fishes

MDPI

Article

Participatory Monitoring Tool to Assess the Sustainability of Tilapia (*Oreochromis niloticus*) Fish Farming in West Africa

Waly Ndianco Ndiaye [1,*], Patrice Brehmer [2,3], Adama Mbaye [1], Fulgence Diedhiou [1], Kamarel Ba [1] and Hamet Diaw Diadhiou [1]

1 ISRA, Institut Sénégalais de Recherches Agricoles, Centre de Recherches Océanographiques de Dakar-Thiaroye, CRODT, Pôles de Recherches de Hann, Route du Front de Terre, Dakar BP 2241, Senegal; ambayeskr@yahoo.fr (A.M.); fulgencediedhiou@gmail.com (F.D.); bakamarel@gmail.com (K.B.); hamet_diadhiou@yahoo.fr (H.D.D.)
2 IRD, University of Brest, CNRS, Ifremer, Lemar, 29280 Plouzané, France; patrice.brehmer@ird.fr
3 IRD, CSRP, Commission Sous Régionale des Pêches, SRFC, Dakar BP 1385, Senegal
* Correspondence: walyndiaye16@outlook.com or waly.ndiaye@isra.sn

Abstract

Sustainable freshwater aquaculture is crucial for food security and economic development in Africa, particularly in North West Africa's less advanced countries. Existing complex monitoring methods are often impractical for these contexts due to technical and resource limitations. We developed and tested a localised tool to evaluate the sustainability of tilapia farms across diverse agroecological zones in Senegal. The approach involved engaging farmers in a participatory process to identify context-relevant indicators for the environmental, social, and economic dimensions of tilapia farming. These indicators were scored to create a composite sustainability index. Key sustainability challenges identified included a 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 policies and practices that promote localised sustainability in sub-Saharan Africa, while 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 programmes. The tool successfully discriminated between farm types, with intensive private farms scoring highest overall (up to 73% of the maximum sustainability score), while extensive farms in the southern region scored lowest (≈40%). The study demonstrates the value of participatory, context-specific tools for diagnosing sustainability and guiding improvements in African aquaculture.

Keywords: farm; tilapia; sustainability; aquaculture; participatory approach; co-construction; localised monitoring; Senegal; West Africa

Key Contribution: Co-constructed sustainability assessment tool for freshwater aquaculture farms in less advanced countries and tilapia farms in Senegal, showcasing varying intensification and agricultural integration. Identification of strengths and weaknesses across sustainability dimensions, highlighting areas for improvement and a localised approach to sustainability monitoring for farms in low-income countries.

Academic Editors: Carlos Eduardo Copatti, Rodrigo Fortes-Silva and Leandro Santos Costa

Received: 27 November 2025
Revised: 26 December 2025
Accepted: 29 December 2025
Published: 3 January 2026

1. Introduction

Africa contributes 2.6% (2,196,000 tons) to global aquaculture production [1], primarily driven by freshwater fish farming [2,3]. This production is dominated by tilapia in Egypt, along with tilapia and catfish in Nigeria and Ghana in West Africa. However, these volumes remain below the continent's true potential [4–6]. In Senegal, the potential for aquaculture production is estimated to be 12,000 tons per year by utilising 5% of the irrigated land in North Senegal [7]. Despite the establishment of a national aquaculture agency in 2014 and the recognition of aquaculture development as a governmental priority for accelerated economic growth [8], Senegalese aquaculture production remains low, amounting to only 1011 tons in 2020 [6]. 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 [9]. However, the aquaculture development policies implemented in recent years have provided only limited support for this sector, focusing predominantly on tilapia and catfish farming. 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 [8,9].

Over the past three decades, aquaculture production has experienced rapid growth, establishing itself as a viable alternative to fishing for providing seafood to the population [10]. This is particularly significant due to the overfishing of many commercially exploited fish stocks [11,12]. However, it is important to note that the claim that aquaculture is 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 [13,14], such as Sardinella [15,16]. Nonetheless, the statement can be considered plausible for aquaculture species that utilise 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 realise its potential for production and socioeconomic impact [4]. 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 [17]. 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. [18] proposed an evolutionary approach that combines local and external participation in technology development and emphasises the transfer of technical knowledge [19]. 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 [20].

Sustainability indicators [21,22] and composite indices are increasingly recognised as valuable tools for policymakers and communication efforts to convey information on country and corporate performance across various areas, including the environment, the economy, society, and technological advancements [23]. 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 [24–26]. 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 [27–30]. 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 using selected indicators that 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 utilised to evaluate the sustainability of fish farms, covering indicators related to fish health, welfare, environmental management, and social responsibility [31,32]. 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 focuses primarily on economic aspects [32]. 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 overlooks broader sustainability dimensions 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 [20,33].

Developing a farm sustainability assessment tool ensures sustainable farming practices [20,27,34]. 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 farm's specific needs and the desired outcomes of the assessment. Existing frameworks and tools, such as those proposed by Rey-Valette et al. [34] and Efole et al. [35], are valuable resources for developing an effective assessment tool.

The main objective of this work was to gain a localised 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 [27,28,36,37], 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 developed a context-specific set of sustainability indicators through participatory methods to assess key operational dimensions of tilapia farms in Senegal, focusing on locally relevant challenges.

2.1. Dimension, Principles, and Indicators

Sustainable development principles for territorial aquaculture sustainability were identified [38], integrating socioeconomic and environmental dimensions aligned with Bueno's [20] framework.

An interdisciplinary team (sociologists, economists, environmentalists, and aquaculturists) conducted field surveys to define core sustainability domains. Through iterative workshops with fish farmers and institutional partners, 19 contextually relevant indicators were co-constructed and validated [27,29,30,39] (Table 1):

- Environmental (7 indicators): Water management, waste handling, production efficiency, chemical usage, etc.
- Social (7 indicators): Labour conditions, gender inclusion, local market linkages, etc.

- Economic (5 indicators): Funding and Autonomy, Sales strategy, Diversity of farm products, Job-producing efficiency (ton per job), and Risk prevention and management system.

Table 1. The 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 commercialised 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

2.2. Sustainability Scoring System

Assessing the sustainability of fish farms involves associating reference values or thresholds with specific indicators [40]. The co-construction of the 19 indicators to evaluate the sustainability of African tilapia farms was based on their importance and the feasibility of measurement. Scaling the fish farm indicators for assessment enables evaluation of the impact of specific practices on fish health [41], the level of waste produced [42], and the farm's impact on local wildlife [43,44]. The sustainability tool covers fish health and welfare indicators (indirectly via chemical usage (hormones/antibiotics), environmental management, and social responsibility. The overall sustainability of the fish farm was assessed using 19 indicators, each rated on a scale from 1 to 5, with 1 indicating "poor" and 5 indicating "very good" sustainability. Thresholds were refined using expert input and statistical agency data. Farms were categorised into sustainability tiers (sustainable to unsustainable) based on cumulative scores (Table 2).

https://doi.org/10.3390/fishes11010027

Table 2. Selected indicators and their scaling according to the thresholds and data value available in fish farm literature review and the Senegalese Statistics National Agency (ANSD), 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 performed between 2013 and 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	Least Sustainable	Unsustainable	Moderately Sustainable	Sustainable	Most Sustainable
Scales [1]	1	2	3	4	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 specialised 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	1–20	21–40	41–50	>50
Rate of production commercialised 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 application	Existing and properly applied	4 + renew regularly

2.3. Farm Selection

The farm selection was carried out based on records obtained from two governmental agencies promoting aquaculture and second agriculture, namely the Agence Nationale de l'Aquaculture (ANA) and the 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 [45].

Three selection criteria for the farms 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 (Figure 1).

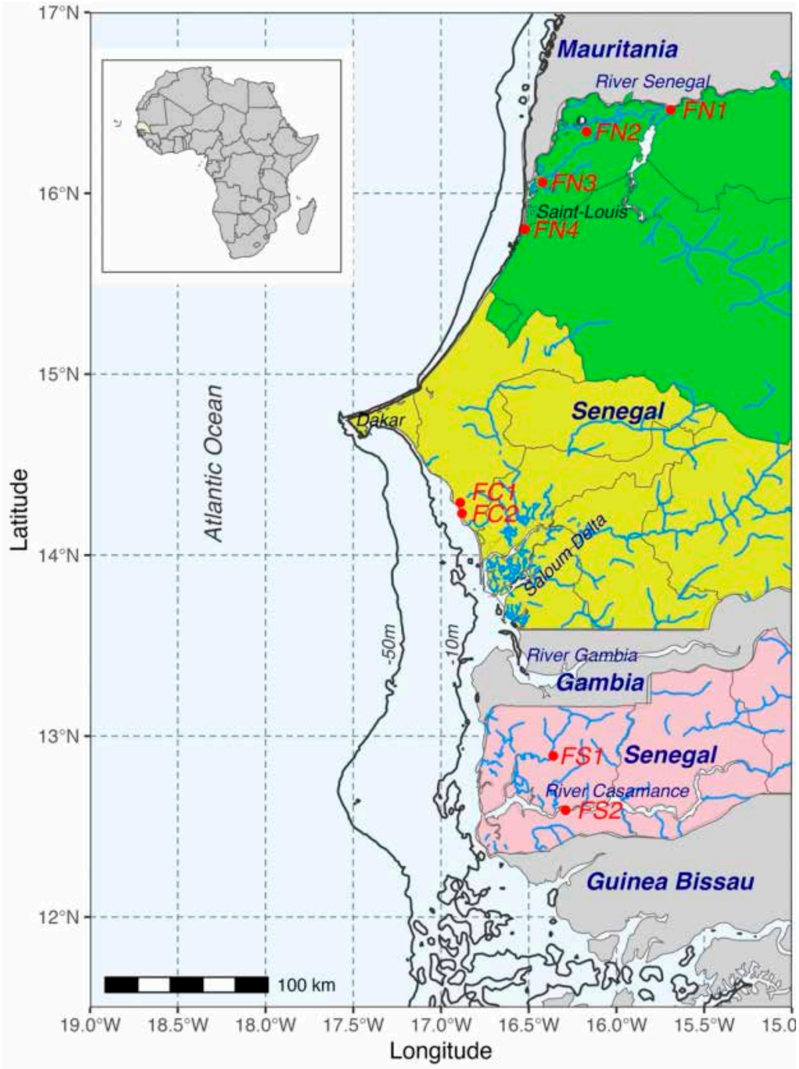

Figure 1. Location of tilapia selection farms within the study framework. These farms mainly concentrate on the country's north (green) coastline and the central part (yellow). FN1−4, FC1−2, FS1−2; F = farm, N = North, C = Centre and S = South (pink). Numbers 1, 2, 3, and 4 indicate the identification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

These criteria aimed to ensure the representativeness of farms with enhanced technology and consistent production across different regions [18]. The farms constituted 16% of Senegal's registered, active tilapia farms, enabling cross-regional comparisons. The farms are classified by location into the North (FN), the central region (FC), and the South (FS), each with an identification number (Table 3).

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 categorises the ownership as local, national, or foreign. FN1−4, FC1−2, FS1−2; F = farm, N = North, C = Centre, and S = South, numbers 1, 2, 3 and 4 were the farm identifier in the area N, C, and 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

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 [46] was used to gather all the measurable inputs after the co-construction stage to avoid bias, as performed before the participatory approach [47]. 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 each farm's activities and outcomes, enabling a thorough assessment of the data provided by the farmers [37]. 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 for each indicator were classified into five levels, with 5 being the "most sustainable" and 1 the "least sustainable" (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 indicator receiving any weighting [28]. The points obtained were added to obtain a value out of 95, the maximum possible. 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 [15].

3. Results

3.1. Farm-Level Sustainability Assessment

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

The environmental assessment focused on critical aspects of sustainable aquaculture, including water management, integration with other products, waste management, production efficiency, and the use of hormones, antibiotics, and chemicals. The farms were also evaluated on their use of non-indigenous species and the frequency of escape events (Table 4). 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.

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 = Centre, S = South, number 1, 2, 3; and 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*. "Rate of production" means "Rate of production commercialised in local markets".

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	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

The social assessment scrutinised 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 workforce's gender diversity and the farms' contributions to local markets. FN1 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 evaluated 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 twice 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 across all three dimensions were used to determine the farms' overall ranking. 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, respectively, highlighting the need for strategic interventions to improve their overall performance.

3.2. Sustainability Performance Across Ownership Categories and Production Systems

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 (Figure 2).

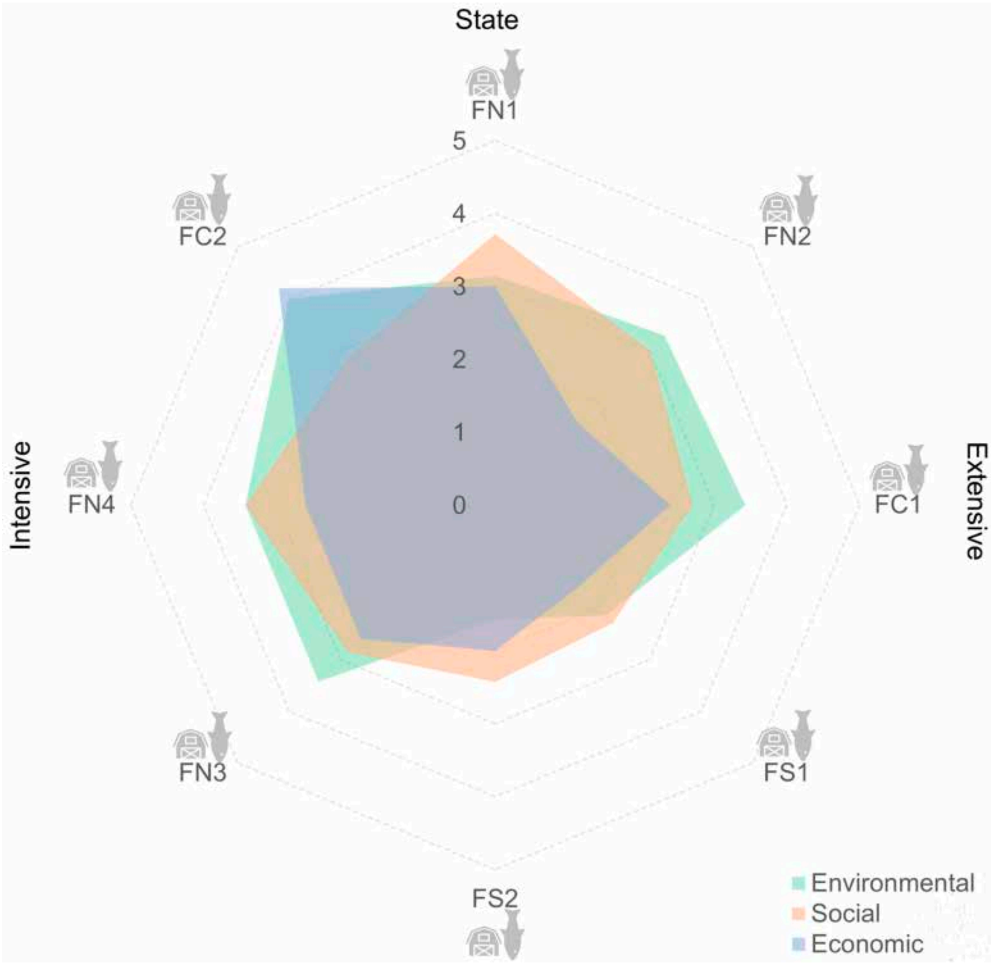

Figure 2. Mean indicator scores (scale 1–5) for the environmental (green), social (red), and economic (blue) sustainability dimensions for each assessed farm. FN1−4, FC1−2, and FS1−2 denote farms in the North, Centre, and South of Senegal, respectively. The polygon vertices represent the average score for each dimension, providing a visual profile of farm performance. State-owned (FN1), intensive private (FC2, FN4, FN3), and extensive private (FN2, FC1, FS1, FS2) farm types.

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 FN1, 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 FN1 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 FN1, also performed well with a subtotal of 12, indicating that public ownership does not necessarily hinder economic performance. Extensive private farms, such as FC1, achieved a subtotal of 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 FN1, 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.

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 interviewed farmers, production from state hatcheries (state farm type) was significantly limited, failing to meet 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 from resource constraints that prevent consistent, timely sorting of fingerlings. As a result, some fish farmers end up with a mixture of males and females rather than the desired monosex male population [46].

Another crucial challenge for fish farmers in developing a sustainable, thriving fish farming sector is the limited availability of high-quality fish feed [47]. 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 utilised in high-quality fish feed formulations, the formulas currently available in the market do not meet the specific requirements of fish farmers [11]. As a result, they often import fish feed from distributors in Western countries or in North African nations. The limited availability of high-quality fish feed further limits farm intensification efforts. Intensification requires a substantial supply of high-quality feed to maximise 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 will drive it to 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 [11].

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

https://doi.org/10.3390/fishes11010027

support is low (<10%) compared with the total production cost for intensive and extensive farms stated above. For state farms, 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 government's support for this sector. Most investments in the aquaculture industry go toward operational costs for government agencies and state-owned farms. However, these entities struggle to meet just one-tenth of the demand for fish feed and fingerlings. This situation raises concerns about the effectiveness of government support for the sector's development.

Preliminary feedback from farmers and institutional partners during the validation workshops was generally positive. Farmers appreciated that the indicators reflected their daily realities and constraints. They found the scoring system intuitive and saw the resulting profile as a useful diagnostic for self-assessment. Institutional actors valued the tool's structured approach to capturing multi-dimensional sustainability, identifying it as a potential support for targeting technical assistance. The main challenge cited was the difficulty for some farmers to recall or track precise economic data, underscoring the need for simplified record-keeping as part of sustainability improvement programmes. The choice of equal weighting for all indicators was a pragmatic decision for this first-stage tool. While different dimensions may hold varying importance, alternative weighting schemes (e.g., expert-based, Analytic Hierarchy Process) were not feasible due to the limited sample size and the risk of introducing external biases inconsistent with the participatory ethos. Future iterations of the tool should incorporate a structured participatory process to assign weights reflecting local stakeholder priorities.

Three distinct types of farms can be identified from our study. The "state farms" (Hatchery types) are the extensive and intensive farms. State farms, categorised as hatchery types, have production objectives centred on providing fingerlings. They employ highly trained personnel who receive substantial remuneration, higher than that received in the other types of fish farms, with equivalent qualifications. These farms also demonstrate workforce diversity, with a significantly higher proportion of female employees. The significant working capital needed to support their operations was public. The FN1 farm symbolises this type of farm, and its production objectives are less focused on commercialisation, instead aiming to support the activity, unlike the two other types of farms. It represents 10% of the farms. They have limited species diversity, focusing on domestic fish species whose reproduction is controlled, unlike extensive farms, which offer more comprehensive multitrophic diversity.

On the other hand, extensive farms prioritise 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 2 to 4 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 that benefit from project support funded by foreign donors (FC2 and FN4) achieve significantly higher economic results than those receiving support from both foreign and local donors (FN3). On the other hand, the latter compensates for its income through intensive 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 [48]. 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 utilise fish waste as fertiliser for crops, creating a sustainable production cycle [49–52]. 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. [28] state that sustainable development leads to transformative, productive and organisational 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 sustainability in its operations, aiming to manage natural resources effectively to meet human needs while preserving or enhancing environmental quality and conserving them [53]. 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 [23]. The level of integration with other products was used to consider environmental aspects and to highlight the efficient use of resources (waste) in the production of different products, thereby generating additional economic benefits [33,44]. 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 sustainability terms, although this is not always the case. The weight of indicators varies depending on community perceptions. 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 of acquiring data in specific contexts, particularly when farmers are reluctant to provide detailed information, especially on economic matters. 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 study's preliminary stages [54,55]. 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 utilisation in decision-making [55].

While Chary et al. [55] suggest that farm-scale models can be valuable tools for improving the sustainability of fish farming, our study takes a more localised and participatory approach. It emphasises 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 localised approach to sustainability monitoring for tilapia farms in West Africa and other low-income countries.

5. Conclusions

The sustainability-monitoring tool, developed through our collaborative approach, provides a practical means to assess tilapia farm performance and identify 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 (i) 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 sustainability interventions in the tilapia farming sector, including 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 the development and refinement of sustainable aquaculture practices. While this seems straightforward in theory, it requires the successful implementation of specific, medium-term practice programmes. Additionally, we recommend promoting sustainable aquaculture in low-income countries where small-scale farming is prevalent, and food sovereignty should be a governmental priority.

Author Contributions: Conceptualisation, W.N.N., A.M. and P.B.; methodology, W.N.N., A.M. and P.B.; validation, W.N.N., P.B., F.D. and H.D.D.; formal analysis, W.N.N. and P.B.; investigation, W.N.N., P.B., F.D. and H.D.D.; resources, W.N.N. and P.B.; data curation, W.N.N. and P.B.; writing—original draft preparation, W.N.N., A.M., K.B. and P.B.; writing—review and editing, W.N.N., P.B. and A.M.; visualisation, W.N.N. and P.B.; supervision, P.B.; project administration, W.N.N. and P.B.; funding acquisition, W.N.N., P.B. and H.D.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the ITACA project (EU-AU ACP) implemented by the CRODT, the AWA project (IRD-BMBF, grant 01DG12073E; Ecosystem approach to the management of fisheries and the marine environment in West African waters) implemented by the Sub-Regional Fisheries Commission (SRFC/CSRP), and the PamTilapia (FNRAA-WAPP 2) project as part of the World Bank's West Africa Productivity Program Phase 2 (2016–2017), implemented by CRODT.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Acknowledgments: This article is written in the context of the "Art Sunu Gueej" initiative (ISRA and IRD), a collaborative platform to act together and put into practice innovative solutions for the blue economy, the adaptation of the fisheries and aquaculture sectors to climate change, and the resilience of oceans and the climate. We want to thank the Senegalese farmers who participated in the study, as well as Moustapha Deme and Anis Diallo (ISRA/CRODT) for their assistance with data collection during the project.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ANA	Agence Nationale de l'Aquaculture
ANIDA	Agence Nationale d'Insertion et de Développement Agricole
AMS	Automate Monitoring System
CRODT	Centre de Recherches Océanographiques de Dakar-Thiaroye
FN	Farms in the North
FNRAA	Fonds national de recherches agricoles et agro-alimentaires
FC	Farms in the central region
FS	Farms in the South
ISRA	Institut Sénégalais de Recherches Agricoles
IRD	Institut de Recherche pour le Développement
ITACA	Improving the Productivity of Tilapia Farms and Hatcheries in Africa
SRFC	Sub-Regional Fisheries Commission

References

1. FAO. *The State of World Fisheries and Aquaculture 2020*; FAO Fisheries Department: Rome, Italy, 2020.
2. Tacon, A.G.; Metian, M.; Parsons, G.J.; Shumway, S.E. A Global Aquaculture and Aquafeed Production Update: 2010 to 2023. *Rev. Fish. Sci. Aquac.* **2025**, 1–10. [CrossRef]
3. Ndebele-Murisa, M.; Mubaya, C.P.; Dekesa, C.H.; Samundengo, A.; Kapute, F.; Yossa, R. Sustainability of Aqua Feeds in Africa: A Narrative Review. *Sustainability* **2024**, *16*, 10323. [CrossRef]
4. Aguilar-Manjarrez, J.; Nath, S.S. *A Strategic Reassessment of Fish Farming Potential in Africa*; CIFA Technical Paper, No. 32; 0379-5616-CIFA/T32; FAO: Rome, Italy, 1998; 170p, Available online: https://www.fao.org/4/w8522e/w8522e.pdf (accessed on 2 April 2024).
5. NEPAD. The NEPAD Agency Fisheries and Aquaculture Programme. 2015–2020. Available online: https://www.nepad.org/publication/nepad-agency-fisheries-and-aquaculture-programme (accessed on 15 January 2018).
6. ANSD. *Situation Economique et Social du Sénégal, Edition 2017–2018*; Agence Nationale de la Statistique et de la Démographie: Dakar, Senegal, 2020.
7. Diallo, A.; Diouf, P.S.; Ngom, M.; Ndiaye, V. L'Aquaculture (Pisciculture et Crevetticulture) Dans la Vallée du Fleuve Sénégal: Potentialité et Perspective. 2003. Available online: https://www.sidalc.net/search/Record/dig-aquadocs-1834-2222 (accessed on 22 April 2024).
8. Diadhiou, H.D.; Deme, M.; Mbaye, A.; Brehmer, P. Le développement de l'Aquaculture au Sénégal: Potentialités, production et difficultés. In *Book of Abstract ICAWA*; Sub-Regional Fisheries Commission: Dakar, Senegal, 2015; p. 113.
9. Ndiaye, W.N.; Diadhiou, H.D.; Nguer, A.T.; Niane, A.; Brehmer, P. Which technical and economic model of aquaculture is adapted to the Senegalese context? In Proceedings of the International Conference ICAWA 2016, Dakar, Senegal, 13–15 December 2016; SRFC/CSRP. pp. 131–132. Available online: https://www.documentation.ird.fr/hor/fdi:010072146 (accessed on 2 April 2024).
10. Folorunso, E.A.; Rahman, M.A.; Sarfo, I.; Darko, G.; Olowe, O.S. Catfish farming: A sustainability study at Eriwe fish farming village in southwest Nigeria. *Aquac. Int.* **2021**, *29*, 827–843. [CrossRef]
11. Baldé, B.S.; Fall, M.; Kantoussan, J.; Sow, F.N.; Diouf, M.; Brehmer, P. Fish-length-based indicators for improved management of the sardinella fisheries in Senegal. *Reg. Stud. Mar. Sci.* **2019**, *31*, 100801. [CrossRef]
12. Diankha, O.; Ba, A.; Brehmer, P.; Brochier, T.; Sow, B.A.; Thiaw, M.; Demarcq, H. Contrasted optimal environmental windows for both sardinella species in Senegalese waters. *Fish. Oceanogr.* **2018**, *27*, 351–365. [CrossRef]
13. Ndiaye, W.N.; Brehmer, P.; Deschamps, M.H.; Corréa, M.; Diédhou, F.; Kantoussan, J.; Vandenberg, G.W. West African context call for rapid implementation of insect meal for fishmeal substitution. *J. Insects Food Feed* **2022**, *8*, S137.
14. Deme, E.H.B.; Ricard, D.; Brehmer, P. Dynamics and mutations in the artisanal Senegalese fisheries management. From centralised resources management to participatory and sustainable dynamics. *Norois* **2019**, *252*, 55–72. [CrossRef]
15. Ba, K.; Thiaw, M.; Lazar, N.; Sarr, A.; Brochier, T.; Ndiaye, I.; Brehmer, P. Resilience of key biological parameters of the Senegalese flat sardinella to overfishing and climate change. *PLoS ONE* **2016**, *11*, e0156143. [CrossRef]
16. Ba, A.; Chaboud, C.; Brehmer, P.; Schmidt, J.O. Are subsidies still relevant in West African artisanal small pelagic fishery? Insights from long run bioeconomic scenarios. *Mar. Policy* **2022**, *146*, 105294. [CrossRef]
17. Brummett, R.E.; Lazard, J.; Moehl, J. African aquaculture: Realising the potential. *Food Policy* **2008**, *33*, 371–385. [CrossRef]
18. Brummett, R.E.; Williams, M.J. The evolution of aquaculture in African rural and economic development. *Ecol. Econ.* **2000**, *33*, 193–203. [CrossRef]

https://doi.org/10.3390/fishes11010027

19. Verceles, L.; Talaue-McManus, L.; Aliño, P. Participatory monitoring and feedback system: An important entry towards sustainable aquaculture in Bolinao, Northern Philippines. *Sci. Diliman* **2000**, *12*, 78–87.
20. Bueno, P.B. Indicators of sustainable small-scale aquaculture development. In *Measuring the Contribution of Small-Scale Aquaculture: An Assessment*; FAO Fisheries and Aquaculture Technical Paper; FAO: Rome, Italy, 2009; Volume 534, pp. 145–160.
21. Bell, S.; Morse, S. *Sustainability Indicators: Measuring the Immeasurable?* 2nd ed.; Earthscan: London, UK, 2012; 251p.
22. Ahimin, A.O.; Mikissa, J.B.; Johnson, S.; N'Guessan Kouamé, F.; Kamanzi, K. Implementing principles, criteria and indicators for sustainable forest management in Gabon. *J. Sustain. For.* **2019**, *38*, 46–53. [CrossRef]
23. Brehmer, P.; Do Chi, T.; Laugier, T.; Galgani, F.; Laloë, F.; Darnaude, A.M.; Fiandrino, A.; Mouillot, D. Field investigations and multi-indicators for shallow water lagoon management: Perspective for societal benefit. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2011**, *21*, 728–742. [CrossRef]
24. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainability assessment methodologies. *Ecol. Indic.* **2009**, *9*, 189–212. [CrossRef]
25. Kapetsky, J.M.A. *Strategic Assessment of Warm-Water Fish Farming Potential in Africa*; FAO: Rome, Italy, 1994; No. 27.
26. Lazard, J.; Rey-Valette, H.; Aubin, J.; Mathé, S.; Chia, E.; Caruso, D.; Clément, O. Evaluation of aquaculture system sustainability: A methodology and comparative approaches. In *Recent Advances in Fish Farms*; IntechOpen: London, UK, 2011; pp. 1–24. [CrossRef]
27. Chia, E.; Rey-Valette, H.; Lazard, J.; Clément, O.; Mathé, S. Évaluer la durabilité des systèmes et des territoires aquacoles: Proposition méthodologique. *Cah. Agric.* **2009**, *18*, 211–219. [CrossRef]
28. Rey-Valette, H.; Clément, O.; Mathé, S.; Lazard, J.; Chia, E. *Guide to the Co-Construction of Sustainable Development Indicators in Aquaculture*; Cirad; Ifremer; INRA, IRD, Université Montpellier 1; Diffusion Cirad-Montpellier: Montpellier, France, 2008; 144p, Available online: https://agritrop.cirad.fr/548450/ (accessed on 18 April 2024).
29. Rey-Valette, H.; Clément, O.; Mathé, S.; Lazard, J.; Chia, E. Quelques postulats relatifs aux indicateurs de développement durable: L'exemple de l'aquaculture. *Nat. Sci. Sociétés* **2010**, *18*, 253–265. [CrossRef]
30. Marchand, F.; Debruyne, L.; Triste, L.; Gerrard, C.; Padel, S.; Lauwers, L. Key characteristics for tool choice in indicator-based sustainability assessment at farm level. *Ecol. Soc.* **2014**, *19*, 46–56. [CrossRef]
31. De Olde, E.M.; Oudshoorn, F.W.; Sørensen, C.A.; Bokkers, E.A.; De Boer, I.J. Assessing sustainability at farm-level: Lessons learned from a comparison of tools in practice. *Ecol. Indic.* **2016**, *66*, 391–404. [CrossRef]
32. Sheikh, M.M.; Riar, T.S.; Pervez, A.K. Integrated Farming Systems: A Review of Farmers Friendly Approaches. *Asian J. Agric. Ext. Econ. Sociol.* **2021**, *39*, 88–99. [CrossRef]
33. Aguado, S.H.; Segado, I.S.; Pitcher, T.J. Towards sustainable fisheries: A multi-criteria participatory approach to assessing indicators of sustainable fishing communities: A case study from Cartagena (Spain). *Mar. Policy* **2016**, *65*, 97–106. [CrossRef]
34. Rey-Valette, H.; Laloë, F.; Le Fur, J. Introduction to the key issue concerning the use of sustainable development indicators. *Int. J. Sustain. Dev.* **2007**, *10*, 4–13. [CrossRef]
35. Efole Ewoukem, T.; Mikolasek, O.; Aubin, J.; Tomedi Eyango, M.; Pouomogne, V.; Ombredane, D. Sustainability of fish pond culture in rural farming systems of Central and Western Cameroon. *Int. J. Agric. Sustain.* **2017**, *15*, 208–222. [CrossRef]
36. Consensus—Sustainable Aquaculture in Europe. Defining Indicators for Sustainable Aquaculture Development in Europe: A Multi-Stakeholder Workshop Held in Ostende (Belgium), November 21–23, 2005, CONSENSUS, European Aquaculture Society. 2006. Available online: http://www.euraquaculture.info/files/CONSENSUS_Workshop.pdf (accessed on 4 March 2023).
37. Rey-Valette, H.; Damart, S.; Roussel, S. A multicriteria participation-based methodology for selecting sustainable development indicators: An incentive tool for concerted decision making beyond the diagnosis framework. *Int. J. Sustain. Dev.* **2007**, *10*, 122–138. [CrossRef]
38. Mbaye, A.A.; Lefèvre, F.G.; Sarr, A.; Sambou, C.; Gueye, A.; Gueye, F.; Sarr, K.Y.; Araba, A.C.; Gaye, C.A.B.; Dieng, M. *A Situational Analysis of Small-Scale Fisheries in Senegal: From Vulnerability to Viability—Challenges and Opportunities for Fisheries Governance*; V2V Working Paper 2022-2; V2V Global Partnership; University of Waterloo: Waterloo, ON, Canada, 2022.
39. Lancker, E.; Nijkamp, P. A policy scenario analysis of sustainable agricultural development options: A case study for Nepal. *Impact Assess. Proj. Apprais.* **2000**, *18*, 111–124. [CrossRef]
40. Opiyo, M.A.; Marijani, E.; Muendo, P.; Odede, R.; Leschen, W.; Charo-Karisa, H. A review of aquaculture production and health management practices of farmed fish in Kenya. *Int. J. Vet. Sci. Med.* **2018**, *6*, 141–148. [CrossRef] [PubMed]
41. Lee, T.C.; Pu'ad, N.M.; Alipal, J.; Muhamad, M.S.; Basri, H.; Idris, M.I.; Abdullah, H.Z. Tilapia wastes to valuable materials: A brief review of biomedical, wastewater treatment, and biofuel applications. *Mater. Today Proc.* **2022**, *57*, 1389–1395. [CrossRef]
42. Nol, P.; Rocke, T.E.; Gross, K.; Yuill, T.M. Prevalence of neurotoxic Clostridium botulinum type C in the gastrointestinal tracts of tilapia (*Oreochromis mossambicus*) in the Salton Sea. *J. Wildl. Dis.* **2004**, *40*, 414–419. [CrossRef]
43. Ndiaye, N.A.; Maiguizo-Diagne, H.; Diadhiou, H.D.; Ndiaye, W.N.; Diedhiou, F.; Cournac, L.; Brehmer, P. Methanogenic and fertilising potential of aquaculture waste: Towards freshwater farms energy self-sufficiency in the framework of blue growth. *Rev. Aquac.* **2020**, *12*, 1435–1444. [CrossRef]

44. N'Souvi, K.; Sun, C.; Zhang, H.; Broohm, D.A.; Okey, M.K.N. Fisheries and aquaculture in Togo: Overview, performance, fisheries policy, challenges and comparative study with Ghana, Mali, Niger and Senegal fisheries and aquaculture. *Mar. Policy* **2021**, *132*, 104681. [CrossRef]
45. Asiedu, B.; Nunoo, F.K. Alternative livelihoods: A tool for sustainable fisheries management in Ghana. *Int. J. Fish. Aquat. Sci.* **2013**, *2*, 21–28.
46. Senghor, M.L.; Diadhiou, H.D.; Sylla, K.B.; Ndiaye, W.; Fall, M. Effect of the 17 alpha Methyl testosterone hormone on market-size tilapia (*Oreochromis niloticus*) and evolution of the environment of the breeding environment. *Int. J. Vet. Sci. Agric. Res.* **2019**, *1*, 29–40.
47. Hoq, M.E.; Das, G.B.; Uddin, M.S. Integration of fish farming with poultry: Effects of chicken manure in polyculture of carps and freshwater prawn. *Indian J. Fish.* **1999**, *46*, 237–243.
48. Gilles, S.; Lacroix, G.; Corbin, D.; Bâ, N.; Luna, C.I.; Nandjui, J.; Lazzaro, X. Mutualism between euryhaline tilapia Sarotherodon melanotheron heudelotii and *Chlorella* sp.—Implications for nano-algal production in warmwater phytoplankton-based recirculating systems. *Aquac. Eng.* **2008**, *39*, 113–121. [CrossRef]
49. Wilde, N.D.; Gilles, S. Production of marine tilapia in a closed circuit in green water: The Integral Recycling Aquaculture System (SARI). *Aquac. Compend.* **2010**, 109409. [CrossRef]
50. Ayinde, O.E.; Ibrahim, H.K.; Salami, M.F.; Ajibola, L.E. Effect of vertical integration on multidimensional well being of fish farmers in lagos state fish hub, Nigeria. *Agric. Trop. Subtrop.* **2017**, *50*, 81–87. [CrossRef]
51. TAC/CGIAR. *A Technical Advisory Committee of the Consultative Group on International Agriculture Research. Sustainable Agricultural Production: Implications for International Agricultural Research*; The World Bank: Washington, DC, USA, 1989.
52. Barreteau, O.; Bots, P.; Daniell, K.; Etienne, M.; Perez, P.; Barnaud, C.; Trebuil, G. Participatory approaches. In *Simulating Social Complexity. Understanding Complex Systems*; Edmonds, B., Meyer, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 197–234. [CrossRef]
53. Roque, A.; Wutich, A.; Quimby, B.; Porter, S.; Zheng, M.; Hossain, M.J.; Brewis, A. Participatory approaches in water research: A review. *Wiley Interdiscip. Rev. Water* **2022**, *9*, e1577. [CrossRef]
54. Andalecio, M.N. Multi-criteria decision models for management of tropical coastal fisheries. A review. *Agron. Sustain. Dev.* **2010**, *30*, 557–580. [CrossRef]
55. Chary, K.; Brigolin, D.; Callier, M.D. Farm-scale models in fish aquaculture—An overview of methods and applications. *Rev. Aquac.* **2022**, *14*, 2122–2157. [CrossRef]