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REVIEW

Influence of Physico-Chemical and Microbiological Water-Quality Variables on Aquaculture Species: A Vaal River Case Study (Gauteng, South Africa)

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This review examines the influence of physico-chemical and microbiological water-quality variables on freshwater aquaculture in the Vaal river (Gauteng, South Africa). Available literature was examined to characterise key water-quality parameters, including total dissolved solids (TDS), electrical conductivity (EC), turbidity, nutrients, heavy metals, microplastics, dissolved oxygen (DO), pH and microbial indicators such as *Escherichia coli*. In particular, this study discusses the interactive effects and aquaculture response in the Vaal river, links microbial dynamics to aquaculture health outcomes, gives the mechanistic interpretation of physico-chemical-biological linkages. The results showed the high TDS concentration (~177 mg/L) in the main stream of the Vaal river system is a potential threat to the agricultural sector, as it could be impacting on crop and aquacultural production and indications on DO concentrations are usually relatively high (>60%). The concentrations of metals in the Vaal river are generally high, leading to frequent fish kills. Furthermore, the high TDS concentrations in the Vaal river evidently influence the turbidity of the water and the higher pH values (6.3-8.7) in the Vaal river can be ascribed to higher algal concentrations. The high concentrations in *E. coli* (240 counts/100 mL) and algal pigments (69 mg/L) constitute a high risk the aquaculture production in the Vaal river system. To address these challenges, the water quality problem must be evaluated and resolved by reconsidering new management strategies and implementing treatment technologies. The findings of this work will assist relevant authorities in choosing appropriate water quality monitoring parameters for aquaculture areas.

Keywords: Vaal river, Water quality, Physico-chemical parameters, Microbiological parameters, Aquaculture, South Africa.

INTRODUCTION

Aquaculture, the cultivation of aquatic organisms such as fish, crustaceans and molluscs, depends heavily on water quality. Key water quality parameters comprise physico-chemical characteristics such as temperature, pH, dissolved oxygen (DO), turbidity, electrical conductivity (EC), total dissolved solids (TDS), salinity, nutrients and *Escherichia coli*, together with microbiological factors such as pathogens, indicator bacteria and harmful algal bloom organisms [1,2]. Recent studies have emphasised the importance of water quality in aquaculture, as physical, chemical and biological parameters directly influence the health, growth and productivity of aquatic organisms [3]. Poor water quality adversely affects growth, survival, feed conversion efficiency and disease resistance, ultimately reducing the economic sustainability of aquaculture operations [3,4].

The Vaal river in Gauteng Province, South Africa, is a major freshwater resource that supports municipal, industrial, agricultural and ecological activities. Water quality has deteriorated over time due to the industrial effluents, mine drainage, municipal wastewater and agricultural return flows. Integrated Water Resource Management in South Africa examined the combined effects of pollution, industrial discharges and habitat modification on the ecological condition of the river [5]. Their findings confirm that these stressors interact synergistically, intensifying ecological degradation. The authors recommended integrated water resources management (IWRM), stricter pollution control measures and continuous ecological monitoring.

The Vaal river supports a diverse aquatic community. Common fish species include smallmouth and largemouth yellowfish, common and mirror carp and African sharptooth catfish (*Clarias gariepinus*) [6]. Other aquatic organisms include mudfish, grass carp, banded tilapia and aquatic macrophytes such as *Stuckenia pectinata* and water hyacinth. The black water snake has also been reported from the river system [6]. The persistence of *Stuckenia pectinata* in the Vaal river and a juvenile grass carp collected from the river [7].

Water pollution in the Vaal river originates from industrial effluents, acid mine drainage, fertiliser and pesticide runoff from agricultural land and untreated or partially treated municipal sewage [8]. These contaminants impair aquatic ecosystem functions and threaten aquatic biodiversity. Communities in rural and peri-urban areas that depend on the river for domestic water, fishing and sanitation are consequently exposed to increased health risks [9].

Evaluating the influence of these water-quality conditions on aquaculture is necessary to determine the suitability of the Vaal river for sustainable fish production [10-12]. This review compiles available information on the physico-chemical and microbiological characteristics of the Vaal River, examines their implications for freshwater aquaculture and discusses opportunities and constraints for aquaculture development within the river system. Particular attention is given to knowledge gaps that limit current understanding and to research and monitoring priorities required to support sustainable aquaculture in the region.

Water hyacinth and sampling sites located upstream and downstream of the Schoonspruit and Keokemoerspruit tributaries of the Vaal River, a major water resource for Gauteng, South Africa, were used to assess the response of water hyacinth to nutrient and heavy metal inputs from these important pollution sources [13].

METHODOLOGY

This review adopts an analytical framework that integrates water-quality drivers, aquaculture system responses, management strategies to examine the influence of physico-chemical and microbiological conditions on freshwater aquaculture. Water-quality variables were evaluated in relation to fish health, growth, survival, feed utilisation and disease occurrence, while management interventions are considered for their potential to reduce environmental stress and support sustainable aquaculture development in the Vaal river system.

Review protocol: This review followed the PRISMA 2020 Statement to provide a transparent and reproducible framework for identifying, screening and synthesising literature on water-quality dynamics and aquaculture responses in the Vaal River. The review protocol covered three areas: (i) physico-chemical and microbiological water-quality studies conducted within the Vaal river catchment, (ii) aquaculture studies examining the effects of water-quality variables on freshwater species in comparable freshwater systems and (iii) management strategies and mitigation measures relevant to aquaculture development.

A comprehensive literature search was performed using PubMed, ScienceDirect and Google Scholar, together with South African journal repositories. Gray literature was considered where relevant. Search strings combined Boolean operators with keywords such as “Vaal River”, “Water quality”, “Physico-chemical”, “Microbiological”, “Aquaculture”, “Freshwater fish farming South Africa” and “Microplastics freshwater”. Publications from 2000 to 2025 were considered and only peer-reviewed articles published in English were retained.

Study selection followed the four stages of the PRISMA framework *viz.* identification, screening, eligibility and inclusion. Retrieved records were imported into a reference management program, where duplicate entries were removed. Two reviewers independently screened titles and abstracts against predefined eligibility criteria. Full-text articles that satisfied the screening criteria were assessed for eligibility and the reasons for exclusion were documented.

Studies conducted within the Vaal river catchment (Gauteng Province) were considered when they reported quantitative physico-chemical or microbiological water-quality data. Aquaculture studies were considered if they investigated the influence of water-quality variables on freshwater fish species and reported findings applicable to conditions in the Vaal river. Marine aquaculture studies, non-empirical publications, articles lacking relevant water-quality information, duplicate records, inaccessible full-text articles and publications in languages other than English were excluded.

The methodological quality of each study was evaluated according to the clarity of research objectives, appropriateness of the study design, sample size and sampling strategy, validity and reliability of measurement methods, data analysis and completeness of reporting. Only studies that met moderate or high methodological quality standards were retained for evidence synthesis. The PRISMA-guided review process provided a systematic synthesis of the available evidence on physico-chemical and microbiological water-quality conditions and their implications for freshwater aquaculture in the Vaal river.

Data extraction and synthesis: For each study conducted in the Vaal River, data were extracted on the measured water-quality variables including TDS, EC, DO, nutrients, *E. coli* counts and the principal findings. From the aquaculture literature, information was compiled on the cultured species, together with the effects of water-quality variables on growth, survival, disease occurrence and feed conversion efficiency. The evidence was organised according to physico-chemical and microbiological parameters and its relevance to aquaculture in the Vaal river system was evaluated.

RESULTS AND DISCUSSION

Water quality drivers: This domain defines the major physico-chemical and microbiological factors governing water quality in the Vaal river and their relevance to aquaculture.

(i) Physico-chemical variables in the Vaal river: Core parameters include TDS, EC, turbidity, nutrients (N, P), heavy metals (Pb, Hg, Cd), microplastics, DO, pH. These variables are analysed in relation to ecosystem processes such as eutrophication and bioaccumulation. Several studies [14-16] have documented water-quality parameters in the Vaal river system that are relevant to aquaculture. Research in relation with changes in water quality and phytoplankton composition identified turbidity, conductivity, nutrient concentrations and temperature as the most significant environmental variables influencing algal abundance.

Analysis of the physico-chemical parameters measured in the Vaal river and guideline values recommended by the World Health Organisation (WHO), Food and Agriculture Organisation (FAO) and South African National Standards (SANS) reveals several issues of conformity and non-conformity. The measured TDS concentration (~177 mg/L) is well below the recommended guideline value of 500 mg/L, suggesting acceptable salinity conditions. In contrast, microbial contamination (~240 counts/100 mL) exceeds the WHO guideline of zero for drinking water, posing a potential public health risk. Algal pigment concentrations (~69 mg/L) are consistent with nutrient enrichment and possible eutrophication of the river system [16], conditions which may reduce DO availability and limit aquaculture productivity. Erasmus *et al*. [17] reported elevated concentrations of several elements suggesting that contaminant exposure may remain a concern even where conventional water-quality indicators, such as TDS, fall within acceptable limits. Microplastics were detected in both the water column (0.13-2.52 particles/m^3) and sediments (29.12-1,095.89 particles/kg), identifying an additional source of contamination not addressed in existing water-quality guidelines [18,19]. The sediment and tissue analyses of *C. gariepinus* collected from four sites along the Vaal river revealed the presence of 15 industrially derived metals [20], pointing to persistent contaminant accumulation which may compromise water quality and the long-term sustainability of aquaculture.

Physico-chemical variables in the Vaal river indicate considerable water quality stress from agricultural, industrial and urban activities. High TDS and EC reflect elevated dissolved salts and pollutants that disrupt aquatic life and limit water use, while increased turbidity reduces light penetration and carries contaminants like nutrients, heavy metals and microplastics [16]. Excess nitrogen and phosphorus drive eutrophication, causing algal blooms and lowering dissolved oxygen, which can lead to fish kills [20]. The accumulation of toxic heavy metals *viz*. Pb, Hg and Cd in biological organisms is associated with health risks and the ingestion of microplastics carrying other pollutants can cause adverse impacts. The slightly alkaline environment increases the impact of chemicals, thereby contributing to adverse effects on ecological systems.

(ii) Microbiological variables in the Vaal river: Microbial indicators include *E. coli*, algal biomass (chlorophyll), total coliform, *etc*. These variables indicate pathogen presence, faecal contamination and organic pollution load. A comparison of microbiological water quality results from the Vaal river with standards set by the WHO, FAO and SANS reveals severe non-compliance and significant health risks. Studies [20] show persistently high levels of heterotrophic bacteria, total and faecal coliforms, staphylococci and streptococci, with variations linked to seasonal flow and pollution inputs. A deep exploration of the spatial and temporal distribution of pollution indicator bacteria, particularly *E. coli* and other coliforms in the lower Vaal river, reported a need for regular monitoring and targeted interventions in high-risk arears. A study by Jordaan *et al.* [12] investigates the relationship between physico-chemical water quality parameters, such as temperature, pH, DO and nutrient concentrations and the presence of microbial communities, particularly bacteria and yeasts, in river systems in South Africa. The findings reveal the ecological effects of water pollution, characterised by changes in the microbial community structure and potential threats to human health. The study also advocates for routine monitoring of both chemical and biological parameters to better manage and protect freshwater resources. Recent reports [21,22] identified *E. coli* concentrations exceeding 40,000 CFU/100 mL downstream of the Vaal Barrage, far above the WHO and SANS guideline for drinking water and beyond the recommended limits for recreational and irrigation use. The FAO guidelines for aquaculture recommend low bacterial loads to minimise fish disease and microbial contamination. *E. coli* concentrations of this magnitude pose substantial risks to aquaculture productivity, food safety and public health. The close association between elevated bacterial counts and sew-age discharge identifies inadequate wastewater infrastructure as a major source of contamination, while seasonal runoff further increases microbial loading. The persistent occurrence of high *E. coli* concentrations across several sections of the Vaal river identifies microbial contamination as a critical challenge for aquaculture and reflects continuing deterioration of water quality.

(iii) Stressor interactions on the Vaal river: The framework explicitly accounts for interactions among water-quality variables. Elevated TDS increases turbidity and reduces light penetration, while high nutrient concentrations combined with favourable pH conditions promote algal blooms. Heavy metals increase toxic stress, particularly under low dissolved oxygen conditions. Water-quality characteristics of the Vaal river relevant to aquaculture include moderate to high TDS and electrical conductivity associated with salinisation, elevated nutrient concentrations, high turbidity and suspended solids, eutrophic conditions that favour algal blooms in several river sections and contamination by microplastics and heavy metals, shows the presence of both legacy and emerging pollutants [23]. Winter [23] also investigated two decades of nutrient loading in the Vaal river and reported persistent eutrophication driven by anthropogenic activities and inadequate wastewater management. Microbial contamination, represented by faecal indicator bacteria, total coliforms and heterotrophic bacterial counts, exhibits pronounced spatial and seasonal variability, with the highest concentrations occurring downstream of urban areas and wastewater discharge points [24,25]. Upstream effluent discharge, tributary inflows and hydrological fluctuations further influence water quality. These conditions reduce the suitability of the Vaal river as a reliable water source for aquaculture unless effective treatment and pollution control measures are implemented.

(iv) Pollution sources and climate change impacts: The multiple pollution sources adversely affect the physico-chemical and microbiological water quality of the Vaal river and its suitability for aquaculture. Effluent discharged from wastewater treatment plants often contains elevated concentrations of nutrients, microorganisms and other contaminants due to the inadequate treatment [12]. Industrial activities in the Gauteng region contribute heavy metals and a range of chemical pollutants to the river [12]. Agricultural runoff associated with fertiliser and pesticide application increases nutrient loading and sediment input [26]. Urban stormwater carries hydrocarbons, plastics and microbial contaminants into the river system. These pollution sources accelerate eutrophication, alter dissolved oxygen, pH, electrical conductivity and increase microbial contamination, reducing water quality for aquaculture [26].

Climate change exerts a substantial influence on the physico-chemical and microbiological characteristics of the Vaal river, affecting the water quality and aquaculture productivity. Changes in rainfall patterns coupled with rising air temperatures increase evaporation, reduce streamflow and intensify drought conditions in South Africa, altering the water availability and pollutant concentrations [27]. Altered hydrological conditions increase nutrient loading and eutrophication, creating favourable conditions for harmful algal blooms and depleted dissolved oxygen concentrations [28]. These changes modify water temperature, electrical conductivity and nutrient dynamics, adversely affecting fish health and production. The anthropogenic pollution from agriculture, industry and urban development intensifies these climate-driven impacts, increasing environmental stress on aquatic organisms and predisposing cultured fish to disease and reduced productivity [29].

Aquaculture system responses: This domain assesses the effects of water-quality conditions on the biological performance and aquaculture productivity.

(i) Aquaculture-relevant water-quality variables: This section summarizes the effects of physico-chemical and microbiological water-quality variables on freshwater aquaculture based on published literature. Temperature, dissolved oxygen (DO), pH, electrical conductivity, total dissolved solids (TDS) and turbidity are among the principal factors governing aquaculture performance [30]. Temperature regulates metabolic activity, feed intake, growth and oxygen demand, while elevated temperatures reduce growth, increase mortality and increase susceptibility to disease in cultured fish [30,31]. Dissolved oxygen is one of the primary limiting factors in aquaculture and concentrations below species-specific requirements, generally around 5 mg/L or higher for many cultured species, cause physiological stress, reduced growth and increased mortality. The pH influences physiological functions, the toxicity of unionised ammonia (NH_3) and the bioavailability of metals and other contaminants. Most cultured freshwater species tolerate a pH range of 6.5-9.0, whereas values outside this range impair metabolic function and may induce toxic effects [31].

High salinity or total dissolved solids (TDS) impose osmoregulatory stress on freshwater species that are not adapted to elevated ionic strength, resulting in poor feed conversion, reduced growth and higher susceptibility to disease [32]. High turbidity and suspended solids reduce water clarity, clog fish gills and filtration systems in intensive culture, impair feeding efficiency in visually feeding species, restrict light penetration, reduce primary productivity in ponds and often reflect upstream disturbances or runoff in flowing waters. According to Mariu *et al*. [30], temperature, pH, salinity and dissolved oxygen govern fish physiology, survival, growth, reproduction and distribution. Lindholm-Lehto *et al.* [31] evaluated water-quality monitoring in recirculating aquaculture systems (RAS) and considered standardised monitoring protocols and real-time assessment fundamental to fish health and efficient system operation.

High nutrient inputs, chemical contaminants and hydrological variability strongly influence water quality and fish health in aquaculture systems [33]. Excess nitrogen and phosphorus promote algal and cyanobacterial blooms, which consume dissolved oxygen during decomposition, release toxins harmful to fish, reduce light penetration and degrade aquatic habitats, increasing the likelihood of fish mortality. Lan *et al*. [33] reviewed the causes, monitoring technologies and treatment strategies for harmful algal blooms (HABs) in nutrient-rich marine environments and emphasised integrated management for reducing ecological and public health risks. Accumulation of ammonia, nitrite and nitrate impairs respiration, disrupts blood chemistry, suppresses growth and weakens immune function, while elevated ammonia concentrations and organic loading in flowing waters further compromise fish health [34]. Heavy metals such as cadmium, lead, mercury, arsenic, copper and zinc accumulate in fish tissues, causing organ damage, growth inhibition, reproductive disorders and food-safety concerns. Microplastics present additional risks through ingestion, adsorption of pollutants and interference with feeding behaviour, reducing fish welfare and product quality. Hydrological characteristics, such as flow stability, sediment transport, substrate composition and water renewal, determine site suitability for aquaculture, whereas runoff and wastewater discharges carrying poor-quality water can impose acute stress or mortality on cultured fish. The recommended ranges of key water quality parameters for aquaculture are summarized in Table-1 and serve as general reference values for maintaining optimal culture conditions and minimizing environmental stress.

(ii) Microbiological variables and aquaculture effects

(a) Faecal indicator bacteria and pathogenic organisms: High concentrations of faecal indicator bacteria, such as *E. coli* and total or faecal coliforms, in aquaculture source water are widely recognised as evidence of microbial contamination and inadequate sanitary conditions [35]. Their presence is commonly associated with pathogenic microorganisms such as *Salmonella*, *Vibrio*, *Aeromonas* and other enteric bacteria and reflects contamination from sewage discharges, agricultural runoff or inadequately treated wastewater. Rochelle-Newall *et al*. [35] examined the challenges of monitoring faecal indicator bacteria in aquatic ecosystems, identified critical knowledge gaps and proposed site-specific monitoring and management strategies. Elevated bacterial loads impair gill function and immune competence in fish, increasing susceptibility to opportunistic infections, reducing feed conversion efficiency, slowing growth and increasing mortality [36,37]. Faecal contamination poses a substantial public health risk through the transmission of zoonotic pathogens, particularly where fish are consumed raw or inadequately cooked. Integration of microbiological and molecular techniques strengthens water-quality surveillance by improving the detection and source attribution of faecal contamination. The use of selected microbial markers at appropriate monitoring sites provides diagnostic information to guide timely public health actions. Adoption of these biological markers facilitates timely intervention and supports effective management of aqua-culture systems and public health.

TABLE-1
FAVOURABLE RANGE OF WATER QUALITY PARAMETERS FOR AQUACULTURE

Parameter	Fresh water	Brackish water	Sea water
Colour	Clean water with greenish hue < 100	Clean water with greenish hue < 100	Clean water with greenish hue < 100
Clay turbidity (mg/L)	Colour units. < 30	Colour units. < 30	Colour units. < 30
Temperature (ºC)	–	–	–
Tropical climate	25-32	25-32	25-32
Temperate climate	10-12	10-12	10-12
pH	7.5-9.5	8.0-8.7	8.0-8.5
Solids (mg/L)			
Total solid	< 500	> 500	> 500
Suspended solid	30-200	25-200	25-200
Dissolved oxygen (mg/L)	5-10	5-10	5-10
Total dissolved free carbon dioxide (mg/L)	< 3	< 3	< 3
Hardness (mg/L)	30-180	> 50	> 50
Alkalinity (mg/L)	50-300	> 50	> 50
Chlorides (mg/L)	31-50	> 500	> 500
Salinity (pH)	< 0.5	10-25	> 30
Nitrogen (mg/L)	< 0.045	< 0.015	< 0.015
Ammonium (mg/L)	0.05	0.5	0.5

(b) Harmful algal blooms (cyanobacteria) and toxins: Cyanobacterial blooms release toxins such as microcystins and anatoxins that impair fish growth and reproduction, cause mortality and pose risks to human health through fish consumption [37]. Bloom development is promoted by elevated nutrient concentrations, warm temperatures and stagnant water, making nutrient-rich and eutrophic river sections particularly susceptible. Cyanobacterial toxins degrade water quality, reduce dissolved oxygen during bloom decomposition and disrupt aquaculture operations through reduced feed intake and lower productivity. Zhang *et al*. [38] reviewed the ecological and public health impacts of cyanobacterial blooms and described their increasing occurrence and consequences for aquatic ecosystems and human populations. Regular monitoring of chlorophyll-a, cyanotoxin concentrations and bloom dynamics remains essential for effective aquaculture management. The nutrient load reduction, flow regulation and selective harvesting represent practical measures for minimising ecological and public health risks. Increased nutrient loading from seasonal runoff promoted summer blooms as indicated by elevated chlorophyll-a concentrations [39].

(c) Microbial community shifts and opportunistic pathogens: Changes in the microbial community are frequently caused by changes in physico-chemical conditions such as temperature, nutrient availability, pH or DO, can favour the proliferation of opportunistic pathogens like *Aeromonas* and *Pseudomonas*, which are known to cause a range of diseases in cultured fish, including ulcerative conditions, septicaemia and respiratory system infections [40,41]. These pathogens proliferate rapidly under environmental stress associated with high organic loading, limited water exchange and pollution, increasing the risk of disease outbreaks that compromise fish health and aquaculture productivity [39,42]. Information on microbial community dynamics in freshwater aquaculture remains comparatively limited, despite the frequent occurrence of eutrophication, deteriorating water quality and anthropogenic contamination in these systems. Obaid *et al*. [39] examined the environmental factors responsible for harmful algal blooms (HABs) in South Africa's Vaal Dam using satellite observations and field measurements and identified nutrient enrichment as a major driver of bloom development. Kapetanovic *et al.* [43] evaluated the response of aquatic microbial communities to environmental change and recognised their importance in ecosystem function and disease dynamics. Harmful algal blooms, heavy metal contamination and other environmental stressors intensify pathogen proliferation, increase virulence and reduce host resistance to infection. An integrated surveillance framework combining microbial communities, water chemistry and fish health strengthens disease prevention in freshwater aquaculture.

(d) Viral pathogens: Freshwater fish viruses proliferate more readily under environmental stress associated with increased ammonia concentrations, low dissolved oxygen, high water temperatures and rapid fluctuations in physico-chemical conditions [44]. Viral pathogens may enter aquaculture systems through contaminated water, infected fish or carrier species and spread rapidly under high stocking densities or inadequate biosecurity. Infection frequently results in mass mortality, reduced growth, impaired immune function and higher susceptibility to secondary bacterial or parasitic infections. Environmental stress increases the probability of viral disease outbreaks through enhanced transmission and reactivation of latent infections. Water-quality management, health surveillance and biosecurity provide the primary defence against viral diseases in freshwater aquaculture. Ahmadivand *et al*. [45] reviewed the emergence of aquatic animal RNA viruses and evaluated the contribution of vaccination and biosecurity to sustainable disease control.

Management and mitigation pathways: This domain translate scientific findings into practical interventions:

(i) Key constraints and risks modelling: Based on the available water-quality data for the Vaal river and evidence from aquaculture studies, several constraints limit its suitability for freshwater aquaculture. Ionic composition, turbidity, microbial contamination and chemical pollutants influence the water quality and fish production. Although the reported TDS concentration is relatively low (~ 177 mg/L), increased sodium, chloride and sulphate concentrations can impose osmotic stress on freshwater fish, particularly in downstream sections affected by mining activities and irrigation return flows where ion concentrations may exceed species tolerance limits [46,47]. High turbidity, nutrient enrichment and eutrophic conditions increase the likelihood of dissolved oxygen depletion, harmful algal blooms, fish mortality and reduced feeding efficiency. Increased concentrations of faecal indicator bacteria, particularly *E. coli*, increase the risk of disease outbreaks and necessitate appropriate biosecurity measures or water treatment before aquaculture use. Heavy metals detected in sediments and fish tissues present an additional concern due to their potential to bioaccumulate in cultured species, reducing product quality and creating food-safety and regulatory issues. Tallon *et al.* [48] reviewed microbial indicators used for detecting faecal contamination in water and discussed their applicability and limitations in water-quality assessment and public health protection.

Aquaculture development in the Vaal river is further constrained by several site-specific environmental pressures. Microplastics present in water and sediments may be ingested by fish and serve as carriers for adsorbed contaminants [49]. Variable inputs from mining, industrial activities, municipal wastewater and natural hydrological fluctuations create rapid changes in water quality that complicate aquaculture management. Lynch *et al*. [50] evaluated trace-element concentrations in *Labeo capensis* from the Vaal Dam and reported generally acceptable levels, although frequent consumption may increase long-term health risks associated with certain metals. Limited baseline information on aquaculture-specific water quality and fish health restricts accurate assessment of production potential in the Vaal River. Site-specific pilot studies, continuous environmental monitoring and regular fish health assessments remain necessary for evaluating water suitability and developing effective aquaculture management practices.

(b) Conceptual model of the effects of Vaal river water quality on aquaculture: A simplified conceptual model describes the influence of Vaal river water quality on aquaculture. River water enters the culture system through the intake, where key variables such as electrical conductivity, total dissolved solids, dissolved oxygen, pH, turbidity, ammonia, microbial indicators and heavy metals are monitored. Increased ionic load and TDS impose osmotic stress on fish, reducing growth, feed efficiency and survival, whereas nutrient enrichment and high turbidity promote algal blooms that alter dissolved oxygen concentrations and release toxins harmful to aquatic organisms [51]. Microbial contamination, particularly elevated *E. coli* concentrations, increases the risk of disease in cultured fish and presents potential public health concerns. Heavy metals and other contaminants accumulate in fish tissues, creating food-safety and regulatory challenges [51,52]. Variations in the river flow and pollutant discharge produce rapid changes in water quality that can disrupt aquaculture operations and increase the likelihood of fish mortality. Integration of water-quality monitoring with microbial surveillance provides a practical basis for risk assessment, early intervention and sustainable aquaculture management.

(c) Practical implications for aquaculture operators: Aquaculture developments in the Vaal river region require careful evaluation of site-specific environmental conditions to ensure sustainable and safe production. Baseline water-quality assessments should be completed before farm establishment and include long-term measurements of total dissolved solids, ionic composition, dissolved oxygen, turbidity, nutrients, microbial contamination, heavy metals and microplastics. Selection of cultured species and production systems should reflect the prevailing water-quality conditions or be supported by appropriate water treatment and conditioning technologies. Odume *et al.* [53] examined stakeholder perspectives on water-quality use and management in the Vaal Barrage Catchment and described governance challenges that influence water-resource management. Continuous monitoring programs should incorporate real-time measurements of DO, TDS, electrical conductivity and turbidity together with routine analysis of microbial indicators and heavy metals. Operational plans should include emergency aeration systems, alternative water supplies and other contingency measures for deteriorating water-quality conditions [54].

Microbial contamination necessitates comprehensive biosecurity measures, such as routine fish health assessment, pathogen surveillance and disinfection of intake water where appropriate [55]. Food-safety management should include regular analysis of heavy metal residues and microbiological quality to ensure compliance with regulatory standards. Close coordination with catchment and water-resource authorities provides valuable information on upstream discharges and short-term changes in water quality [56,57]. Practical mitigation measures, such as settling ponds, alternative intake locations, predefined operational thresholds and risk-management plans for production losses, improve the resilience of aquaculture systems during poor water-quality events [58]. Bereda [59] reviewed major sources of food contaminants, their implications for human health and strategies for reducing contamination risks across the food production chain. Economic planning should account for the costs of water treatment, environmental monitoring, biosecurity and potential production losses while considering the benefits associated with maintaining high product quality. Successful aquaculture development in the Vaal river catchment depends on comprehensive site evaluation, continuous monitoring of physico-chemical and microbiological water quality parameters, effective biosecurity and adaptive management practices.

Recommended future research

Experimental freshwater facilities, such as ponds, lakes, or flow-through channels, should be established to evaluate fish growth, health, survival, feed conversion and contaminant uptake under representative Vaal river water quality conditions. Baseline pilot studies should include comprehensive water quality characterisation at prospective intake sites through seasonal and discharge-based monitoring of physico-chemical variables, such as TDS, ionic composition, DO, pH, turbidity, ammonia, nitrite, heavy metals and microplastics, together with microbiological indicators including *E. coli*, total coliforms and fish pathogens. Species suitability studies should identify fish species and strains capable of tolerating prevailing Vaal river conditions. Contaminant transfer studies are required to quantify the accumulation of heavy metals and microplastics in cultured fish and evaluate associated food-safety implications and commercial value. Risk models that incorporate discharge events and short-term water-quality fluctuations would improve prediction of production losses and operational disruptions. Economic assessments should incorporate the costs associated with water-quality monitoring, treatment, mitigation measures and insurance into cost benefit analyses. Integrated catchment and aquaculture management frameworks involving water-resource authorities, aquaculture operators and regulatory agencies would facilitate coordinated management of water resources and aquaculture activities. Food-safety studies should examine consumer acceptance, regulatory compliance and market potential of fish cultured under variable water-quality conditions in both domestic and international markets.

Conclusion

This systematic review identifies the Vaal river as a potentially valuable freshwater resource for aquaculture, although its use is constrained by elevated ionic loads, turbidity, nutrient enrichment, microbial contamination and pollutants such as heavy metals and microplastics. Evidence from the aquaculture literature associates these water quality characteristics with adverse effects on fish growth, health, survival, feed efficiency and food safety. Sustainable aquaculture development in the Vaal river requires site-specific water quality assessment, continuous environmental monitoring, appropriate species and production-system selection and effective risk-management measures, such as water treatment, biosecurity and contingency planning. Existing knowledge gaps concerning aquaculture under Vaal river conditions warrant pilot-scale production trials, long-term environmental monitoring and economic feasibility studies. The long-term success of aquaculture in the Vaal river catchment depends on sound water-quality management, integrated catchment governance, adaptive production practices and compliance with food safety and regulatory requirements.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

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