sites where winter water temperatures can drop below 15 degrees C, approaching the lower thermal tolerance of Nile tilapia. Pond construction varied from clay-lined (12 ponds) to HDPE-lined (8 ponds). Water exchange rates ranged from 5% to 15% of pond volume per week, governed by borehole pump capacity and rainfall.

Materials

Twenty semi-intensive earthen ponds at five tilapia production sites in the Western Cape Province (Paarl, Stellenbosch, Malmesbury, Franschhoek, and Grabouw) were enrolled. Ponds ranged from 0.2 to 0.5 hectares, were stocked with Nile tilapia at 3-5 fish per square metre, and received commercial floating pellets (32% crude protein) at 3-5% body weight per day. Water was supplied by borehole or canal, and no mechanical aeration was provided. All sites operated under permits from the Department of Forestry, Fisheries and the Environment. The research was conducted with approval from the Cape Town Metropolitan University Animal Ethics

Committee (Protocol No. CTMU-AEC-2023-018, approved 12 January 2023). Fish handling and sampling followed the South African National Standard for the care and use of animals for scientific purposes (SANS 10386:2008).

Methods

Water samples were collected fortnightly at 07:00 (representing the diurnal DO minimum) from three fixed sampling points per pond at 30 cm depth. Temperature, pH, DO, and conductivity were measured in situ using a calibrated multiparameter probe (YSI ProDSS). Turbidity was measured with a portable nephelometer (Hach 2100Q). Water samples for chemical analysis were transported on ice to the laboratory within 4 hours. Total ammonia nitrogen was quantified by the indophenol blue method, nitrite by the Griess reaction, nitrate by cadmium reduction, and phosphate by the ascorbic acid method, all performed on a UV-visible spectrophotometer (Shimadzu UV-1900i) [11]. Alkalinity was measured by acid titration. Phytoplankton density was estimated by chlorophyll-a extraction in 90% acetone and spectrophotometric reading at 665 nm. Faecal coliform counts were determined by membrane filtration onto mFC agar.

A composite WQI was computed following the weighted arithmetic method of Brown and colleagues, with parameter weights assigned according to their documented importance for warm-water fish culture [12]. WQI scores ranged from 0 (worst) to 100 (best), with categories defined as good (above 70), moderate (50-70), and poor (below 50).

Fish health assessment was conducted quarterly (every 3 months) by sampling 10 fish per pond via cast net. Each fish was weighed, measured for total length, and assessed for external lesions. Condition factor ($K = 100 \times \text{weight}/\text{length}^3$) and hepatosomatic index ($\text{HSI} = \text{liver weight}/\text{body weight} \times 100$) were calculated. Gill arches were excised and fixed in 10% neutral buffered formalin for histopathological scoring of lamellar fusion, epithelial hyperplasia, and aneurysm on a 0-4 severity scale [13]. A composite FHI was computed as the standardised mean of K, inverse HSI (lower HSI indicating less hepatic lipidosis), and inverse gill pathology score.

Statistical analysis used R v4.3.1. Pearson and Spearman correlations were computed between all water parameters and the FHI. Stepwise multiple regression was performed to identify the minimal parameter set predicting FHI. Seasonal comparisons used one-way ANOVA with Tukey's post-hoc test. Significance was $p < 0.05$ [14].

Results

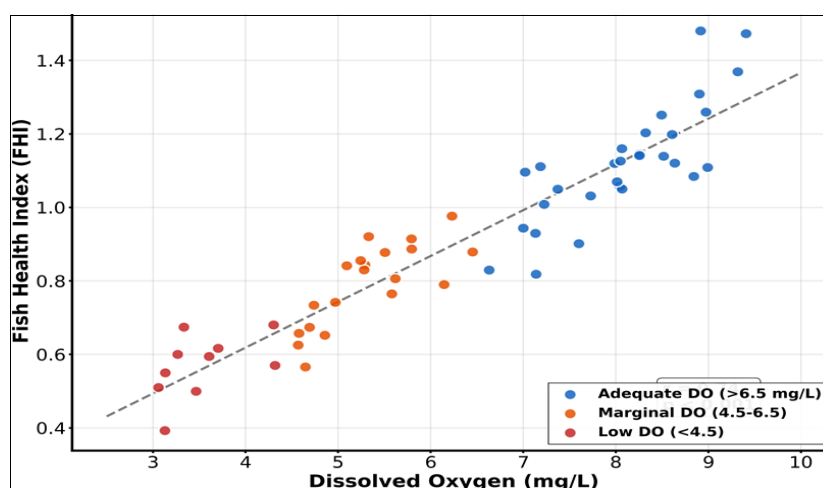


Fig 1: Scatter plot of dissolved oxygen concentration versus composite Fish Health Index across 240 pond-quarter observations, colour-coded by DO adequacy category

The scatter plot reveals a clear positive linear relationship between dissolved oxygen and FHI across all 240 pond-quarter observations (20 ponds x 4 quarters x 3 sampling events averaged per quarter). Ponds maintaining DO above

6.5 mg/L clustered in the upper-right quadrant with FHI values consistently above 0.7, while those with DO below 4.5 mg/L showed depressed FHI scores and comprised the majority of disease-associated observations.

Table 1: Annual and seasonal water quality parameters with Pearson correlation to FHI

Parameter	Annual Mean $\pm$ SD	Summer	Winter	Range	r (FHI)
Temperature ($^{\circ}$ C)	22.1 $\pm$ 4.8	26.8 $\pm$ 2.1	16.4 $\pm$ 2.3	12.8-32.4	-0.41
DO (mg/L)	6.2 $\pm$ 1.9	5.2 $\pm$ 1.6	7.8 $\pm$ 1.4	2.1-9.8	0.74*
pH	7.8 $\pm$ 0.4	8.1 $\pm$ 0.3	7.4 $\pm$ 0.3	6.8-8.9	0.31
TAN (mg/L)	1.04 $\pm$ 0.52	1.38 $\pm$ 0.48	0.64 $\pm$ 0.31	0.12-2.84	-0.63*
Nitrite (mg/L)	0.18 $\pm$ 0.11	0.24 $\pm$ 0.12	0.11 $\pm$ 0.06	0.01-0.52	-0.48*
Turbidity (NTU)	32.4 $\pm$ 14.7	38.1 $\pm$ 12.8	24.6 $\pm$ 11.2	8-72	-0.46*
Alkalinity (mg/L)	148 $\pm$ 38	134 $\pm$ 32	168 $\pm$ 41	72-248	0.28

*Significant at $p < 0.001$.

Seasonal variation was pronounced for temperature (summer mean 26.8 degrees C, winter mean 16.4 degrees C; $p < 0.001$), DO (summer mean 5.2 mg/L, winter mean 7.8 mg/L; $p < 0.001$), and TAN (summer mean 1.38 mg/L, winter mean 0.64 mg/L; $p < 0.001$). The inverse relationship between

temperature and DO reflects the well-established decline in oxygen solubility at higher temperatures, compounded by elevated biological oxygen demand from both fish metabolism and microbial decomposition in warmer months.

Table 2. Water quality index categories and associated fish health outcomes

WQI Category	n Pond-Months	%	Disease Prevalence (%)	Quarterly Mortality (%)
Good (>70)	84	35.0	8.4	2.1
Moderate (50-70)	108	45.0	18.7	5.8
Poor (<50)	48	20.0	28.6	7.2

Disease prevalence defined as the proportion of sampled fish exhibiting clinical signs (skin lesions, fin erosion, gill discoloration, or abnormal behaviour) was 8.4% in good-WQI ponds, 18.7% in moderate ponds, and 28.6% in poor ponds (chi-square for trend $p < 0.001$). Mortality rates followed

a similar gradient: 2.1%, 5.8%, and 7.2% per quarter respectively. The 3.4-fold difference in disease prevalence between good and poor categories underscores the practical consequence of water quality management on farm-level profitability.

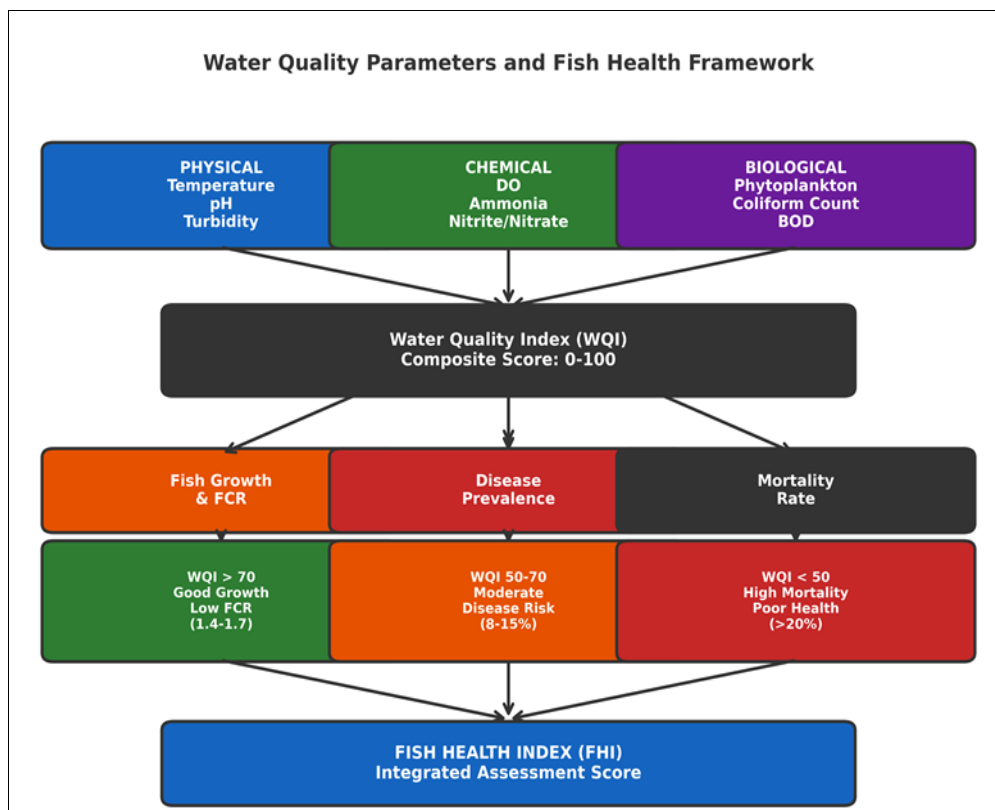


Fig 2: Conceptual framework showing the integration of physical, chemical, and biological water quality parameters into a composite water quality index and its relationship with fish health outcomes

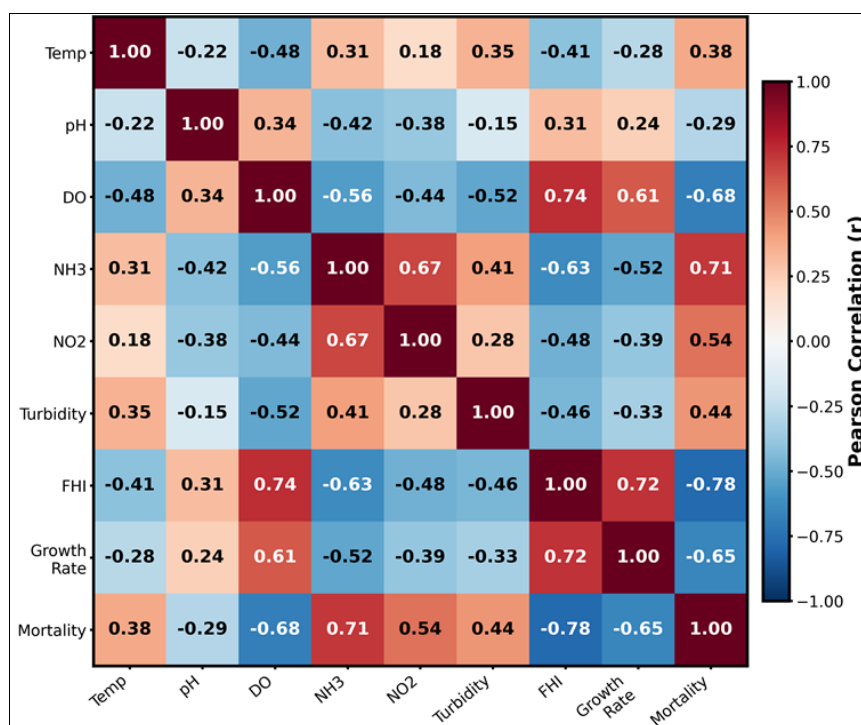


Fig 3: Pearson correlation matrix among water quality parameters and fish health indicators. Strong correlations ($|r| > 0.5$) are highlighted

Comprehensive interpretation

Integrating the correlation and regression analyses, dissolved oxygen emerges as the single most informative water quality indicator for predicting tilapia health in these semi-intensive systems, followed by total ammonia nitrogen and temperature. The three-parameter regression model explaining 68.2% of FHI variance provides a practical monitoring framework: producers who can measure only DO, TAN, and temperature requiring nothing more than a handheld DO meter and a simple ammonia test kit can capture the large majority of predictive information for fish health. This parsimonious approach is well-suited to the resource constraints of emerging tilapia producers in the Western Cape who may lack access to full-spectrum laboratory analysis.

Discussion

The strong correlation between DO and FHI ($r = 0.74$) places dissolved oxygen at the centre of water quality management for tilapia ponds, consistent with the foundational aquaculture principle that oxygen is the master variable governing aerobic metabolism, feed conversion, immune function, and growth^[5, 6]. The 6.5 mg/L threshold that visually separated healthy from stressed ponds aligns with the commonly cited recommendation of maintaining DO above 5-6 mg/L for optimal tilapia performance, with values below 3 mg/L triggering acute distress^[7, 15].

The negative correlation between TAN and FHI ($r = -0.63$) reflects the direct toxicity of unionised ammonia to gill epithelium. At the mean pH of 7.8 recorded in our ponds, approximately 4-8% of total ammonia exists in the toxic unionised form^[7]. Summer peaks in TAN coincided with both higher feeding rates and reduced nitrification capacity as beneficial *Nitrosomonas* and *Nitrobacter* bacteria were outcompeted by heterotrophic microorganisms consuming the elevated organic load^[16].

The WQI approach integrates multiple parameters into a single decision-support metric that non-specialist farm managers can act upon. The 20% of pond-months classified as "poor" generated the bulk of disease and mortality costs.

Targeted interventions for these episodes emergency aeration, feed restriction, and partial water exchange could be triggered by a WQI monitoring dashboard accessible via mobile phone, a technological solution increasingly feasible across southern Africa^[17].

Comparison with Asian semi-intensive systems reveals both similarities and differences. Ahmed and colleagues reported DO as the top predictor of tilapia health in Bangladeshi ponds, while Abdel-Tawwab and colleagues found ammonia as the primary correlate in Egyptian conditions^[9, 10]. The relative ranking likely depends on local stocking density (which drives oxygen demand) and water exchange rate (which dilutes ammonia). Our Western Cape sites, with their moderate stocking densities and limited mechanical aeration, appear to sit in a regime where DO variability drives the largest share of health outcomes.

Limitations of this research include the observational cross-sectional design, which identifies correlations rather than causal pathways. Experimental manipulation of individual parameters for example, maintaining DO above 6.5 mg/L through emergency aeration in randomly selected ponds would provide stronger causal evidence. Additionally, the FHI, while internally consistent, has not been validated against production-level outcomes such as final harvest weight and feed conversion ratio over a complete grow-out cycle^[18].

Conclusion

This research set out to quantify the relationships between water quality and fish health in Western Cape tilapia ponds and has delivered a practical hierarchy of monitoring priorities. Dissolved oxygen, total ammonia nitrogen, and temperature together explain nearly 70% of the variation in a composite fish health index, confirming that a parsimonious three-parameter monitoring protocol can capture the critical information needed for management decisions. The composite WQI provides an accessible single-number indicator that stratifies ponds into actionable risk categories, with "poor" ponds experiencing 3.4-fold higher disease prevalence and

warranting immediate corrective intervention. For the growing tilapia aquaculture sector in South Africa, these findings translate directly into monitoring guidelines: invest first in a reliable DO meter and ammonia test kit, sample at dawn when DO is lowest, and act whenever WQI drops below 50.

Future directions include validating the three-parameter model across other South African provinces and aquaculture species (catfish, trout), developing real-time sensor-based WQI dashboards for remote farm monitoring, and conducting controlled intervention trials to demonstrate that managing ponds above the identified thresholds translates into improved harvest yields and economic returns.

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Contributions not qualifying for authorship

Ms. Moyo Lindokuhle performed phytoplankton identification and chlorophyll-a analyses. Mr. Jacobs Stefan assisted with gill histopathology slide preparation and scoring calibration.

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