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Economic performance and scalability of small-scale aquaculture systems: a comparative analysis of pond, cage, and aquaponics systems in the Lake Victoria basin, Uganda

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Abstract
This study evaluates the economic performance, scalability, and resource efficiency of three small-scale aquaculture systems ponds, cages, and aquaponics in the Lake Victoria basin, Uganda. Data were collected from 169 respondents across Buikwe, Mpigi, and Wakiso districts through structured interviews, production records, and field observations. Financial performance was assessed over 5 years using net present value (NPV) and benefit–cost ratio (BCR) as key indicators. Results show that cage culture is the most economically viable and scalable system, with a BCR of 1.10 and a cumulative NPV of USD 1327.10, driven by efficient water use and high turnover. Pond systems were economically feasible, with a BCR of 1.03 and an NPV of USD 266.74, but they had limited scalability due to land requirements and lower long-term returns. Aquaponics systems were economically unsustainable, showing a BCR of 0.66 and a negative NPV of USD 3150.05, mainly because of high input costs and technical complexity. The study highlights the need for targeted interventions such as affordable input access, infrastructure development, and financial support to improve less profitable systems. Policy support, technological innovation, and capacity-building initiatives are recommended to boost productivity, increase adoption, and promote sustainable aquaculture development.

Keywords Economic performance, Net present value (NPV), Benefit cost ratio (BCR), Scalability, Resource efficiency, Financial sustainability, Aquaculture systems

1 Introduction

Small-scale aquaculture is as a vital livelihood strategy for communities within the Lake Victoria basin, contributing to food security, income generation, and employment opportunities [4, 20, 22]. The rising demand for fish as a primary source of animal protein driven by rapid population growth and the decline of wild fish stocks has accelerated the adoption of various aquaculture production systems, including pond culture, cage culture, and more recently, aquaponics [17, 19]. These systems vary considerably in their input demands, infrastructural requirements, technical complexity, and labour intensity, all of which influence their suitability and scalability within different socioeconomic and ecological settings [18, 30].

While pond and cage systems have been practiced in the Africa for decades, aquaponics a closed-loop system integrating aquaculture with hydroponic plant production has gained attention due to its efficient resource use and environmental sustainability [25, 31]. By recycling nutrient-rich effluent from fish tanks to nourish plants, aquaponics minimises water use and reduces waste output, offering a promising solution for land- and water-constrained urban and peri-urban areas [31]. Furthermore, its potential to localise food production contributes to reduced greenhouse gas emissions by decreasing reliance on long-distance transportation and cold-chain infrastructure [32].

However, aquaponics systems often require high initial capital investment, technical expertise, and intensive management, which pose significant barriers to adoption among resource-constrained and small-scale farmers [22, 26]. Pond and cage aquaculture systems typically entail lower start-up costs and technical demands, making them more accessible to rural smallholders [25, 29]. Nonetheless, these systems are not without limitations, as they are susceptible to environmental variability, disease outbreaks, and challenges related to water quality and availability [19, 24]. Additional barriers such as limited market access, high feed costs, and inadequate extension services further constrain their scalability [28, 33].

The Lake Victoria basin in Uganda remains a critical ecological and economic zone, supporting millions of livelihoods through fisheries and aquaculture [3, 24]. Yet, increasing environmental pressures, including overfishing, pollution, land-use change, and climate variability, are undermining the productivity and resilience of natural fish stocks [3, 23]. These trends highlight the need to develop scalable aquaculture systems that can sustainably meet local food and economic needs [4, 9]. In this context, scalability encompasses not only the technical feasibility of expanding production systems, but also the social, economic, and institutional conditions that enable their successful replication across different community contexts [30]. Evaluating scalability therefore requires a multidimensional framework that incorporates access to financial capital, land and water resources, supportive regulatory policies, and the availability of technical training and extension services [33]. In Uganda, initiatives aimed at promoting aquaculture including policy reforms, capacity building, and institutional support have shown varying degrees of success [19, 22]. Moreover, persistent gender disparities in access to resources, decision-making power, and training opportunities continue to hinder equitable growth in the sector [20, 28, 34].

Despite the increasing adoption of aquaculture practices, comprehensive comparative analyses of the economic performance and scalability of pond, cage, and aquaponics systems in remain scarce [17]. Most existing studies focus on individual production systems or isolated case studies, limiting broader understanding of which systems offer the greatest potential for sustainable, inclusive, and context-specific scaling [25, 30]. This study provides a comparative assessment of the scalability of pond culture, cage culture, and aquaponics systems in Uganda's Lake Victoria basin. The findings inform evidence-based decision-making by policymakers, development agencies, and other stakeholders committed to advancing sustainable aquaculture.

2 Materials and methods

2.1 Study area

This study was conducted in the districts surrounding Uganda's Lake Victoria basin, specifically Buikwe (0.761029°N, 33.040723°E), Wakiso (0.054163°N, 32.518079°E), and Mpigi (0.305544°N, 32.037822°E) (Fig. 1). These districts were selected due to their active engagement in small-scale aquaculture interventions and the significant role of fish farming in local livelihoods. The Lake Victoria basin serves as a critical ecological and economic hub, particularly for aquaculture and capture fisheries, which contribute substantially to food security, household income, and employment. In addition to fisheries, these districts also support diverse agricultural activities. Mpigi and Wakiso are well known for coffee cultivation, while Buikwe is a key area for sugarcane production. Farmers in these regions grow a wide variety of crops, including bananas, cassava, potatoes, maize, beans, and pineapples, as well as horticultural products like tomatoes and vegetables. Livestock farming is also an integral part of the agricultural systems, with dairy and beef cattle, goats, and poultry being commonly reared [10]. The combination of favorable altitude and consistent rainfall makes these districts particularly suitable for integrated agriculture–aquaculture systems, enhancing both productivity and sustainability in rural livelihoods.

2.2 Study design

This study employed a quantitative and qualitative, comparative cross sectional design to assess and compare the economic, technical, and socioeconomic aspects of three small-scale aquaculture practices; pond system, cage system, and aquaponics.. A cross sectional design was chosen because it enables the collection of data at a specific point in time, making it ideal for providing a snapshot of the current status of each aquaculture system. This approach allowed the study to directly compare the economic performance, technical feasibility, and socioeconomic implications of each system, offering a broader understanding of their relative scalability. The comparative nature of the design facilitated an exploration of differences in the systems' operational and economic metrics, providing findings into the factors that influence their potential for expansion across different communities. In addition to comparing the three systems, this methodology enabled the study to assess the scalability of each aquaculture practice by analyzing factors such as (BCR) and Net Present Value (NPV. These measures were critical in determining which system offers the most sustainable and economically viable and scalable

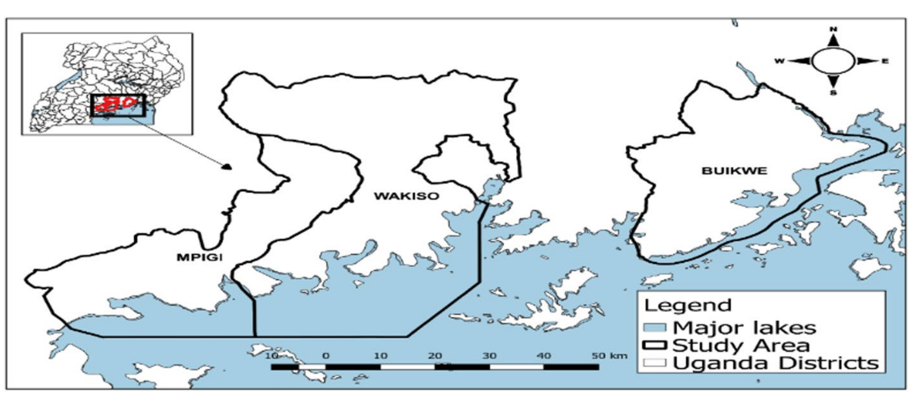

Fig. 1 Geographical location of the study area

option for small-scale farmers. The study design also incorporated socioeconomic indicators to account for factors such as accessibility to resources, gender dynamics, and market integration, which are essential considerations in evaluating the overall feasibility of scaling up aquaculture practices.

2.3 Population and sample size

The target population comprised small-scale aquaculture farmers operating within the Lake Victoria basin. These farmers were involved in one of three primary aquaculture systems: pond, cage, or aquaponics. A total of 169 respondents were included in the study, distributed as follows: 117 farmers using pond culture, 39 using cage culture, and 13 using aquaponics. The sample distribution was based on a stratified sampling technique, which grouped farmers by aquaculture system. This method was employed to ensure proportional representation of each aquaculture practice within the study sample, reflecting their actual prevalence in the Lake Victoria basin. Pond aquaculture system, being the most widely adopted system, constituted the largest stratum, followed by cage culture and aquaponics, respectively. This approach enhanced the representativeness of the sample and allowed for more accurate comparative analyses across the three systems. The use of stratified sampling is particularly appropriate in this context as it improves the statistical efficiency of the study and ensures that even less common practices such as aquaponics were adequately captured. Furthermore, this sampling method supports the study's objective of assessing the scalability of each system by ensuring that system-specific factors influencing adoption and expansion are reliably captured within each subgroup. To minimise potential biases, additional care was taken to ensure that within each stratum, respondents were selected from a range of geographic locations across the basin and from farms of varying sizes. This intra-stratum diversity helped account for location differences in environmental conditions, infrastructure access, and market proximity, as well as operational differences tied to farm scale.

2.4 Data collection

Data were collected through structured questionnaires and interviews, which were designed to capture both qualitative and quantitative information from aquaculture farmers. The questionnaires included sections on the economic performance of the systems, including costs, revenues, and profitability metrics, as well as operational details such as fish production yields, resource utilization, and input/output ratios. Socioeconomic factors, such as access to land, water, and financial resources, were also included to assess the broader enabling environment for aquaculture. Additionally, the questionnaires gathered information on the farmers' educational background, gender, and household dynamics, as these are important factors in understanding the socioeconomic context of aquaculture scalability [16]. Interviews were conducted with a subset of respondents to gather more detailed qualitative data, including the challenges faced by farmers in implementing these systems, their perceptions of the systems' sustainability, and the role of local government and development agencies in supporting aquaculture. These interviews allowed for a deeper exploration of the factors influencing the scalability of each system, providing valuable contextual information that complemented the quantitative data. All data collection instruments were pretested to ensure clarity, validity, and reliability before the full scale study.

2.5 Data analysis

Data were analyzed using both descriptive and inferential statistical techniques. Descriptive statistics such as means, medians, and standard deviations were used to summarize the economic, technical, and socioeconomic aspects of the different aquaculture systems. Inferential statistics, including analysis of variance (ANOVA) and regression analysis, were employed to compare the economic performance of the systems across the three aquaculture types and to examine the relationships between various factors influencing scalability. In particular, the study focused on key economic metrics such as Benefit Cost Ration (BCR) and net present value (NPV), which were calculated for each system to assess their financial viability and potential for scaling up. To ensure robustness and contextual relevance of the economic evaluations, the NPV calculations were based on projected cash flows over a 5-year investment horizon, incorporating annual net returns for each system. Costs included both capital expenditures and operational costs, which were discounted to present value using a 10% discount rate. This rate reflects the opportunity cost of capital in Uganda's agricultural sector and aligns with benchmarks used in similar studies. Revenue projections were based on reported average selling prices and production volumes obtained from primary survey data and validated with regional market data market prices over the past 5 years. To account for variability, sensitivity analysis was conducted on key cost and revenue parameters, assessing how changes in input prices, yields, or market prices would impact NPV and BCR outcomes. Econometric analysis was conducted using multiple linear regression models to examine the determinants of financial performance (NPV and BCR) across systems. Independent variables included system type (dummy-coded), farm size, access to extension services, distance to market, and years of farming experience. The models were estimated using ordinary least squares (OLS), and diagnostic tests were performed to assess multicollinearity, heteroscedasticity, and model specification errors. Adjusted R-squared values and significance levels were reported to evaluate model fit and explanatory power. This econometric framework allowed the study to identify key drivers of profitability and scalability while controlling for potential confounding factors.

Net Present Value (NPV) formula to account for the time value of money:

$$\mathrm{NPV} = \sum_{\mathrm{T}=0}^{\mathrm{T}} \frac{\mathrm{B_t} - \mathrm{C_t}}{(1+\mathrm{r})^{\mathrm{t}}}$$

where: $\mathrm{B_t}$ = benefits in year t (These benefits are defined by the revenue from fish production: Quantity x market price). $\mathrm{C_t}$= cost in year t (capital investments + operational costs + maintenance costs). r= discount rate (reflecting opportunity cost or interest rate), given at 10%. T = time horizon, system of 5 years.

On the other hand, Benefit Cost Ration was obtained using the formula below;

$$\mathrm{BCR} = \frac{\text{Total Present Value of Benefits}}{\text{Total Present Value of Costs}}$$

where by the decision criterion is; If BCR > 1: The system is economically feasible. If BCR < 1: The system is not economically feasible.

Additionally, the study employed econometric models to estimate the impact of socioeconomic variables on the performance and scalability of aquaculture systems. This included analyzing the influence of factors such as gender, education level, and access to financial resources on the scalability of different systems. The results were then compared to determine which system pond culture, cage culture, or aquaponics is most suitable for expansion in the context of the Lake Victoria basin, considering both economic and social factors. Furthermore thematic analysis was done for qualitative data.

3 Results and discussion

3.1 Challenges and perceptions of aquaculture sustainability

These results highlight key factors affecting the long-term viability and productivity of aquaculture practices (Table 1). The findings suggest that while aquaculture holds promise, there are hurdles that need to be addressed to improve its overall viability and scalability. The major challenges identified are: Water quality management was the most commonly reported challenge, with 45% of respondents acknowledging it. Water quality is crucial in aquaculture as it directly affects the health and growth of aquatic species, and poor water management can lead to fish disease outbreaks and high mortality rates. This finding aligns with other studies [16], which emphasize that poor water quality, particularly in small-scale, extensive systems, is a critical limiting factor in aquaculture productivity. According to Edwards et al. [7], water quality management techniques such as proper filtration systems, water circulation, and regular monitoring are essential for maintaining high yields and minimizing environmental impact in intensive aquaculture systems. The need for better water management practices is further compounded by the increasing competition for water resources [10]. Disease outbreaks were reported by 40% of respondents as a challenge on fish farming. This is consistent with findings from other studies, such as those by Reverter et al. [31], which suggest that disease is one of the major threats to the sustainability of aquaculture systems worldwide. Intensive systems, which often have higher stocking densities, are more vulnerable to disease transmission. The high incidence of disease in aquaculture is linked to factors such as poor water quality, overcrowding, and inadequate biosecurity measures [11]. The respondents' concerns over disease outbreaks highlight the need for improved management practices, such as disease surveillance, vaccination programs, and biosecurity protocols, to prevent and mitigate disease risks. High feed costs was a challenge, reported by 35% of respondents. Feed is the largest operational cost in aquaculture, accounting for up to 60–70% of total production costs [34]. This issue has been widely recognized, with authors highlighting the need for more cost-effective and sustainable feed options [27]. Alternative feed sources, such as plant-based or insect-based feeds, have been proposed as potential solutions to reduce feed costs and reliance on fishmeal [34]. Additionally, the development of feed efficiency technologies and practices, such as precision feeding, could help mitigate the impact of rising feed costs on aquaculture profitability [12]. Lack of Technical Expertise was identified by 30% of respondents as a major barrier. This challenge

Table 1 Challenges and perceptions of aquaculture sustainability

Challenge	Percentage of respondents reporting issue (%)	Respondents (n = 169)
Water quality management	45	76
Fish disease outbreaks	40	68
High fish feed costs	35	59
Lack of technical expertise	30	51
Access to market	25	42
Climate variability	20	34

is often associated with limited access to training and knowledge in rural or resource-limited settings. Previous studies, such as those by Adekoya and Faturoti [2], highlight that aquaculture farmers, particularly in developing countries, often lack access to training programs that teach modern aquaculture practices, including water quality management, disease control, and efficient feeding strategies. Technical expertise is essential for optimizing production systems and ensuring sustainability. Therefore, investing in training programs and extension services is crucial for improving the knowledge and skills of aquaculture farmers [16, 28]. Access to market was reported as a challenge by 25% of respondents, which is consistent with findings from study by [23]. Limited access to markets can restrict farmers' ability to sell their products, often leading to lower prices or the inability to reach larger, more lucrative markets. Smallholder farmers, in particular, face difficulties due to limited transportation, inadequate cold chain infrastructure, and poor market information systems. A study by Dey et al. [6] suggests that improving market access through better infrastructure, organized value chains, and market information systems could improve the economic viability of small-scale aquaculture operations. Climate variability was cited as a challenge by 20% of respondents. Climate change including temperature fluctuations, changes in rainfall patterns, and extreme weather events has become an increasingly important issue in aquaculture [32]. These changes can affect water temperature, salinity, and the availability of water resources, which are crucial factors in aquaculture productivity. In regions where aquaculture is heavily dependent on natural water bodies, climate variability poses a significant threat to sustainability. Previous studies have stressed the importance of adaptive management strategies, such as adjusting stocking densities and improving water management practices, to cope with the effects of climate change on aquaculture [4]

3.2 Impact of socioeconomic factors on the performance of aquaculture

The results in Table 2 indicate that both gender and access to financial resources influence aquaculture system performance, with important implications for scalability. The positive coefficients for gender 0.15 for pond system, 0.12 for cage system, and 0.18 for aquaponics ($p<0.05$) suggest that being male is associated with moderately better outcomes across all systems. This likely reflects underlying disparities in access to resources, labor, and decision-making roles, highlighting the need for targeted interventions to remove structural and cultural barriers that limit women's participation and success in aquaculture. Similarly, access to financial resources shows the strongest positive effect 0.45 for pond culture, 0.55 for cage culture, and 0.4 for aquaponics ($p<0.001$) indicating that financial capital is a key driver of performance, enabling investment in better inputs, infrastructure, and training. Therefore, improving financial inclusiveness through credit schemes, subsidies, or grants, along with promoting gender equity, is essential for enhancing the scalability and overall impact of aquaculture technologies. The results

Table 2 Impact of socioeconomic factors on the performance of aquaculture systems

Variables	Pond culture	Cage culture	Aquaponics	*p* value
Gender (male/female)	0.15	0.12	0.18	$p<0.05$
Education level	0.2	0.35	0.25	$p<0.01$
Access to financial resources	0.45	0.55	0.4	$p<0.001$
Age of fish farmer	0.05	0.1	0.08	$p>0.1$
Experience in fish farming	0.25	0.3	0.2	$p<0.05$

(Table 2) further reveal several important socioeconomic factors that influence the performance of different aquaculture systems. A key finding was the positive effect of gender on the performance of aquaponics, with male farmers reporting better results in this system. This aligns with findings by Kato et al. [16], who noted that male farmers often dominate certain forms of agriculture and aquaculture due to a combination of cultural norms and access to resources. The increased attractiveness of aquaponics to male farmers may stem from the relatively new and innovative nature of the system, which could appeal to male farmers who may be more likely to engage with novel technologies [14]. However, the influence of gender on both pond and cage culture was less pronounced, with males showing only marginally higher participation rates, suggesting that gender may play a more nuanced role in the scalability of different aquaculture systems. Previous studies, such as those by Muir et al. [23], have also shown that gender often has limited influence on traditional aquaculture systems, where both males and females are equally involved, but the dynamics can shift when new, capital-intensive systems are introduced. Education level emerged as another crucial determinant, with a stronger positive impact on the performance of cage culture (coefficient of 0.35). This suggests that individuals with higher education levels are more likely to adopt and perform better in systems that require technical expertise, such as cage culture. This finding supports the study by Reverter et al. [31], who emphasized that technical knowledge is critical for the successful implementation and operation of intensive systems, where understanding water management, disease control, and feeding strategies is essential. Education also showed a positive correlation with pond culture and aquaponics, though the effect was less pronounced. This suggests that while education facilitates better performance in all systems, the technical requirements are more demanding in cage culture, making education an even more significant factor in its adoption. The most remarkable finding from the analysis was the significant role of financial resources, which had the highest impact on the adoption of cage culture (coefficient of 0.55). Cage culture, being a capital-intensive system, requires substantial upfront investment in infrastructure, such as cages, nets, and water quality management systems. Farmers with greater access to financial resources are thus more likely to invest in such systems, which have higher operational costs but also higher potential returns. This result is consistent with Tacon and Metian [34], who highlighted that financial capital is often a key barrier to the widespread adoption of intensive aquaculture systems. Pond culture and aquaponics also showed significant, albeit lower, effects, underscoring the importance of financial support for all types of aquaculture. This suggests that access to financing, either through government programs or private investment, could play a pivotal role in promoting aquaculture as a sustainable livelihood option for smallholder farmers. Interestingly, the analysis found no significant effect of age on system performance, suggesting that both younger and older farmers were equally likely to engage with all three types of aquaculture. This is consistent with the findings of Adekoya and Faturoti [2], who suggested that age is less likely to be a determining factor in the aquaculture technologies, particularly in contexts where aquaculture is a traditional practice and older farmers are as involved as younger ones. Experience in aquaculture was another important determinant of success. More experienced farmers were more likely to adopt pond culture and cage culture, with moderate but significant impacts on their performance (coefficients of 0.25 and 0.30, respectively). This result is consistent with studies by Dey et al. [6] and Edwards et al. [8], which found that prior experience plays a critical role in the effective management of aquaculture systems, especially in systems like pond and cage culture that require knowledge of water quality management and disease control [15]. In contrast, experience had a lesser effect on aquaponics, suggesting that this system may appeal more to farmers with less prior experience, or those willing to invest time in learning new techniques. The relative ease of entry into aquaponics, with lower capital requirements and a focus on integrated, multifunctional farming, may make it more accessible to novice or less experienced farmers. Overall, the econometric models indicate that cage culture is the most scalable system in the Lake Victoria basin, primarily driven by financial access and higher educational levels. This finding aligns with other studies that have highlighted the potential for intensive aquaculture systems to generate higher returns on investment when the necessary financial and technical support is available [12]. However, both pond system and aquaponics show promise, particularly for farmers with lower capital or educational barriers. This suggests that targeted interventions, such as financial support, education programs, and extension services, could enhance the sustainability of these systems.

3.3 Viability and scalability of aquaculture systems in the Lake Victoria basin

The comparative economic assessment of small-scale aquaculture systems, including pond systems, cage systems, and aquaponics, shows differences in financial performance. The cage system emerged as the most economically viable option, achieving a benefit–cost ratio (BCR) of 1.10 and a cumulative net present value (NPV) of 1327.10 USD over a 5-year horizon. Annual NPVs remained positive throughout, starting at 318.26 USD in Year 1 and tapering to 217.38 USD by year 5, indicating consistent profitability. This strong performance is supported by a total revenue of 5200 USD against an operating cost of 4108 USD, with major cost components including feed (1092 USD), fingerlings (257 USD), labor (2340 USD), energy (195 USD), maintenance (325 USD), and other operational expenses (156 USD), resulting in a net revenue of 1092 USD. Pond culture, while still profitable, demonstrated limited scalability with a lower BCR of 1.03 and a cumulative NPV of 266.74 USD. Yearly NPVs declined from 63.97 USD to 43.69 USD over the 5-year span. The system incurred a total cost of 2158 USD primarily in feed (624 USD), labor (1170 USD), and other inputs yielding a net revenue of 962 USD from a total revenue of 3120 USD. While pond systems remain a feasible option for farmers with constrained capital, their long-term sustainability hinges on improvements in operational efficiency, particularly in feed and water management (Table 3).

Aquaponics, in contrast, underperformed financially despite its environmental appeal. It recorded a BCR of 0.66 and a cumulative NPV of – 3150.05 USD, with annual NPVs consistently negative from – 755.43 USD in year 1 to – 515.97 USD in year 5. The high operating cost of 3250 USD driven by labor (1560 USD), feed (1170 USD), energy (200 USD), and other inputs outweighed its total revenue of 3705 USD, resulting in a modest net revenue of 455 USD.

Sensitivity analyses demonstrated that reducing operational costs by 10%, 20%, and 30% led to incremental financial improvements: net revenue increased to 706 USD, 937 USD, and 1308 USD, respectively, and mean NPVs improved from – 630.01 USD to – 328.80 USD. However, even under a 30% cost reduction scenario, NPVs remained negative, indicating that cost efficiency alone may not be sufficient for financial sustainability.

Table 3 BCR and NPV analysis for scalability of the small-scale aquaculture systems

Parameter	Pond system	Cage system	Aquaponics	Aquaponics (10% cost reduction)	Aquaponics (20% Cost reduction)	Aqua-ponics (30% cost reduction)
Feed cost	624	1092	1170	1053	936	819
Fingerlings	125	257	134	134	134	134
Labor cost	1170	2340	1560	1404	1248	1092
Energy cost	104	195	200	180	160	140
Maintenance cost	156	325	234	211	187	164
Other operational cost	104	156	130	117	104	91
Total operating cost	2158	4108	3250	2999	2768	2397
Total Revenue	3120	5200	3705	3705	3705	3705
Net revenue	962	1092	455	706	937	1308
Mean NPV	53.35	265.42	− 630.01	− 479.89	− 404.34	− 328.8
SD (NPV)	8.02	39.9	94.72	–	–	–
Mean BCR	1.03	1.10	0.66	–	–	–
SD (BCR)	0.103	0.11	0.066	–	–	–
NPV 1	63.97	318.26	− 755.43	− 679.89	− 604.34	− 528.8
NPV 2	58.15	289.33	− 686.76	− 618.08	− 549.41	− 480.74
NPV 3	52.87	263.02	− 624.32	− 561.89	− 499.46	− 437.02
NPV 4	48.06	239.11	− 567.57	− 510.81	− 453.74	− 396.7
NPV 5	43.69	217.38	− 515.97	− 464.37	− 412.77	− 361.16
Total NPV	266.74	1327.10	− 3150.05	− 2835.05	− 2520.04	− 2205.04

$1 USD = UGX 3750

This underscores the need for comprehensive support strategies, including government-backed subsidies, innovative financing models for example microloans, or public private partnerships that could offset start up and operational burdens [5, 13]. Furthermore, targeted training and extension services could enhance technical efficiency and reduce input waste, indirectly improving profitability.

These findings align with previous studies [14, 22] highlighting Cage culture's scalability through efficient resource use and production intensity, while also reflecting documented challenges in Pond culture scalability due to suboptimal input management [1, 27]. Likewise, the financial limitations of aquaponics reinforce earlier evidence of high capital and technical demands acting as barriers to adoption in resource-constrained contexts [19, 21].

3.4 Qualitative insights on scalability challenges from aquaculture famers

A recurring concern across all three districts was the difficulty in maintaining consistent water quality. Farmers in Buikwe, for example, frequently rely on natural water bodies, which become heavily compromised during dry spells. 10 farmers in explained, *"We often have to rely on natural water sources, and during the dry season, the water quality deteriorates rapidly. It's hard to keep the fish healthy when the water turns muddy, and we don't have enough funds to invest in filtration systems."* This underscores the widespread lack of access to water treatment technologies and technical knowledge related to water quality management. Disease outbreaks were also cited as a persistent challenge, particularly in densely stocked ponds in Mpigi. Several farmers expressed frustration over the lack of veterinary support and the absence of affordable or effective disease management tools. One farmer from Mpigi shared, *"We have had several outbreaks of fish diseases, and it's always hard to know how to prevent them. Sometimes it feels like there's no* *solution, especially in crowded ponds. The government should do more to support us with vaccines or better diagnostic tools."* These concerns reflect the limited technical extension services available to many rural fish farmers. Feed affordability and availability emerged as another major issue. In Wakiso, where some farms operate at a semi-commercial level, fluctuations in feed prices were particularly impactful. A respondent from this area remarked, *"Feed prices have gone up a lot in recent years. It's hard to keep up. We've tried using alternative feeds like plant-based ingredients, but they don't always give the same results as fishmeal."* The cost and inconsistency of feed sources remain a financial burden, particularly for farmers operating with minimal margins. Lack of formal training was also identified as a significant barrier to effective aquaculture management. Farmers in Buikwe noted they began farming without any structured education or guidance. One farmer stated, *"I didn't receive any formal training before starting my farm. I learned by trial and error. It would have been great to have some experts come and show us how to manage the ponds and improve production."* This reveals the urgent need for targeted capacity-building programs and field-based training workshops to enhance technical knowledge. Infrastructure and market access constraints were particularly acute in Mpigi, where some farmers reported high transport costs and spoilage due to poor road networks. A respondent from Mpigi commented, *"We produce a lot of fish, but there's no market nearby, and transporting the fish to town is expensive. By the time I get there, the fish may not be fresh anymore, and it's hard to sell them at a good price."* These challenges reduce profitability and discourage expansion efforts. Climate variability was another critical concern raised in all three districts. Farmers reported erratic weather patterns that disrupt pond conditions and management schedules. One farmer in Buikwe observed, *"The weather has become so unpredictable. Some years, we have too much rain, and the ponds overflow; other years, there's not enough water. It's hard to plan when you can't rely on the weather."* These conditions point to the pressing need for climate-adaptive aquaculture strategies and infrastructure, such as rainwater harvesting systems and improved pond designs.

3.5 Conclusion and recommendations

The scalability assessment indicates that cage aquaculture is the most financially viable and scalable small-scale aquaculture system in the Lake Victoria basin. It provides the highest return on investment, as evidenced by both the benefit–cost ratio (BCR) and net present value (NPV) calculations, making it the most suitable option for farmers seeking to expand their operations. The pond system offers moderate financial returns and remains a feasible option, although its scalability is limited. In contrast, the aquaponics system faces significant financial challenges and is not recommended for expansion under the current financial conditions. Policymakers and stakeholders in the aquaculture industry must consider these economic factors when making decisions about supporting or promoting small-scale aquaculture systems in the region. Cage aquaculture has demonstrated substantial financial potential. To enhance its scalability, increased access to affordable inputs, such as fish feed and fingerlings, is essential. Credit facilities and loan options tailored for small-scale farmers would further encourage broader participation. Additionally, the establishment of organized cooperatives can enable fish farmers to negotiate better market prices and reduce input costs through bulk purchasing. Policymakers should consider introducing tax incentives or subsidies to support small-scale farmers adopting cage aquaculture, thereby making the model more accessible and attractive.

Pond systems require targeted interventions to improve their productivity and profitability. The adoption of low-cost, high-efficiency technologies, such as solar-powered water pumps, can minimize operational costs. Furthermore, training farmers on best management practices including optimal stocking density and improved feeding strategies would enhance financial returns. Access to improved fish breeds with faster growth rates and higher yields would also make pond systems more competitive and scalable. Clear policy support for extension services, access to affordable inputs, and regionally adapted training programs can improve the viability of pond-based aquaculture.

Aquaponics systems, while offering environmental and nutritional benefits, require technological innovations and cost-reduction strategies to improve economic viability. Collaboration between development partners, private sector actors, and research institutions is necessary to design cost-effective solutions, such as energy-efficient equipment and advanced water recycling technologies. Awareness programs highlighting the environmental advantages of aquaponics could stimulate interest and garner support from policymakers and farmers. Financing models, including subsidies or grants for pilot systems, would help alleviate the initial financial burden. Capacity-building programs should focus on equipping farmers with technical knowledge to operate aquaponics systems efficiently and manage their finances effectively. Moreover, regular extension services would bridge knowledge gaps and provide tailored support to address local challenges. Training and support programs specifically aimed at aquaponics sustainability, particularly for youth and women, could unlock new economic opportunities and drive innovation in the sector.

Policies addressing the specific challenges faced by small-scale aquaculture farmers, including access to credit, affordable inputs, and technical support, should be developed and implemented. Governments and institutions should prioritize research aimed at identifying region-specific solutions and creating platforms for stakeholder engagement. Policy frameworks that balance environmental sustainability with economic objectives will support the long-term development of the aquaculture sector. Further research is needed to explore cost-efficient methods for improving aquaponics systems and addressing the scalability challenges of pond and cage systems. Studies integrating technological advancements with local practices will provide practical strategies for enhancing aquaculture productivity and sustainability.

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Author contributions
SB conceived the study design, conducted surveys and focus group discussions, oversaw data collection, performed data analysis and interpretation, and drafted the manuscript. ML and SR provided essential supervision, guidance, and revisions to the manuscript.

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Data availability
The data sets analysed during this current study are available from corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate
The study methods were reviewed and approved by the Department of Aquaculture and Fisheries and authorized by the LUANAR Research Ethics Committee (LUANAR-REC) at the Lilongwe University of Agriculture and Natural Resources in 2023. All methods were carried out in accordance with relevant guidelines and regulations. Informed verbal consent was obtained from all participants prior to data collection, with strict assurances of confidentiality.

Consent to publish
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Clinical trial
Not applicable.

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