IJCMS: Indonesian Journal of Coastal and Marine Studies
e-ISSN: 3124-1247 - Volume 2, Issue 3, 2026 - Pages 149-157
https://ejurnal.itbm.ac.id/ijcms

Environmental Determinants and Sustainability Status of Nile Tilapia (*Oreochromis niloticus*) Culture in Tarpaulin Ponds in Topoyo Village, Central Mamuju Regency, Indonesia

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ARTICLEINFO

Received: 15 September 2026
Revised: 20 October 2026
Accepted: 30 October 2026
Published: 21 November 2026

Keywords:
Nile tilapia; tarpaulin pond; water quality; sustainability

ABSTRACT

Tarpaulin ponds are increasingly used for Nile tilapia (Oreochromis niloticus) farming in rural Indonesia because they require little land and capital, yet their performance depends strongly on water quality and farm management. This study identified the environmental factors that most influence tilapia culture in tarpaulin ponds and assessed the sustainability of this farming system in Topoyo Village, Central Mamuju Regency, West Sulawesi. A descriptive quantitative case study was conducted, combining weekly measurements of water temperature, pH, dissolved oxygen (DO), ammonia, nitrite, nitrate, and transparency with fish growth observations, in-depth interviews, participatory observation, and documentation. Sustainability was evaluated with the Rapid Appraisal for Fisheries (RAPFISH) technique using multidimensional scaling (MDS) for the ecological and economic dimensions, supported by leverage and Monte Carlo analyses. The ecological dimension obtained a sustainability index of 61.43 (moderately sustainable; R^2 = 92.45%, stress = 14.44%), and the economic dimension an index of 83.18 (sustainable; R^2 = 93.73%, stress = 19.41%). Leverage analysis showed that nitrite (13.54), ammonia (12.65), DO (10.95), pH (8.83), and parasites or pathogens (8.49) were the most sensitive ecological attributes, reflecting irregular water quality monitoring, the absence of aeration in some ponds, and outbreaks of fungal and parasitic disease. Business profit (3.55), feed availability (2.41), access to capital (2.26) and contribution to household income (2.02) were the most sensitive economic attributes. Monte Carlo simulations indicated that both ordinations were stable. Improving nitrogen and oxygen management through regular monitoring, aeration, and biofloc technology, together with better access to feed, capital, and markets, is essential to enhance the productivity and sustainability of tarpaulin-pond tilapia farming in rural areas.

DOI: *https://doi.org/10.63249/ijcms.v2i3.189*

INTRODUCTION

Aquaculture has become a central pillar of global food production, providing animal protein, employment and income to millions of households (Naylor et al., 2021). In Indonesia, freshwater aquaculture plays a strategic role in food security and rural livelihoods, and Nile tilapia (*Oreochromis niloticus*) is one of its most important commodities. Tilapia grows rapidly, tolerates a wide range of environmental conditions and has flesh that is widely accepted by consumers. Since its introduction from Africa, Nile tilapia has spread to many countries, where it makes important social and economic contributions and holds a growing share of the global fish market (Geletu & Zhao, 2023). These traits make it suitable for farmers operating at small, medium and large scales.

In rural Indonesia, an increasing number of small-scale farmers culture tilapia in tarpaulin ponds. These ponds are made of plastic sheeting supported by a frame of wood, bamboo or bricks, and they can be installed on small plots near houses. Compared

with earthen ponds, tarpaulin ponds are cheaper to build, easier to clean and drain, and less prone to seepage and soil-borne disease. They therefore offer a practical option for households with limited land and capital. Aquaculture of this kind can stimulate the rural economy beyond the farm itself, generating income and spillover benefits for local communities (Filipski & Belton, 2018).

The success of tilapia culture, however, depends far more on water quality and management than on the type of pond. A systematic review of factors that cause yield gaps in Nile tilapia found that growth, feed conversion and survival are affected by many environmental and management factors, and that yield is strongly influenced by fish survival (Mengistu et al., 2020). Another review showed that stocking density, feeding rate and frequency, water temperature, DO, pH, and ammonia, nitrite and nitrate concentrations can significantly alter body weight, survival, feed intake, feed conversion and health in Nile tilapia (Abd El-Hack et al., 2022). Unfavourable conditions cause stress, reduce appetite and growth, and can lead to mass mortality.

Nitrogenous compounds are among the most critical water quality variables in intensive and semi-intensive tilapia culture. Ammonia is the main nitrogenous waste of fish and is also produced by the decomposition of uneaten feed and faeces. Un-ionised ammonia is highly toxic because it diffuses readily across gill membranes and disrupts nervous, osmoregulatory and energy metabolism (Randall & Tsui, 2002). In juvenile Nile tilapia, the specific growth rate was significantly reduced when un-ionised ammonia exceeded 0.068 mg N L^{-1}, and concentrations below 0.1 mg N L^{-1} were recommended for pond culture (El-Shafai et al., 2004). High levels of total ammonia nitrogen as ammonium were also found to be stressful and harmful to the growth of Nile tilapia juveniles (da Silva et al., 2013).

Nitrite, the intermediate product of nitrification, is equally hazardous. It is actively taken up across the gills and oxidises haemoglobin to methaemoglobin, which cannot carry oxygen, leading to functional hypoxia and, at high concentrations, death (Kroupová et al., 2005). Nitrite problems are common in small ponds where nitrifying bacteria are poorly established and feed inputs are high. Because ammonia and nitrite toxicity both increase when DO is low and pH is high, these parameters must be managed together rather than separately.

Several technologies can help small-scale farmers control nitrogen in tilapia ponds. Manipulating the carbon-to-nitrogen ratio of the culture water encourages heterotrophic bacteria to assimilate ammonia into microbial biomass, which can then be consumed by the fish (Avnimelech, 1999). This principle underlies biofloc technology, which improves water quality, recycles nutrients and can reduce feed requirements and water exchange (Crab et al., 2012). Aeration, regular partial water exchange and controlled feeding are simpler measures that are within reach of most rural farmers. Despite their benefits, these practices are applied unevenly in small-scale tarpaulin pond systems.

The economic viability of tilapia farming is closely linked to its environmental performance. Feed is usually the largest operating cost, and the expansion of aquaculture has increased dependence on compounded aquafeeds and their raw materials (Tacon & Metian, 2008). Poor water quality lowers feed efficiency and survival, raising production costs per kilogram of fish. At the same time, farmed fish has become an important and affordable source of animal protein for low- and middle-income consumers in the Global South, which creates stable demand for products such as tilapia (Belton et al., 2018). The sustainability of tilapia farming therefore depends on both ecological and economic dimensions, and on the interactions between them.

Assessing sustainability across multiple dimensions requires methods that combine diverse information. The Rapid Appraisal for Fisheries (RAPFISH) technique was developed as a multidisciplinary rapid appraisal method in which attributes in ecological, economic, social, technological and ethical fields are scored and ordinated to evaluate the comparative sustainability of fisheries (Pitcher & Preikshot, 2001). Later developments introduced a constrained multidimensional ordination scaled to place data points within an evaluation space, together with tools to identify influential attributes and test uncertainty (Pitcher et al., 2013). RAPFISH has since been widely adapted to aquaculture systems in Indonesia because it can integrate field measurements with farmer interviews and secondary data.

Topoyo Village in Central Mamuju Regency, West Sulawesi, has abundant freshwater resources, a tropical climate suitable for tilapia, and strong community interest in aquaculture. Tarpaulin pond farming has expanded rapidly in the area, but farmers report highly variable results. Some achieve good growth and harvests, while others face slow growth, high mortality and poor feed efficiency. These differences suggest that water quality and pond management vary considerably among farms and that some practices are not sustainable in the long term.

Most previous studies of environmental factors in tilapia culture have focused on earthen ponds, concrete tanks or floating net cages, and have assessed water quality without linking it to farm economics. Few studies have documented tarpaulin pond systems in West Sulawesi, and none has combined water quality assessment with a multidimensional sustainability appraisal in Central Mamuju. Information on which environmental and economic attributes most strongly influence the sustainability of this farming system is needed to design practical interventions for local farmers and extension services (Mengistu et al., 2020; Abd El-Hack et al., 2022).

This study therefore aimed to (1) identify the environmental factors that most influence Nile tilapia culture in tarpaulin ponds in Topoyo Village; and (2) assess the ecological and economic sustainability of this farming system using RAPFISH with multidimensional scaling, leverage and Monte Carlo analyses. The results are intended to support locally adapted management strategies that can also serve as a reference for other rural areas with similar conditions.

METHODS

A descriptive quantitative case study was conducted in Topoyo Village, Central Mamuju Regency, West Sulawesi Province, Indonesia, a location selected purposively because it is an active centre of Nile tilapia culture in tarpaulin ponds. Data were collected through direct measurement of water quality, observation of fish growth, in-depth interviews, participatory observation and documentation. Water temperature, pH, DO, ammonia (NH_3), nitrite (NO_2^-), nitrate (NO_3^-) and transparency were measured weekly with standard field instruments, as these are the parameters most strongly linked to tilapia growth, feed conversion and survival (Abd El-Hack et al., 2022; Mengistu et al., 2020). Ammonia and nitrite were interpreted against published tolerance thresholds for Nile tilapia, because their toxicity determines the safe operating range of intensive ponds (El-Shafai et al., 2004; Randall & Tsui, 2002). Fish growth was assessed from increments in body weight and total length. Respondents, including tarpaulin pond farmers, fisheries extension officers and other stakeholders, were selected purposively, and economic data were collected through structured questionnaires and interviews.

Sustainability was assessed with the RAPFISH technique (Pitcher & Preikshot, 2001), adapted for aquaculture and applied to the ecological and economic dimensions. Each attribute was scored on an ordinal scale between a "bad" and a "good" reference condition, and the scores were ordinated by multidimensional scaling (MDS) to produce a sustainability index from 0 to 100 for each dimension (Pitcher et al., 2013). Goodness of fit was evaluated with the coefficient of determination (R^2) and the stress value, a measure of the mismatch between the original distances and the ordination (Kruskal, 1964); stress below 25% was considered acceptable (Kavanagh & Pitcher, 2004). Index values were classified as unsustainable (0.00–25.00), less sustainable (25.01–50.00), moderately sustainable (50.01–75.00) and sustainable (75.01–100.00) (Kavanagh & Pitcher, 2004). Leverage analysis was used to identify the attributes with the greatest influence on each index, measured as the change in root mean square of the ordination when each attribute is removed, and Monte Carlo simulation was used to assess the effect of scoring uncertainty on the results (Pitcher et al., 2013).

RESULTS AND DISCUSSION

Central Mamuju Regency lies between 1°43′41.577″ and 2°19′19.182″ S and between 119°7′27.285″ and 119°52′31.656″ E in West Sulawesi Province. It covers 3,014.37 km² and has a coastline of 86.21 km. The regency consists of five districts, Pangale, Budong-Budong, Tobadak, Topoyo and Karossa, of which four (Pangale, Budong-Budong, Topoyo and Karossa) border the coast and include 18 coastal villages. Topoyo District combines abundant surface and groundwater with a humid tropical climate, conditions that favour freshwater aquaculture throughout the year.

Overall sustainability status

Tarpaulin-pond tilapia farming in Topoyo Village was moderately sustainable in the ecological dimension and sustainable in the economic dimension (Table 1). Both ordinations had a good fit, with R^2 above 92% and stress values below the 25% threshold.

Table 1.
Sustainability indices and goodness-of-fit statistics of the RAPFISH ordinations for tilapia culture in tarpaulin ponds, Topoyo Village

Dimension	Sustainability index	Category	R^2 (%)	Stress (%)
Ecological	61.43	Moderately sustainable	92.45	14.44
Economic	83.18	Sustainable	93.73	19.41

The contrast between the two dimensions indicates that farming is profitable enough to sustain participation, but that its environmental foundation is weaker. This pattern is common in small-scale aquaculture, where farmers can earn acceptable returns in the short term while water quality and disease risks accumulate. Because fish growth, feed conversion and survival all depend on water quality (Mengistu et al., 2020), weaknesses in the ecological dimension are likely to erode economic performance over time if they are not addressed.

Ecological dimension

The ecological index of 61.43 places the system in the moderately sustainable category (Figure 1). The ordination required two iterations and showed a good fit (R^2 = 92.45%; stress = 14.44%), well below the 25% threshold considered acceptable for

RAPFISH ordinations (Kavanagh & Pitcher, 2004; Kruskal, 1964). Leverage analysis identified five attributes with the greatest influence on the ecological index: nitrite, ammonia, DO, pH and parasites or pathogens (Table 2; Figure 2).

Table 2.
Most sensitive attributes identified by leverage analysis (change in root mean square, %) for the ecological and economic dimensions

Dimension	Attribute	Leverage (%)
Ecological	Nitrite	13.54
Ecological	Ammonia	12.65
Ecological	Dissolved oxygen	10.95
Ecological	pH	8.83
Ecological	Parasites and pathogens	8.49
Economic	Business profit	3.55
Economic	Feed availability	2.41
Economic	Access to capital	2.26
Economic	Contribution to household income	2.02

Nitrite and ammonia were the two most sensitive attributes, consistent with field observations that water quality was not monitored regularly in several ponds. In small tarpaulin ponds with limited water volume and high feeding rates, ammonia from fish excretion and decomposing feed accumulates quickly, and nitrite builds up when nitrifying bacteria cannot oxidise it fast enough. Un-ionised ammonia is highly toxic to fish because it crosses the gills easily and disrupts nervous and energy metabolism (Randall & Tsui, 2002). In juvenile Nile tilapia, growth was significantly reduced above 0.068 mg L^{-1} un-ionised ammonia nitrogen (El-Shafai et al., 2004), and high total ammonia nitrogen concentrations impaired growth and caused stress (da Silva et al., 2013). Nitrite converts haemoglobin to methaemoglobin, reducing oxygen transport and causing mortality at high concentrations (Kroupová et al., 2005). The high leverage of these attributes indicates that nitrogen management is the most effective entry point for improving ecological sustainability.

DO was the third most sensitive attribute because several ponds had no aeration and did not apply biofloc or other intensive water management. Oxygen supply limits feeding, growth and survival of Nile tilapia, and low DO also increases the toxicity of ammonia and nitrite (Abd El-Hack et al., 2022). In unaerated tarpaulin ponds, oxygen falls sharply at night and after heavy feeding, exposing fish to repeated hypoxic stress. Installing low-cost aerators and adjusting stocking density and feeding to the oxygen capacity of the pond are therefore priority measures.

pH was the fourth most sensitive attribute, reflecting the traditional management practised by many farmers. pH controls the proportion of total ammonia present in the toxic un-ionised form, which increases sharply as pH rises (Randall & Tsui, 2002). Experiments with Nile tilapia juveniles showed that the harmful effects of high ammonium levels depended on water pH (da Silva et al., 2013). Without regular monitoring and buffering, daily pH fluctuations in ponds with dense phytoplankton can therefore turn moderate ammonia levels into toxic ones.

The fifth attribute was the presence of parasites and pathogens: several farmers reported mass mortality associated with fungal and parasitic infections. Disease

outbreaks in small ponds are often triggered by poor water quality, which weakens fish immunity, and survival is a major determinant of tilapia yield gaps (Mengistu et al., 2020). Water quality, feeding, stocking density and disease risk interact closely in Nile tilapia culture (Abd El-Hack et al., 2022). Improving nitrogen and oxygen management would thus also reduce disease incidence.

Biofloc technology offers an integrated way to address several of these attributes at once. By raising the carbon-to-nitrogen ratio of the culture water, it allows heterotrophic bacteria to convert ammonia into microbial protein (Avnimelech, 1999). Biofloc systems improve water quality, recycle nutrients and can lower feed requirements and water exchange (Crab et al., 2012). For farmers who cannot adopt biofloc, regular water quality testing, partial water exchange, aeration and controlled feeding remain effective, low-cost alternatives.

Monte Carlo analysis showed a compact distribution of simulated ordination points around the RAPFISH result (Figure 3), indicating that scoring errors and uncertainty in attribute values had little effect on the ecological index (Pitcher et al., 2013).

Economic dimension

The economic index of 83.18 places the system in the sustainable category (Figure 4). The ordination showed a good fit (R^2 = 93.73%; stress = 19.41%). Leverage analysis identified four sensitive economic attributes: business profit, feed availability, access to capital and contribution to household income (Table 2; Figure 5). Their leverage values were lower than those of the ecological attributes, indicating that the economic index is less sensitive to changes in any single attribute.

Business profit was the most sensitive economic attribute because some farmers had not yet achieved optimal harvests and returns. Difficult market access and fluctuating selling prices limit the income that small producers obtain from their fish. Demand for tilapia is nevertheless robust, because farmed fish has become an important and affordable source of animal protein for low- and middle-income consumers in the Global South (Belton et al., 2018). Strengthening market links, for example through collective marketing or direct contracts with local traders, could therefore raise profitability.

Feed availability was the second most sensitive attribute, as many farmers still depended on government feed assistance. Feed is the largest operating cost in tilapia farming, and the expansion of aquaculture has increased reliance on compounded aquafeeds whose ingredients are subject to price fluctuations (Tacon & Metian, 2008). Dependence on external assistance makes production vulnerable when support ends. Biofloc systems can partly reduce feed requirements by allowing fish to consume microbial flocs (Crab et al., 2012), and locally produced feeds could further reduce costs.

Access to capital was the third sensitive attribute: most farmers financed their operations from their own savings, and formal credit was not well structured. Limited capital constrains investment in aeration, water quality testing and better pond infrastructure, linking the economic and ecological weaknesses identified in this study. Improving access to microcredit or group-based financing would allow farmers to adopt the management practices recommended above.

The fourth attribute was the contribution of tilapia farming to household income. Many farmers treated tarpaulin ponds as a secondary activity rather than a main livelihood, which limited the time and resources devoted to pond management.

Aquaculture can generate substantial income and spillover benefits in rural economies when it is developed as a commercial activity (Filipski & Belton, 2018). Extension programmes that demonstrate the profitability of well-managed tarpaulin ponds could encourage farmers to invest more effort in this enterprise.

Monte Carlo analysis again showed a compact distribution of simulated points (Figure 6), indicating that the economic ordination was robust to uncertainty in attribute scoring (Pitcher et al., 2013).

Implications and limitations

The results show that the sustainability of tarpaulin-pond tilapia farming in Topoyo Village is limited mainly by its ecological dimension, and specifically by nitrogen, oxygen, pH and disease management. Interventions that target these attributes, such as regular water quality testing, aeration and biofloc technology, are likely to yield the greatest gains in both fish growth and farm income (Abd El-Hack et al., 2022; Crab et al., 2012). In the economic dimension, better access to feed, capital and markets would consolidate the profitability already achieved by many farmers.

This study has several limitations. The sustainability appraisal covered only the ecological and economic dimensions, whereas RAPFISH can also evaluate social, technological and institutional fields (Pitcher & Preikshot, 2001). The influence of environmental factors on growth was inferred from leverage analysis and field observations rather than from a statistical model linking measured water quality to growth data. Future studies should report the measured water quality ranges and growth performance of each pond, test their relationships statistically, and extend the appraisal to social and institutional dimensions (Mengistu et al., 2020; Pitcher et al., 2013).

CONCLUSION

Nile tilapia (*Oreochromis niloticus*) culture in tarpaulin ponds in Topoyo Village, Central Mamuju Regency, is economically sustainable but only moderately sustainable from an ecological perspective. The RAPFISH appraisal produced an ecological sustainability index of 61.43 (moderately sustainable; R^2 = 92.45%, stress = 14.44%) and an economic index of 83.18 (sustainable; R^2 = 93.73%, stress = 19.41%), and Monte Carlo simulations confirmed that both ordinations were stable. The environmental factors with the greatest influence on the system were nitrite, ammonia, dissolved oxygen, pH, and the presence of parasites and pathogens. These attributes reflect irregular water quality monitoring, the lack of aeration in several ponds, limited adoption of biofloc technology, and recurrent fungal and parasitic disease. In the economic dimension, business profit, feed availability, access to capital and the contribution of farming to household income were the most sensitive attributes, linked to fluctuating prices, dependence on government feed assistance, informal financing and the secondary status of pond farming in many households. Improving nitrogen and oxygen management through routine water quality testing, aeration and biofloc systems should therefore be the priority, supported by better access to feed, credit and markets. Integrating these environmental and economic measures would raise productivity and strengthen the long-term sustainability of tarpaulin-pond tilapia farming in rural West Sulawesi and similar areas.

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