Participatory monitoring tool to assess the sustainability of Tilapia (*Oreochromis niloticus*) fish farming in West Africa

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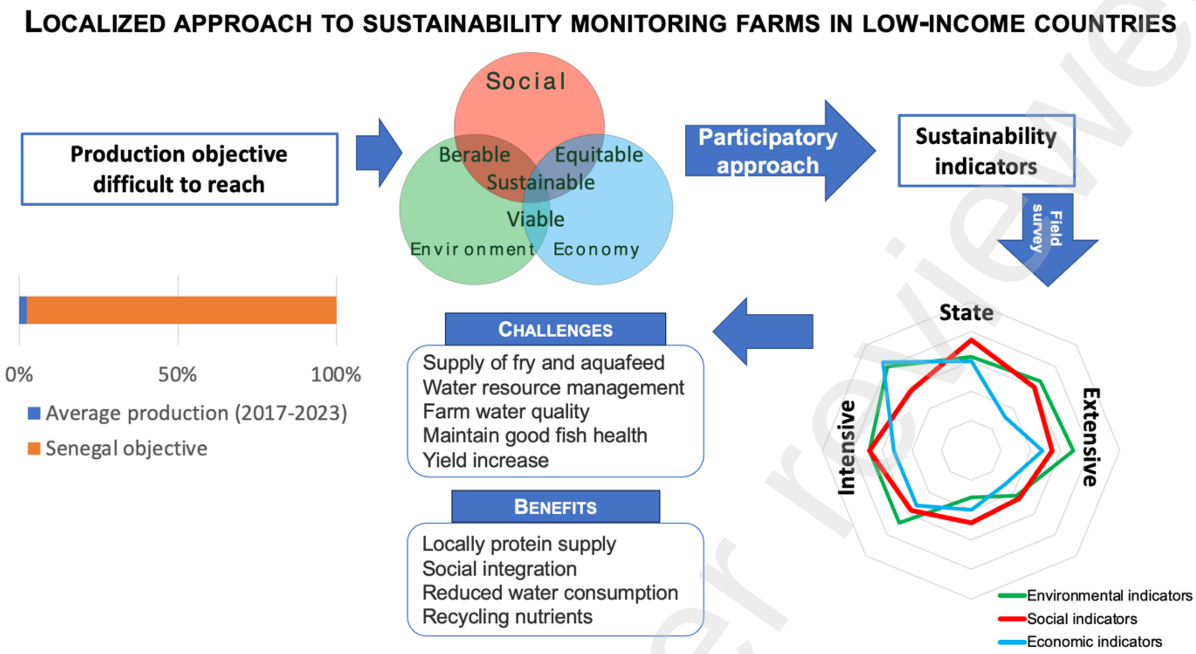
Highlights

- Co-constructed sustainability assessment tool for freshwater aquaculture farms in less advanced countries
- Tilapia farms in Senegal, showcasing varying intensification and agricultural integration
- Identification of strengths and weaknesses in sustainability dimensions, highlighting areas for improvement
- Localized approach to sustainability monitoring farms in low-income countries

23 **Graphical Abstract**



Abstract

Sustainable freshwater aquaculture is crucial for food security and economic development in Africa, particularly in North West Africa's less advanced countries. We developed and tested a localized tool to evaluate the sustainability of tilapia farms across diverse agroecological zones in Senegal. The approach involved engaging eight farms in a participatory process to identify context-relevant indicators related to environmental, social, and economic dimensions of tilapia farming. These indicators were scored to create a composite sustainability index.

Key sustainability challenges identified included lack of technical support, profitability issues, inadequate environmental management, and social welfare concerns. However, we found promising potential for integrated community-based farms. The sustainability indicators inform policy and practices promoting localized sustainability in sub-Saharan Africa, considering smallholder farms' unique needs and characteristics.

These assessments contribute to implementing targeted interventions, improved resource management, and enhanced social and environmental outcomes in the freshwater farming industry. Collaboration and knowledge sharing among stakeholders can significantly contribute to developing sustainable aquaculture practices, though successful implementation requires specific, medium-term practice programs.

This research not only aids in implementing targeted interventions and improved resource management in smallholder aquaculture but also has the potential to enhance food security and economic resilience in low-income countries across the region.

Keywords: Farm, Tilapia, Sustainability, Aquaculture, participatory approach, Senegal, West Africa.

1. Introduction

The African continent produces 2.6 % (2,196,000 tons) of global aquaculture production (FAO, 2020), mainly led by freshwater fish production: tilapia in Egypt and West Africa by tilapia and catfish from Nigeria and Ghana. These productions are considered low, given the potential of this continent (Aguilar-Manjarrez and Nath, 1998; NEPAD, 2014; ANSD, 2020). In Senegal, the potential for aquaculture production is estimated to be 12,000 tons per year by utilizing 5% of the irrigated land in North Senegal (Diallo et al., 2003). Despite the establishment of a national aquaculture agency in 2014 and the recognition of aquaculture development as a governmental priority for accelerated economic growth (Diadhiou et al., 2015), Senegalese aquaculture production remains low, amounting to only 1,011 tons in 2020. The predominant contributor to this low aquaculture production in Senegal is mangrove oyster farming, which has been practised for centuries by the coastal local population, particularly women's economic interest groups (Ndiaye et al., 2017). However, the aquaculture development policies implemented in recent years have provided weak support for this sector, focusing predominantly on fish farming of tilapia and catfish. This imbalance in the sector's support policy reflects an irrational approach that does not align with the social and economic importance of the aquaculture sub-sector in Senegal (Diadhiou et al., 2015; Ndiaye et al., 2017). Over the past three decades, aquaculture production has experienced rapid growth, establishing itself as a viable alternative to fishing activities in providing seafood for the population (Fol Orunso et al., 2021). This is particularly significant due to the overfishing of many commercially exploited fish stocks (Baldé et al., 2019; Diankha et al., 2018). However, it is important to note that the assertion of aquaculture as a solution is not without controversy. The production of carnivorous species in aquaculture relies heavily on fish stocks, particularly small pelagic fish, which are crucial for food security in West Africa (Ndiaye et al., 2022; Deme et al., 2023) such as Sardinella (Ba et al., 2016; Ba et al., 2021). Nonetheless, the statement can be considered plausible for aquaculture species that utilize low levels of fishmeal, such as tilapia, carp, and catfish.

The growth of tilapia farming in sub-Saharan Africa highlights the importance of conducting sustainability assessments tailored explicitly to smallholder farms. Despite four decades of research and development and significant financial investments, fish farming in Africa has struggled to fully realize its potential in terms of production and socioeconomic impact (Aguilar-Manjarrez and Nath, 1998). Ineffective institutional arrangements and project-driven initiatives have hindered the achievement of desired outcomes in terms of food security and economic growth, as predicted by development agencies (Brummett et al., 2008). However, certain countries, such as Nigeria and Ghana, have made significant progress.

In assessing the contribution of aquaculture to rural economies and food security, Brummett et al. (2000) proposed an evolutionary approach that combines local and external participation in technology development and emphasizes the transfer of technical knowledge (Verceles et al., 2000). This approach aims to enhance the productivity of fish production systems while promoting environmental and social sustainability. This observation aligns with sustainability, encompassing economic development, social stability, and environmental integrity (Bueno et al., 2009).

Sustainability indicators (Bell and Morse, 2008) and composite indices are increasingly recognized as valuable tools for policymakers and communication efforts to convey information regarding country and corporate performance in various areas, including the environment (Brehmer et al., 2011), economy, society, and technological advancements (Singh et al., 2009). Approximately 37 % of sub-Saharan Africa has suitable conditions for small-scale artisanal fish farming, which, if effectively implemented, could significantly contribute to household food security (Kaspersky, 1994; Aguilar-Manjarrez and Nath, 1998; Brummet et al., 2008). However, decision-makers and managers need specific information regarding the on-site impacts and sustainability of fish farms at the community level.

The Evaluation of Aquaculture System Sustainability established the importance and appropriateness of the Principles, Criteria, and Indicators approach for assessing the sustainability of aquaculture systems (Lazard et al., 2011; Chia et al., 2009; Lazard, 2014; Rey-Valette et al., 2008, 2010). It focused on assessing sustainability at the regional and national levels but not at the microscale, i.e. the farm level. Scaling fish farm indicators for assessment involves evaluating the sustainability of fish farms based on selected indicators, which can assess the impact of specific practices on fish health, waste production levels, and the farms' impact on local wildlife. The Farm Sustainability Assessment Tool can be utilized to evaluate the sustainability of fish farms, covering indicators related to fish health, welfare, environmental management, and social responsibility (Marchand et al., 2014; De Olde et al., 2016). These indicators can then be used to create a score reflecting the overall sustainability of a fish farm. It is important to acknowledge that a realistic approach to evaluating the sustainability of fish farms often tends to focus primarily on economic aspects (Sheikh 2021). However, it is worth noting that the economic approach has limitations, as it does not fully consider these farms' social and environmental impacts. This limited evaluation approach disregards the broader dimensions of sustainability when assessing fish farms. Therefore, it is important to supplement economic evaluations with assessments encompassing the social and environmental dimensions to obtain a more holistic view of the farms' sustainability performance (Bueno et al. 2009).

Developing a farm sustainability assessment tool ensures sustainable farming practices (Bueno et al., 2000; Lazard et al., 2011). Such a tool can measure the impact of various farming practices on a farm's sustainability and identify areas for improvement. It also enables the comparison of different farms' sustainability and the evaluation of the environmental, economic, social, and technical impacts associated with different farming approaches. When creating a farm sustainability assessment tool, it is essential to consider the specific needs of the farm and the desired outcomes of the assessment. Existing frameworks and tools, such as those proposed by Rey-Valette et al. (2008) and Efole et al. (2017), are valuable resources for developing an effective assessment tool.

The main objective of this work was to gain a localized understanding of the sustainability status of fish farms in the West African context rather than conducting a global assessment. This approach is consistent with previous work (Chia et al., 2009; Lazard, 2014), highlighting the significance of adapting sustainability assessments to local environments' unique characteristics and requirements. By explicitly examining the contributions of tilapia farms to sustainable development at the local level, this work aims to provide valuable insights for improving the sustainability of aquaculture practices in the region.

2. Materials and methods

We have developed sustainable indicators for assessing the sustainability of fish farms, with a focus on the contribution of tilapia farms to local sustainable development. The approach employed a co-construction methodology to identify and validate the most relevant indicators, providing an overview of the farms' sustainability.

2.1. Dimension, principles, and indicators

Identifying sustainable development principles is crucial for assessing the contribution of aquaculture activities to the sustainability of territories (Rey-Valette et al. 2007a). These principles encompass the socioeconomic and environmental aspects of the territories, aligning with the definition of sustainable development provided by Bueno et al. (2009). These principles and indicators were validated using the co-construction approach (Rey-Valette et al. 2009; 2010; Lazard et al. 2014). An interdisciplinary team of sociologists, economists, environmentalists, and aquaculturists conducted a field survey to analyse fish farms' economic, social, and environmental sustainability dimensions. Subsequent meetings with fish farmers and institutional partners were held to validate the principles and select the most relevant indicators for the specific context of fish farming in Senegal (Mbaye et al., 2022). Through a co-construction approach, seven environmental, seven social, and five economic indicators were selected to monitor tilapia farms' sustainability (Table 1).

2.2. Sustainability barometer

Assessing the sustainability of fish farms involves associating reference values or thresholds with specific indicators (Lancker and Nijkamp, 2000). The co-construction of the 19 indicators to evaluate the sustainability of African tilapia farms was based on their importance and feasibility of measurement. Scaling the fish farm indicators for assessment allows for the evaluation of the impact of specific practices on fish health (Opiyo et al., 2019), the level of waste produced (Lee et al., 2022), and the impact of the farm on local wildlife (Nol et al., 2004; Ndiaye et al., 2019). The sustainability tool covers fish health and welfare indicators, environmental management, and social responsibility. The overall sustainability of the fish farm was assessed using a set of twenty indicators, each rated on a scale from 1 to 5, representing "poor" to "very good" sustainability (Table 2).

Then, the interdisciplinary team and the data provided by the national statistical agencies (Faye et al., 2021) allow the validation of the co-construct indicators. The assessment also included a sustainability diagnosis method, categorizing the farm as sustainable, near sustainable, approaching sustainable, far from sustainable, or unsustainable based on the obtained ratings. Additionally, estimates provided by scientists were used to determine the impact of indicators such as water management, sales strategy, and diversity of farm products on sustainability (Table 2). [insert Table 2]

2.3. Farms selection

The farm selection was carried out based on records obtained from two governmental agencies promoting aquaculture and second agriculture, *i.e.*, Agence Nationale de l'Aquaculture (ANA) and Agence Nationale d'Insertion et de Développement Agricole (ANIDA). A list of 95 farms from these Senegalese governmental agencies provided details on the type of infrastructure, surface area, and/or volume of each farm, as well as a typology of farm infrastructure in each area, including tanks, cages, and ponds (N'Souvi et al., 2021).

Three selection criteria for the farms' selection were adopted. (i) Production capacity was considered to include farms with varying output levels, ranging from small-scale to large-scale operations. (ii) Farms with enhanced technology were included to understand the sustainability implications of advanced farming practices and assess their potential benefits or challenges. (iii) Representativeness of eco-geographical areas was also a key consideration to ensure that the selected farms were spread across various agroecological zones in Senegal.

These criteria aimed to ensure the representativeness of farms with enhanced technology and consistent production across different regions (Bueno et al., 2009). Out of the pool of 95 farms existing and recorded by Senegalese governmental agencies, 15 farms were selected for interviews based on criteria previously stated. This represents 16 % of the total number of farms in Senegal. The farms are classified based on their location as farms in the North (FN), central region (FC), and in the South (FS), with an identification number.

2.4. Surveys

The surveys were conducted in two stages. The first stage involved validating the measurable inputs, while the second stage focused on validating the indicators. To establish the validated indicators, an interview survey sheet (Asiedu and Nunoo 2013) was used to gather all the measurable inputs after the co-construction stage to avoid bias, as done before the participatory approach (Deme et al., 2019). The inputs were collected from each of the five farms included in the study. In addition to the measurable inputs, additional information was gathered to gain a comprehensive understanding of the activities and outcomes of each farm, allowing for a thorough assessment of the data provided by the farmers (Mbaye et al., 2022). A group comprising the interdisciplinary team, farm managers and employees conducted the interviews, ensuring a well-rounded perspective during the assessment process.

2.5. Farm sustainable assessment

The measurements of each indicator were classified on a scale of five levels, with five being the "most sustainable" and one being the "least sustainable" (whereas 2: Unsustainable, 3: Moderately sustainable, 4: Sustainable). The points obtained for each indicator were compiled to establish a ranking between the farms for the three dimensions considered, *i.e.* economic, social, and environmental, regarding their sustainability. The indicators were weighted equally, with no weighting given to any one indicator (Chia et al., 2009). The points obtained were added to get a value out of 95, the maximum value reachable. The ranking was based on the total value obtained from the farm. On the other hand, an overview was also made according to the three dimensions defined. The average point obtained in each dimension was calculated for each farm (Brummett et al., 2008).

3. Results

Result by farm

The present study comprehensively evaluated only eight aquaculture farms (FN1-FN4, FC1-FC2, FS1-FS2) on fifteen farms chosen at the beginning to assess their performance across environmental, social, and economic dimensions. The farms were scored on a range of indicators within each dimension, and a final ranking was established based on the cumulative scores.

The environmental assessment focused on critical aspects of sustainable aquaculture, including water management, integration with other products, waste management, production efficiency, and using hormones, antibiotics, and chemicals. The farms were also evaluated on their use of non-indigenous species and the frequency of escape events. FC2 achieved the highest subtotal score of 28, indicating superior environmental stewardship, followed closely by FN2 and FN3 with subtotals of 24. Conversely, FS1 and FS2 demonstrated the least favourable environmental performance with subtotals of 15 and 11, respectively.

The social assessment scrutinized the farms' labour practices, including the number of direct workers, qualifications in aquaculture, salary levels, occupational safety, and compliance with working hour regulations. It also considered the gender diversity of the workforce and the farms' contribution to local markets. FC1 secured the top position in this category with a subtotal of 26, reflecting a strong commitment to social responsibility. FN2 and FN3 followed with subtotals of 24 and 21, while FS1 and FS2 again ranked lower with subtotals of 16 and 17.

The economic assessment gauged the farms' financial health, sales strategies, product diversity, job creation efficiency, and risk management capabilities. In this category, FC2 again excelled with a subtotal of 21, showcasing a robust economic foundation. FN1 and FN2 ranked third and seventh, respectively, with subtotals of 15 and 8. FS1 and FS2 trailed with subtotals of 8 and 10, indicating room for improvement in their economic performance.

The aggregate scores from all three dimensions were used to determine the overall ranking of the farms. FC2 maintained its lead with a total score of 69, underscoring its well-rounded performance across all indicators. FC1 and FN2 followed with total scores of 55 and 52, respectively. In contrast, FS1 and FS2 ranked last with total scores of 39 and 38, highlighting the need for strategic interventions to enhance their overall performance.

Result by type of farm

The study also evaluated the performance of aquaculture farms, distinguishing between three types: state-owned farms, intensive private farms, and extensive private farms. The assessment was conducted across environmental, social, and economic indicators, with a final ranking based on the cumulative scores for each farm type, including state farms.

Intensive private farms, particularly FC2, achieved the highest subtotal score of 28 in environmental management, indicating efficient water management, waste management, and low chemical usage. State farms, represented by FC1, also performed well, suggesting that public ownership does not preclude strong environmental practices. Extensive private farms, such as FN2 and FN3, showed competitive environmental performance with subtotals of 24, highlighting the potential for sustainability across different farm types.

In the social aspect, state farms like FC1 ranked first with a subtotal of 26, reflecting a commitment to social responsibility that may be facilitated by public oversight and resources. Intensive private farms, such as FC2, followed closely with a subtotal of 20, indicating that private intensive operations can also maintain high social standards. Extensive private farms, including FN2, demonstrated strong social performance with a subtotal of 24, suggesting that social indicators are also a priority for extensive operations.

Economically, intensive private farms like FC2 led with a subtotal of 21, showcasing effective funding, sales strategies, and risk management. State farms, represented by FC1, also performed well with a subtotal of 12, indicating that public ownership does not necessarily hinder economic performance. Extensive private farms, such as FN1, achieved a subtotal 13, demonstrating that economic viability is achievable across farm types, possibly through adaptation to local market conditions and economies of scale.

The total scores indicate that intensive private farms, like FC2, excel in overall performance with a total score of 69, suggesting a well-rounded approach to environmental, social, and economic sustainability. State farms, such as FC1, ranked second with a total score of 55, highlighting the potential for public entities to perform competitively. Extensive private farms, like FN2, ended in the ranking with a total score of 52, underscoring the sustainability of extensive operations.

[insert Table 4 and Figure 2]

4. Discussion

The Senegalese case study has revealed that one of the main challenges fish farmers face is the limited availability of high-quality fingerlings. According to the information reported by the interviewed farmers, the production of state hatcheries (state farm type) was significantly limited to meet the farmers' needs. To overcome this shortage of fingerlings, farmers directly source them from dedicated breeding ponds or purchase them from other farmers. However, it is important to note that these fingerlings are often of mixed populations rather than being monosex. This significantly impacts the low productivity and yields within the farms. This issue arises due to resource constraints, which prevent the consistent and timely sorting of fingerlings. As a result, some fish farmers end up with a mixture of males and females instead of the desired mono-sex male population (Senghor et al., 2019).

Another crucial challenge fish farmers face in developing a sustainable and thriving fish farming sector is the limited availability of high-quality fish feed (Baldé et al., 2020). For many years, the availability of quality fish feed has been a persistent problem in Senegal and across sub-Saharan Africa. While food manufacturers have access to a wide range of agricultural ingredients and by-products that can be utilized in high-quality fish feed formulations, the formulas currently available in the market do not meet the specific requirements of fish farmers (Ndiaye et al., 2022). As a result, they often resort to importing fish feed from distributors based in Western countries or closer to North African nations. The inadequate availability of quality fish feed further contributes to the limitation of farm intensification efforts. Intensification requires a substantial supply of high-quality feed to maximize yields and profitability, offsetting investment costs. However, due to the lack of suitable feed options, fish farmers face challenges in achieving the desired levels of intensification on their farms. Economic and social factors drive it will face additional obstacles due to fluctuations in availability and the rising cost of the key ingredient in fish feed: fishmeal. These challenges will further hinder the efforts to achieve intensified fish farming practices in the region (Ndiaye et al., 2022).

Regarding government support, public authorities provide limited financial assistance to fish farming, including help building ponds, supplying fingerlings and brood stock, providing feed occasionally, and offering monitoring and advice. However, this support is low (< 10%) vs total production cost for intensive and extensive farms stated above. For state farms, hatchery type, almost all the charges (90%) to support their operations are provided by the government. This highlights a fact that should prompt us to question the support provided by the government for this sector. Most investments in the aquaculture industry go towards the operational costs of government agencies and state-owned farms. However, these entities struggle to meet just one-tenth of the fish feed and fingerlings demand. This situation raises concerns about the effectiveness of government support for developing this sector.

Three distinct types of farms can be identified from our study. The “state farms” (Hatchery types) the extensive and intensive farms. State farms, categorized as hatchery types, have production objectives centred on providing fingerlings. They employ highly trained personnel who receive substantial remuneration, higher than those received in the other types of fish farms, with equivalent qualifications. These farms also demonstrate diversity in their workforce, with a significantly larger proportion of female employees. The significant working capital needed to support their operations was public. The FN1 farm symbolizes this type of farm, and its production objectives are less focused on commercialization, instead aiming to support the activity compared to the two other types of farms. It represents 10% of the farms. They have limited species diversification, focusing on domestic fish species whose reproduction is controlled, unlike extensive farms with a more comprehensive multitrophic diversification. On the other hand, extensive farms prioritize diversification in their production objectives. They rely on project-based initiatives for financing, with working capital dependent on project outcomes and government support. These farms have relatively low production output, primarily focusing on the local market. Employment opportunities are limited, and female employees are generally absent. Typically, extensive farms consist of two to four ponds at most and are locally owned with limited financial resources. These types of farms represent more than half of the farms and are present in the North (FN2), the central region (FC1), and the South (FS1 and 2), where they are almost extensive. Unlike intensive farms, these farms have relatively low production output, primarily supplying the local market. Intensive farms have production goals centred on exports and supplying restaurants. They primarily employ male workers who receive average levels of remuneration. The workload in these farms is high, reflecting their intensive production practices. Intensive farms have substantial financing, allowing the establishment of permanent structures such as raceways or tanks. Either domestic or foreign owners with significant financial resources own them. These farms demonstrate the highest productivity levels, achieving self-sufficiency in fingerlings and feed. However, they receive limited governmental support. However, beyond this financial autonomy, intensive farms benefiting from project support financed by foreign donors (FC2 and FN4) have significantly higher economic results than those resistant to foreign and local donors (FN3). On the other hand, the latter compensates its income with intense diversification of its activities.

To mitigate production costs and generate additional income, it is suggested that fish farming be harmoniously integrated with other traditional activities (Ndiaye et al., 2020). This integration can help create a more sustainable and economically viable approach to fish farming; by combining tilapia farming with rice cultivation or market gardening, farms can utilize fish waste as fertilizer for crops, creating a sustainable production cycle (Hoq et al., 1999; Gilles et al., 2008; Ayinda et al., 2017). This highlights the resilience of fish farmers, who should be supported through initiatives to promote and enhance their practices. One such initiative could involve promoting and implementing strategic and well-thought-out species associations, such as rice-fish farming, horticulture-aquaculture integration, and poultry-fish farming.

Chia et al. (2009) state that sustainable development leads to transformative productive and organizational practices, creating new research objectives and situations that necessitate methodological renewal. This transformation is a reference, constraint, and performative action for all economic activities. Consequently, each production system must address the question of sustainability in its operations, aiming to manage natural resources effectively to meet human needs while preserving or enhancing environmental quality and conserving natural resources (TAC/CGIAR, 1989). Achieving a comprehensive estimation of sustainability requires a clear definition of the dimensions and a robust methodology.

While the various dimensions considered in sustainability assessments are often consistent, assigning a dimension to an indicator with multidimensional effects can be challenging (Brehmer et al., 2011). The level of integration with other products was used to consider environmental aspects and highlight the efficient use of resources (waste) to produce different products, generating additional economic benefits (Ndiaye et al., 2019; Sheikh et al., 2021). The farms' sustainability assessment with ratings allows for quick identification of the sustainable activity segment and helps identify the dimensions of fish farms that require improvement.

Each indicator weighed the terms of sustainability, although this is not always the practice case. The weight of indicators varies depending on the perception of the communities. Therefore, there is a need to improve the tool by incorporating a weighting system that allocates the weight and relevance given by local actors to each indicator. This necessitates a preliminary ranking allocation for all indicators and dimensions.

For almost half of the selected farms for this study, the data were patchy, incomplete, unrealistic, or missing. This highlights the challenges faced in acquiring data in specific contexts, mainly when farmers are reluctant to provide specific information, especially related to economic aspects. Farmers may hesitate to disclose specific income-related data due to concerns about potential repercussions from state agencies. To address this challenge, it is crucial to establish collaboration and involve farmers in the preliminary stages of the study (Barreteau et al., 2013; Roque et al., 2022). The co-design approach has proven effective in developing sustainable indicators for fish farms. It helps tailor the indicators to the specific context of the fish farm, making them relevant and applicable. Furthermore, involving stakeholders in the indicator development process increases the likelihood of their acceptance and utilization in decision-making (Andalecio, 2010).

While Chary et al. (2022) suggest that farm-scale models can be valuable tools for improving the sustainability of fish farming, our study takes a more localized and participatory approach. It emphasizes the importance of working closely with local stakeholders to develop tools that are relevant and applicable to their specific context. This study's *ad hoc* monitoring tool exemplifies a localized approach to sustainability monitoring for tilapia farms in West Africa and other low-income countries.

5. Conclusion

The sustainability-monitoring tool, developed through our collaborative approach, provides a practical means of assessing the performance of tilapia farms and identifying areas for improvement. It also offers valuable insights into the characteristics of tilapia farming in sub-Saharan countries. The co-construction approach underscores the importance of collaboration between scientists and stakeholders in developing efficient field surveys. Prerequisites to allow small-scale farmers in West African countries to overcome challenges and promote sustainable aquaculture practices are to improve access to finance through, *e.g.* microcredit, (ii) provide enough technical support, and (iii) ensure access to fish markets. Thus, further research should focus on the long-term impacts of the sustainability interventions implemented in the tilapia farming sector, involving the effectiveness of access to finance, technical support, and fish markets in promoting sustainable practices and improving the livelihoods of small-scale farmers. Collaboration and knowledge sharing among stakeholders can significantly contribute to developing and refining sustainable aquaculture practices. While this seems straightforward in theory, it requires the successful implementation of specific, medium-term practice programs. Additionally, we recommend promoting sustainable aquaculture in low-income countries where small-scale farming is prevalent, and food sovereignty should be a governmental priority.

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Author contributions

The authors confirm their contribution to the paper as follows: study conception and design: WNN and PB; data collection: WN, PB, FD, HDD; Participative approach: WN, PB, FD, HDD, AM; analysis and interpretation of results: WNN, PB; draft manuscript preparation: WNN, AM, KB and PB; Funding: WNN, PB, HDD. NMR analysis: WN, PB, AM; Review: WNN, PB, AM, KB, AI: Claude (AI language model) assisted with English rewording. All authors approved the final version of the manuscript.

Declaration of Interests:

All authors participated in the study and approved the final version of the manuscript. The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Tables

Table 1: Sustainability indicators used in our study are divided into three dimensions (Environmental, Social and Economic) and various sustainability Principles.

Dimension	Principle	Indicators
Environmental	Ensure the efficient use of natural resources	Water management Production per surface Waste management Level of integration with other products
	Protect biodiversity and respect animal well-being	Use of hormones, antibiotics, and chemicals Use of non-indigenous species Number of escape events/year
Social	Strengthen the integration of aquaculture in local development	Number of direct workers Workers with aquaculture qualification Average salary
	Contribute to community development and poverty alleviation	Number of occupational accidents Daily hours worked/national legislation Presence of women workers
	Contribute to food security and healthy nutritional needs	Rate of production commercialized in local markets
Economic	Strengthen financial management of enterprises	Funding and autonomy Diversity of farm products Job-producing efficiency Sales strategy
	Strengthen risk assessment and crisis management capabilities	Risk prevention and management system

Table 2: Selected indicators and their scaling according to the thresholds and data value available in fish farm literature review and Senegalese Statistics National Agency (ANSD, 2017), sp.: fish species reared. [1]When a farm does not meet the criteria of the previous class; it is brought back to one class. [2]Sensors in ranked priority: 1-oximeter, 2-thermometer, 3-pH-meter, 4-Automate Monitoring System (AMS). [3]SMIG: "Salaire minimum interprofessional garanti" guaranteed minimum wage at the survey date in Senegal. Data collection was done between 2013-2018. [4]Funding refers to the initial Investment in infrastructure, *e.g.*, building ponds and locals, providing sensors. A darker shade on the colour scale indicates a higher level of sustainability for the indicator: 1 “least sustainable” to 5 “most sustainable

Caption Scales[1]	Least sustainable 1	Unsustainable 2	Moderately sustainable 3	Sustainable 4	Most sustainable 5
Environmental indicators					
Water management[2]	50 % of staff trained	100% of staff trained	2 + use of 2 sensors	2 + use of 3 sensors	4 + AMS
Level of integration with other products	1 sp. produce	2 sp. produced	3 sp. produce	3 sp. + Use effluents for crops	4 sp. + farmed land animals
Waste management	Effluents untreated	Mechanical filtration of effluent	Settling ponds	Concrete wetlands, including crops	Settling ponds and wetlands
Production per surface (tons ha^{-1})	0-3	3-5	5-8	8-12	< 12
Use of hormones, antibiotics, and chemicals	5	4	3	2	1
Use of non-indigenous species	4	3	2	1	0
Number of escape events/year	4	3	3	1	0
Social indicators					
Number of direct workers	< 3	3 to 5	5 to 8	8 to 10	> 10
Workers specialized in qualification (%)	< 20	20-40	40-60	60-80	80-100
Average salary (in SMIG)[3]	< 2	2-3	3-4	5-5	> 5
Number of occupational accidents ($Year^{-1}$)	> 20	15-20	20-30	30-40	< 50
Daily hours worked/national legislation	< 1.5	1.5-1.3	1.3-1.2	1.2-1.1	1.1-1.0
Presence of women workers (%)	0-10	10-20	20-30	30-40	< 50
Rate of production commercialized in local markets (%)	0-20	20-40	40-60	60-80	80-100
Economic indicators					
Funding and Autonomy[4]	100% funding from the state	50% funding from the state	Own funding	3 + produce fingerlings	4 + supply own feed
Sales strategy	no sales strategy	sale at farm	2 + sales at the local market	2 + sales at restaurants	3 + sales according to market demand
Diversity of farm products	1	2	3	4	> 4
Job-producing efficiency (ton per job)	< 0.5	0.5-1	1-2.5	2.5-5	> 5
Risk prevention and management system	Not existing	Existing but has expired	Existing but no proof of its	Existing and properly	4 + renew regularly

			application	applied	

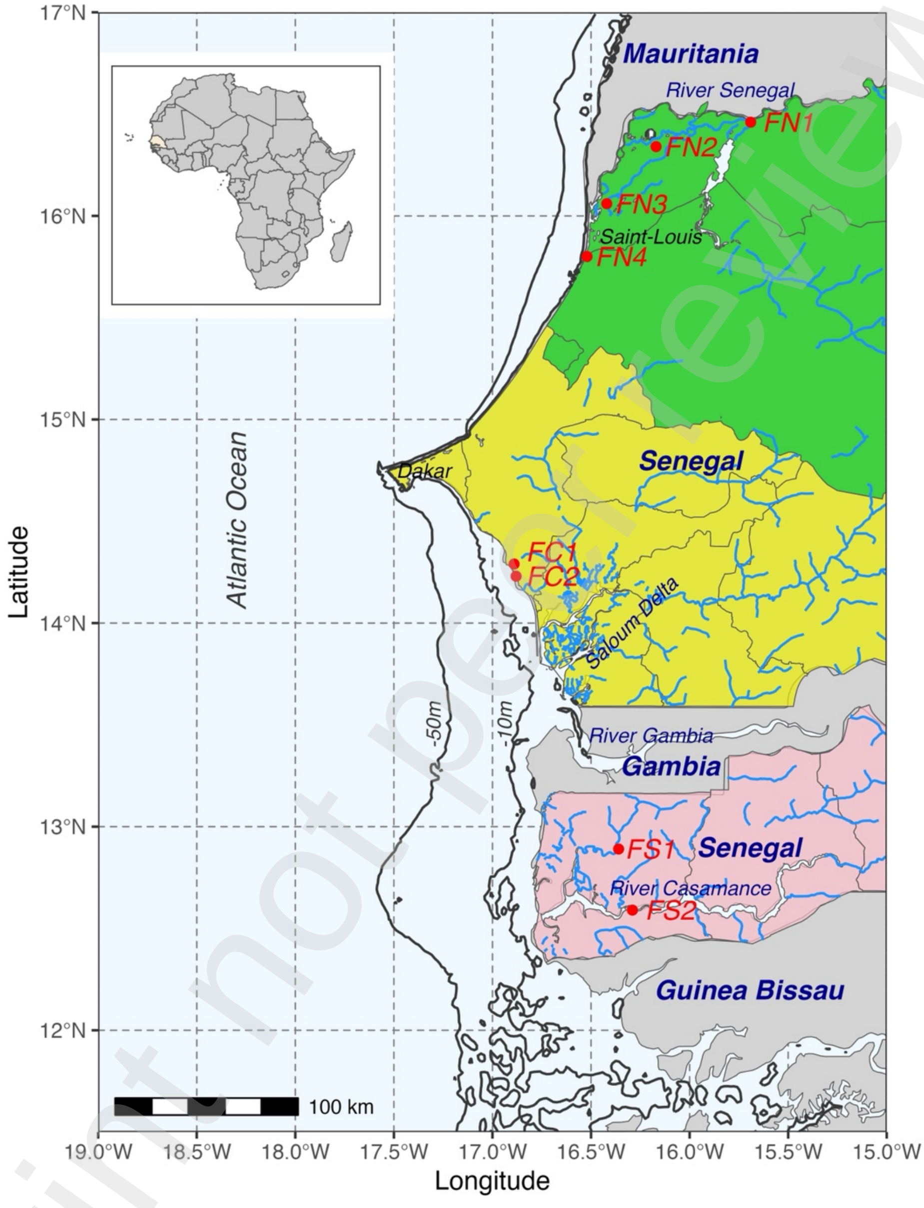
Table 3: Selected farm characteristics and ownership in different aquaculture systems. Information about the characteristics of farms, including their location, aquaculture system, and ownership. The owner's origin categorizes the ownership, whether local or national and, in one case, foreign. FN1-4, FC1-2, FS1-2; F=farm, N=North, C=Center, S=South, numbers 1, 2, 3 and 4 were the farm identifier in the area N, C, S.

ID Farms	Area	Location Type	System	Owner	Owner origin
FN1	Urban	Inland	Intensive, aerated static ponds and raceways	State	National
FN2	Rural	Inland	Extensive aerated static ponds	Family	National
FN3	Urban	Inland	Intensive aerated static ponds	Private	National
FN4	Rural	Costal	Intensive, aerated tanks and inshore-sheltered cages	Village association	National
FC1	Rural	Inland	Extensive, minimal exchange ponds	Private	National
FC2	Urban	Costal	Intensive, inshore-sheltered cages	Private	Foreigner
FS1	Rural	Inland	Extensive, ponds	Private	National
FS2	Urban	Inland	Extensive, ponds	Private	National

Table 4: Assessment of sustainability: comparative analysis of environmental, social, and economic indicators. The analysis presents several environmental (7), social (7), and economic (5) indicators for eight selected farms. The results indicate that FC2 Farm ranks highest. FN1-4, FC1-2, FS1-2; F=farm, N=North, C=Center, S=South, number 1, 2, 3; 4 indicate the identification number allocated to the farm in the area N, C, or S. A darker shade on the colour scale indicates a higher level of sustainability for the indicator. ex: exequo.

Farm	FN1	FN2	FN3	FN4	FC1	FC2	FS1	FS2
Environmental indicators								
Water management	4	1	2	3	1	4	1	1
Level of integration with other products	2	3	4	4	4	5	2	1
Waste management	2	3	3	1	3	1	1	1
Production per surface	3	1	1	1	1	5	1	1
Use of hormones, antibiotics, and chemicals	3	5	5	5	5	4	1	1
Use of non-indigenous species	3	5	4	5	5	4	4	1
Number of escape events/year	5	5	5	5	5	5	5	5
Subtotal	22	23	24	24	24	28	15	11
Rank	6	5	2	2 ex	2 ex	1	7	8
Social indicators								
Number of direct workers	2	2	2	2	1	3	2	2
Workers with aquaculture qualification	5	4	2	2	1	3	1	1
Average Salary	2	1	1	2	1	2	1	1
Number of occupational accidents	5	5	5	5	5	5	5	4
Daily hours worked/national legislation	5	3	4	5	5	1	1	3
Presence of women workers	2	1	1	3	1	1	1	1
Rate of production commercialized in local markets	5	5	5	5	5	5	5	5
Subtotal	26	21	20	24	19	20	16	17
Rank	1	3	4 ex	2	6	4	8	7
Economic indicators								
Funding and autonomy	1	1	3	2	2	5	1	3
Sales strategy	3	3	3	3	3	5	2	2
Diversity of farm products	3	2	5	3	5	3	1	1
Job-producing efficiency	3	1	1	1	1	4	3	1
Risk prevention and management system	5	1	1	4	1	4	1	3
Sub-total	15	8	13	13	12	21	8	10
Rank	2	7	3	3 ex	5	1	7 ex	6
Total	63	52	57	61	55	69	39	38
Total ranking	2	6	4	3	5	1	7	8

Figure 1: Location of tilapia selection farms within the study framework (in red line). These farms mainly concentrate on the country's north (green) coastline and centre part (yellow). FN1-4, FC1-2, FS1-2; F = farm, N = North, C = Center and S = South. Numbers 1, 2, 3, and 4 indicate the identification number allocated to the farm in areas N, C, or S.



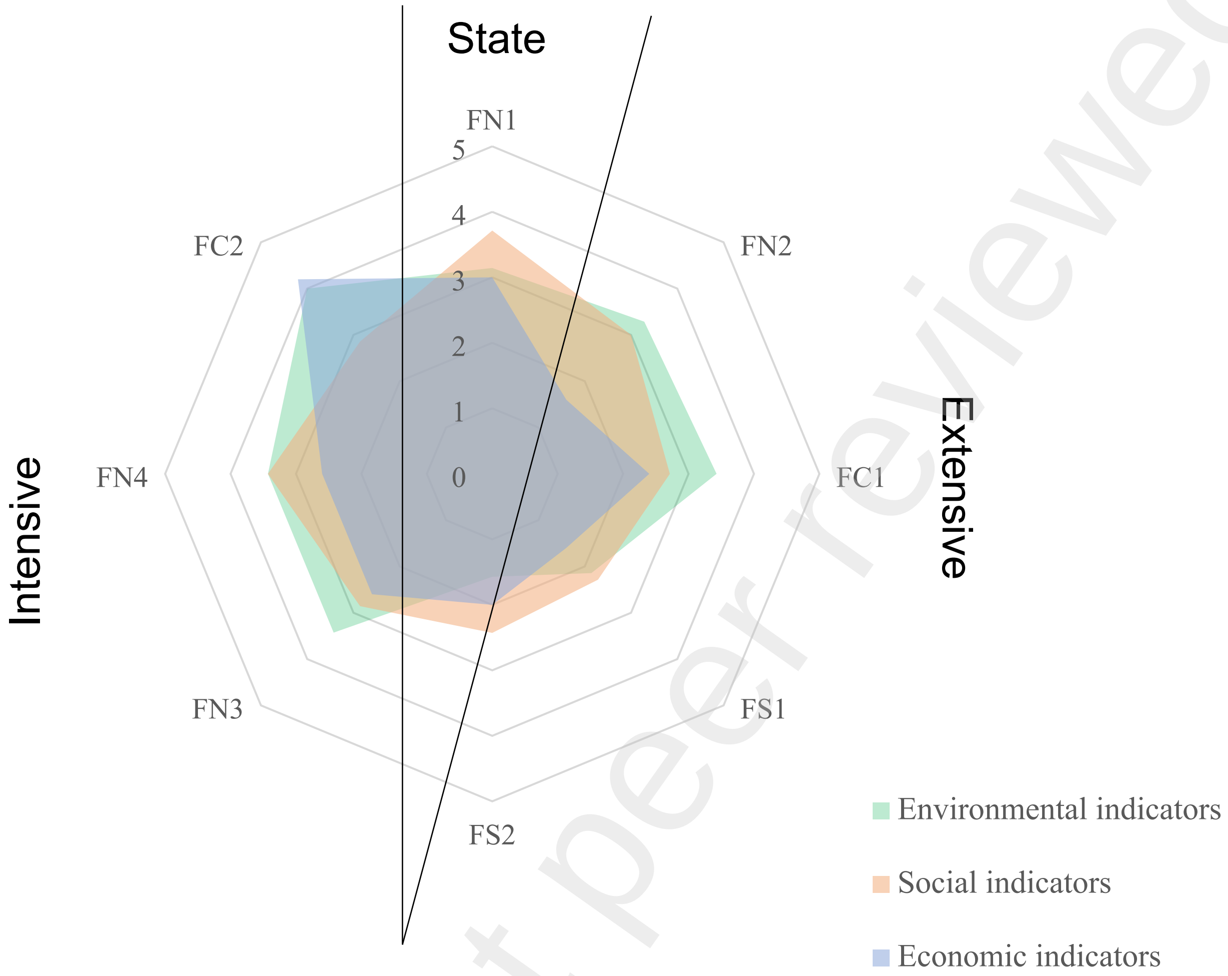


Figure 2: Mean value of the ranking 1 to 5 of each of the three dimensions of sustainability for each farm, i.e., using environmental (green circle), social (red circle) and economic (blue circle) indicators. FN1-4, FC1-2, FS1-2; F = farm, N = North, C = center and S = South. Numbers 1, 2, 3 and 4 indicate the identification number allocated to the farm in areas N, C, or S. In this graph, we observe the average results for each dimension obtained across different types of farms. The state-owned farm, represented by FN1, is shown alongside intensive farms, which are primarily located on the left side of the graph and include FC2, FN4, and FN3. Extensive farms are predominantly positioned on the right side of the graph, encompassing FN2, FC1, FS1, and FS2. This visual representation allows for a comparative analysis of the mean values across various dimensions for these distinct farming methods, offering insights into the performance and characteristics of state-owned, intensive, and extensive aquaculture operations.