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Optimizing small-scale aquaculture systems in the Lake Victoria Basin Uganda through analysis of profitability drivers

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Abstract

Small-scale aquaculture offers potential for improving livelihoods, food security, and economic growth. However, African fish farmers struggle to achieve profitability. This study investigated the financial performance of three small-scale aquaculture systems (ponds, cages, and aquaponics) in Uganda's Lake Victoria Basin to identify variables influencing profitability. Using stratified random sampling, 169 fish farmers from Mpigi, Wakiso, and Buikwe districts were interviewed. Econometric analysis of small-scale aquaculture systems was performed using LIMDEP 9.0 software. Profitability was measured using key financial criteria such as gross margin, net farm income, and net return on investment. Furthermore, a linear regression model was used to analyse attributes influencing profitability. The analysis considered variables such as farm size, stocking density, access to extension services, and other crucial determinants. The results revealed that cage culture achieved a positive gross margin, while pond and aquaponics systems faced financial challenges due to high fixed and variable expenses, including feed, labour, and infrastructure. Farm size and fish prices have an impact on profitability. Nevertheless, high fish feed costs, predator problems, and poor technical support hinder financial performance. To improve the financial sustainability of aquaculture systems, the study recommends cost-effective feed management practices, offering financial assistance in the form of low-interest loans, extending training, and market linkages.

Keywords Small-scale aquaculture, Profitability drivers, Aquaculture systems, Cost-profit analysis, Financial performance. gross margin

1 Introduction

Globally, the aquaculture sector has experienced growth due to increasing demand for fish as a primary source of protein and the need to reduce pressure on wild fish stocks [22]. Aquaculture contributes to local food security and economic activities [43, 44]. However, the aquaculture sector faces persistent challenges, including the depletion of key inputs such as seed and feed due to escalating demand, as well as environmental concerns linked to intensive production practices [18]. These challenges necessitate sustainable solutions, such as improved hatchery technologies, efficient feed formulations,

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and ecosystem-based management approaches, to ensure long-term viability and productivity [22, 40]. Aquaculture has emerged as a viable alternative to catch fisheries, especially in regions where small-scale and artisanal fisheries dominate fish production but face significant resource and operational limitations [2, 7, 24, 39].

In Uganda, aquaculture was introduced in the 1950s but remains primarily subsistence-orientated due to socio-economic constraints [25]. Traditional practices involving small ponds with minimal inputs and reliance on family labour are common [38]. However, rising fish prices and the need for sustainable production methods have led the Ugandan government, international organisations, and study institutions to promote small-scale aquaculture systems such as ponds, cages, and aquaponics. These efforts have resulted in increased investments in small-scale aquaculture technologies [24, 33, 37]. Despite these developments, challenges persist, particularly regarding the economic and operational sustainability of small-scale aquaculture systems in the Lake Victoria basin. Studies provided insights into the growth and challenges of aquaculture globally and regionally, relating to fish health and conflicts for resources [23]. However, systematic study on the financial performance and profitability drivers of small-scale aquaculture systems in Uganda, particularly in the Lake Victoria Basin, is lacking [37]. Furthermore, there is a scarcity of knowledge on the specific costs and economic profits associated with systems such as ponds, cages, and aquaponics, as well as the constraints faced by local fish farmers [36, 61]. Our study explores small-scale aquaculture systems in Ugandan communities along Lake Victoria. Specifically, we focus on (1) analysing the costs and profitability drivers associated with various small-scale aquaculture systems (pond, cage, and aquaponics) and (2) identifying the challenges encountered by local fish farmers in adopting and maintaining these aquaculture systems. The study informs sustainable aquaculture development strategies in Uganda and similar socio-economic contexts and thus contributes to Uganda's National Development Plan III and Vision 2040, aiming at innovation-driven economic growth [37]. Additionally, this study intends to drive policy development to scale up small-scale aquaculture, making it a reliable and sustainable food and income source for local communities.

2 Materials and methods

2.1 The study area

The study was carried out in selected 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° S, 32.037822° E). These districts (Fig. 1) were purposively selected because of their established small-scale aquaculture systems and the prominence of fish farming activities in the area [37]. The Lake Victoria Basin is an important ecological and economic zone, supporting not only small-scale aquaculture and capture fisheries but also a wide range of other economic activities such as agriculture, water transportation, and ecotourism. These selected districts, which are at a moderate altitude and receive significant rainfall throughout the year, are ideal for agricultural practices [30]. For example, Mpigi and Wakiso are well-known for coffee cultivation [37], whereas Buikwe is known for sugarcane cultivation. Farmers in these districts also grow a variety of crops, including coffee, bananas, cassava, potatoes, maize, beans, and pineapples, as well

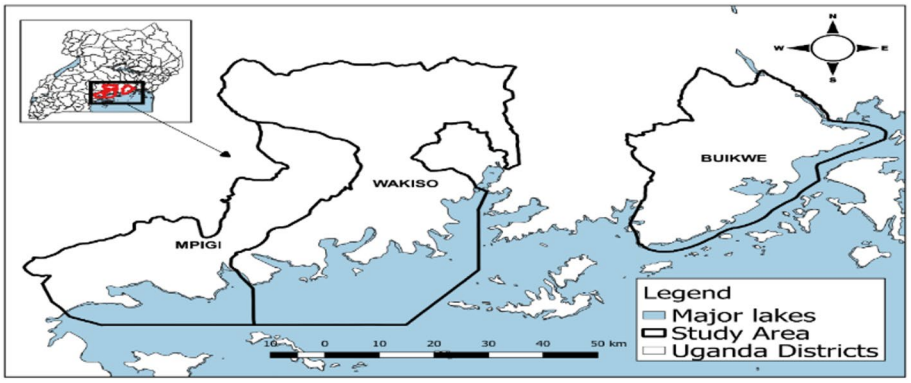


Fig. 1 Geographical map of the study area

as horticultural produce like tomatoes and vegetables. Livestock farming is also common in the area, with dairy and beef cattle, goats, and poultry being the most popular [37].

2.2 Data collection

Data collection was conducted in November 2023, targeting 169 fish farmers across three purposively selected districts (Fig. 1). To ensure a comprehensive and representative sample, we employed a stratified random sampling technique. We divided the population of fish farmers into distinct subgroups based on the types of aquaculture systems they practice (pond, cage, and aquaponics). The rationale for using stratified sampling was to ensure that each production system is adequately represented within the sample, allowing for more analysis of the different aquaculture farming systems and their associated challenges. The final sample population was 49 farmers from Mpigi, 55 from Wakiso, and 65 from Buikwe. The allocation was proportional to the number of fish farmers in each district. Before the main survey, we pre-tested the survey tool on eight fish farms, two in Wakiso, three in Buikwe, and three in Mpigi, to assess its reliability and clarity. Data collection focused on gathering information on farmers' aquaculture experience, system type, fish species farmed, aquaculture products, income, demographics, production cycles, credit access, group affiliations, record-keeping practices, access to extension services, etc.

2.3 Data analyses

We coded and analysed data using LIMDEP 9.0 econometric software [29]. To determine the profitability and cost structures. The financial performance of small-scale aquaculture systems was analysed using enterprise budget data derived from survey responses, covering the three aquaculture systems: pond culture, cage culture, and aquaponics. This analysis provided detailed estimates of inputs and outflows, enabling the calculation of key financial metrics to evaluate the profit systems. It considered a fixed investment and depreciation over an estimated lifespan of five years, ensuring a realistic assessment of their impact on profitability. The key financial metrics calculated include:

$$\text{Gross Margin (GM)} = \text{Total Revenue (TR)} - \text{Total Variable Cost (TVC)} \quad (1)$$

Net Farm Income (NFI))

$$\text{Net Farm Income} = \text{Gross Margin} - \text{Total Fixed Cost} \quad (2)$$

Net Return on Investment

$$\text{Net Return on Investment} = \text{Total Cost over Net Farm Income} \quad (3)$$

We employed a multiple linear regression analysis to examine the factors influencing gross margin (GM), which serves as a proxy for profitability (Table 1). This method is widely used in econometric studies to estimate the relationship between a continuous dependent variable and multiple explanatory variables. The statistical significance of each predictor was evaluated using the t-test, where the t-statistic was calculated as the ratio of the estimated coefficient to its standard error. The resulting p-values indicate whether each coefficient significantly differs from zero. To further investigate the relationships between individual variables and GM, we applied different statistical tests based on variable type. Specifically, for continuous independent variables, we computed Pearson's correlation coefficients (r) to assess the strength and direction of their linear association with GM. For categorical variables, we used chi-square tests of independence to determine whether the distribution of GM significantly varied across the categories.

Our estimated linear equation took the following form:

$$GM = \beta_0 \beta_1 x_1 \beta_2 x_2 \ldots \beta_n x_n \in$$

where GM represents the gross margin, our measure of profit profits,

β_0 Is the intercept. $\beta_1, \beta_2, \ldots, \beta_n$ The coefficients for each explanatory variable. $x_1, x_2, \ldots, x_n$ Denote the determinants hypothesized to affect profits, and $\in$ Is the error term, capturing unexplained variability.

3 Results

3.1 Cost and profit performance of small-scale pond aquaculture system

The variable costs comprised the majority of the total expenses, accounting for 93% of the total costs (Table 2). Among these, the largest contributors were feed costs (35%), labour during production (25%), and fingerlings (25%), which together accounted for

Table 1 Factors influencing profitability in small-scale aquaculture included in the model

Variable	Effect on gross margin
Gross margin (US$)	Dependent Variable
System size (m^2)	+
Fingerlings stocked (number)	+
Contracted manager (1 = yes, 0 = no)	±
Production cycle (months)	±
Fish farmer group membership (1 = yes, 0 = no)	+
Extension services access (1 = yes, 0 = no)	+
Keeping records (1 = yes, 0 = no)	+
Experience in fish farming (years)	+
Fish price per unit (US$/kg)	+
Fish harvested (kg)	+
Feed cost (US$)	−
Predators (1 major constraint, 0 otherwise)	−
Participation in training programmes (1 = yes, 0 = no)	+
Species farmed	±
Access to credit (1 = yes, 0 = no)	+

Table 2 Cost distribution and profit performance of small-scale pond aquaculture system

Cost category	Average cost (US$)	Total cost (%)
Variable costs		
Fingerlings	308	25
Cost of feeds	256	35
Labour at production	308	25
Labour at harvesting	7	7
Net purchase	72	7
Transportation costs	3.6	0.3
Total variable costs (TVC)	961	93
Fixed costs		
Pond construction	60	5.8
Pond rent	15	1.4
Total fixed costs (TFC)	75	7
Total costs (TVC + TFC)	1036	100
Total revenue (TR)	530	
Gross margin (TR - TVC)	– 431	
Net farm income (NFI)	– 506	
Net Return on investment (NRI)	– 49%	

Table 3 Cost and profit performance of small-scale cage aquaculture system

Cost category	Average cost (US$)	Total Cost (%)
Variable costs		
Fingerlings (fish seed)	375	15
Fish feed	550	22
Labour at production	250	10
Labour at harvesting	125	5
Transportation costs	100	4
Maintenance	75	3
Total Variable Costs (TVC)	1475	59
Fixed costs		
Cage setup	750	30
Total fixed costs (TFC)	750	30
Total costs (TVC + TFC)	2225	
Total revenue (TR)	2500	
Gross margin (TR - TVC)	1025	
Net farm income (NFI)	275	
Net return on investment (NRI)	12%	

85% of the total variable costs. Other variable costs included labour at harvesting (7%), net purchases (7%), and transportation costs (0.3%). Fixed costs, comprised of 7% of the total costs, were significantly smaller compared to variable costs. These fixed costs included pond construction (5.8%) and pond rent (1.4%). The total costs, including both variable and fixed costs, amounted to US$1,036 (Table 2). However, the total revenue generated from the pond aquaculture system was only US$530, resulting in a gross margin of -US$431. This indicates that variable costs exceeded revenue. The net farm income was -US$506, and the net return on investment was – 49%.

3.2 Cost and profit performance of small-scale cage aquaculture system

The total variable costs accounted for 59% of the total expenses in the small-scale cage aquaculture system (Table 3). The largest contributors to variable costs were feed (22%), fingerlings (15%), and labour during production (10%), which together represented

47% of the total variable costs. Other minor variable costs included labour at harvesting (5%), transportation (4%), and maintenance (3%). Fixed costs made up 30% of the total expenses. The total expenses, combining both variable and fixed costs, amounted to US$2,225 (Table 3). The total revenue generated was US$2,500, resulting in a gross margin of US$1,025. The net farm income was US$275, and the net return on investment was 12%.

3.3 Cost and profit performance of small-scale aquaponics system

The analysis of the small-scale aquaponics system identified several challenges, predominantly arising from high infrastructure and operational costs, which outweighed revenue generation. Initial setup costs constituted 30% of total expenses, placing a financial strain on fish farmers due to substantial upfront investments in essential infrastructure, including tanks, pipes, and filters (Table 4). Variable costs, accounting for 54% of the overall expenses, were primarily driven by factors such as nutrients, growth media, and labour. Notably, feed and nutrients represented 60% of the total variable costs. The system's financial performance was further underscored by negative gross margins and a net farm income of – $1,133 and – $2,745, respectively. The poor profitability of the system was further emphasised by a net return on investment of – 77%, indicating a negative return on the capital invested.

3.4 Variables affecting the gross margin in small-scale fish farming with pond system

In small-scale aquaculture with pond systems, eight variables affected the gross margin significantly (Table 5). Pond size ($r = 0.4$, $p < 0.01$), stocking density ($r = 0.3$, $p < 0.05$), experience in fish farming ($r = 0.4$, $p < 0.01$), fish price per unit ($r = 0.5$, $p < 0.001$), and fish harvested ($r = 0.4$, $p < 0.01$) all showed significant positive correlations with gross margin. Additionally, having a contracted manager ($p < 0.05$), access to extension services ($p < 0.05$), and keeping records ($p < 0.01$) were also significant factors influencing gross

Table 4 Cost and profit performance of small-scale aquaponics system

Category	Average cost (US$)	Total cost (%)
Variable costs		
Fingerlings costs	212	6.0
Fish feed	158	60
Labour at production	151	4.2
Labour at harvesting	106	3.0
Vegetable seeds	107	3.0
Nutrients and growth medium	214	60
Total variable costs (TVC)	1933	54
Fixed costs		
System setup cost	1074	30
Pumps and aerators	214	6.1
Water and utilities cost	53	1.5
Electricity cost	104	3.0
Maintenance cost	161	4.50
Total fixed costs (TFC)	1611	45.0
Total revenue (TR)	800	–
Gross margin (TR–TVC)	– 1133	–
Net farm income (NFI)	– 2745	–
Net return on investment (NRI)	– 77%	–

Table 5 Descriptive statistics of variables and their relationships with gross margin (GM) in small-scale pond-based aquaculture: pearson's r (DF = 167) and p-values for continuous variables, and chi-square p-values for categorical variables

Variable	Mean	SD	Variable versus gross margin
Gross margin (US$)	– 430	–	-
Pond size (m^2)	2500	750	$r = 0.40$ (167), $p < 0.01$
Stocking density (fish/m^2)	1.2	0.4	$r = 0.3$(167), $p < 0.05$
Contracted manager	0.4	–	$p < 0.05$
Production cycle (months)	7.5	2	$p = 0.68$
Fish farmer group membership	0.5	–	$p = 0.07$
Extension services access	0.6	–	$p < 0.05$
Keeping records	0.7	–	$p < 0.01$
Experience in fish farming (years)	5.5	3	$r = 0.4$(167), $p < 0.01$
Fish price per unit (US$/kg)	4.2	1.5	$r = 0.5$(167), $p < 0.001$
Fish harvested (kg)	2000	800	$r = 0.4$(167), $p < 0.01$

Table 6 Descriptive statistics of variables and their relationships with gross margin (GM) in small-scale cage-based aquaculture: pearson's r (DF = 167) and p-values for continuous variables, and chi-square *p*-values for categorical variables

Variable	Mean	SD	Variable vs. gross margin	*p*-value
Gross margin (US$)	1500	–	-	–
Cage size (m^2)	100	25	$r = 0.2$(167)	$p < 0.03$
Stocking density (fish/m^2)	4.5	1	$r = 0.20$(167)	$p < 0.04$
Contracted manager	0.6	–	$r = 0.2$(167)	$p = 0.06$
Production cycle (months)	6	1.5	$r = -0.05$(167)	$p = 0.60$
Group membership	0.7	–	–	$p = 0.09$
Extension services access	0.6	–	–	$p < 0.04$
Keeping records	0.75	–	–	$p < 0.03$
Experience (years)	3	1.2	$r = 0.3$(167)	$p < 0.02$
Fish price per unit (US$/kg)	3.5	1.2	$r = 0.3$(167)	$p < 0.01$
Fish harvested (kg)	450	120	$r = 0.3$(167)	$p < 0.02$
Feed cost (US$)	400	150	r = -0.2(167)	$p < 0.04$
Predators	0.1	–	–	$p < 0.05$

margin. The production cycle ($p = 0.68$) and fish farmer group membership ($p = 0.07$) did not show significant effects.

3.5 Variables affecting the gross margin in small-scale fish cage system

Variables affecting gross margin in small-scale aquaculture with cage systems (Table 6) identified several key factors influencing financial performance. Cage size ($r = 0.2$, $p < 0.03$) and stocking density ($r = 0.20$, $p < 0.04$) both exhibited positive correlations with gross margin, suggesting that larger cages and higher stocking densities may improve profitability. Additionally, experience in fish farming ($r = 0.3$, $p < 0.02$), fish price per unit ($r = 0.3$, $p < 0.01$), and the quantity of fish harvested ($r = 0.3$, $p < 0.02$) were positively associated with gross margin, emphasising their importance in financial outcomes. Access to extension services ($p < 0.04$) and keeping records ($p < 0.03$) were also found to positively impact gross margin, contributing to better financial results. The effect of contracted management on gross margin was positive but non-significant ($r = 0.2$, $p = 0.06$). Production cycle duration ($r = -0.05$, $p = 0.60$) and group membership ($p = 0.09$) showed no significant effect on gross margin, indicating that these variables have limited influence on profitability. Feed costs ($r = -0.2$, $p < 0.04$) had a negative relationship with gross margin,

Table 7 Descriptive statistics of variables and their relationships with gross margin (GM) in small-scale aqauponics-based aquaculture: pearson's r (DF = 167) and p-values for continuous variables, and chi-square *p*-values for categorical variables

Variable	Mean	SD	Variable versus gross margin	*p*-value
Gross margin (US$)	− 1133	–	–	–
System size (m^2)	24	6	$r = 0.2(167)$	$p < 0.03$
Stocking density (fish/m^2)	0.9	0.2	$r = 0.2(167)$	$p < 0.04$
Contracted manager	0.2	–	$r = 0.18(167)$	$p = 0.06$
Production cycle (months)	4	1.2	$r = -0.2(167)$	$p = 0.60$
Group membership	0.4	–	$r = 0.15(167)$	$p = 0.09$
Extension services access	0.35	–	–	$p < 0.04$
Keeping records	0.5	–	–	$p < 0.03$
Experience (years)	2	1	$r = 0.3(167)$	$p < 0.02$
Fish price per unit (US$/kg)	2.5	0.8	$r = 0.3(167)$	$p < 0.01$
Fish harvested (kg)	150	45	$r = 0.3(167)$	$p < 0.02$
Feed cost (US$)	120	40	$r = -0.2(167)$	$p < 0.04$
Predators	0.15	-	–	$p < 0.05$

suggesting that higher feed costs may reduce profitability. Finally, the presence of predators ($p < 0.05$) significantly affected gross margin, highlighting the negative impact of predator-related losses on the financial viability of the system.

3.6 Variables affecting the gross margin in small-scale aquaponics system

The analysis of variables affecting gross margin in small-scale aquaponics systems (Table 7) revealed several factors with significant influence on financial performance. System size ($r = 0.2$, $p < 0.03$) and stocking density ($r = 0.2$, $p < 0.04$) exhibited positive correlations with gross margin, suggesting that larger system sizes and higher stocking densities may improve profitability. Access to extension services ($p < 0.04$) and keeping records ($p < 0.03$) all showed significant positive associations with gross margin, indicating the beneficial impact of these practices on financial outcomes. Experience in fish farming ($r = 0.3$, $p < 0.02$), fish price per unit ($r = 0.3$, $p < 0.01$), and the amount of fish harvested ($r = 0.3$, $p < 0.02$) are also positively correlated with gross margin, highlighting their importance in achieving higher profitability. The length of the production cycle ($r = -0.2$, $p = 0.60$) was not significantly associated with gross margin, suggesting that the production cycle duration does not substantially affect profitability. The effects of group membership ($r = 0.15$, $p = 0.09$) and contracted management ($r = 0.18$, $p = 0.06$) on gross margin were positive but non-significant. Feed costs ($r = -0.2$, $p < 0.04$) were negatively correlated with gross margin, indicating that higher feed costs reduce profitability. Lastly, the presence of predators ($p < 0.05$) had a significant impact on gross margin, underlining the negative financial effect of predator-related losses.

3.7 Farmer perceptions on financial strain and support needs in aquaculture systems

In pond aquaculture, farmers emphasised the financial strain caused by high input costs, particularly for feed, labour, and fingerlings. One farmer remarked, "*Feed is the biggest cost. We spend so much on it, and sometimes it feels like it eats up all our profits*," while another highlighted the burden of labour costs, stating, "*Labour costs are high, and we don't have machines to help us. It's a lot of manual work, that adds to our costs*." In cage aquaculture, similar financial pressures were observed, with farmers in Wakiso and Mpigi pointing to the high costs of cage setup materials such as frames and nets. One

farmer from Wakiso noted, "*The cost of materials like frames, nets, and anchors is too high; we often need loans to cover these expenses, which adds financial risk.*" Additionally, rising feed costs were a common concern, with a farmer in Mpigi commenting, "*The expense of feed keeps increasing, and it's directly affecting our profits. We can't keep up with these prices.*"

Pond and cage systems farmers also highlighted the need for external support to sustain their operations, with one farmer in Buikwe suggesting, "*We need subsidies for cage setup, after and maintenance to reinvest and sustain cage fish farming in the long run*," farmers in Wakiso noted, "*The extension services have been very helpful. They give us advice on feeding and water quality, which has helped us improve our yields.*" Similarly, in aquaponics systems, farmers in Wakiso and Mpigi expressed concerns about the significant infrastructure costs, especially for setting up tanks and filtration systems. One farmer stated, "*The system setup, especially tanks and filtration, takes up a large portion of our money, but it's essential for the system to function.*"

4 Discussion

4.1 The cost analysis of the three small-scale aquaculture systems

In small-scale pond aquaculture systems, the main cost drivers are feed, labour, and fingerlings. Feed is one of the major observed expenses, aligning with the findings of Opiyo et al. (2015) [51], who highlighted feed as a primary cost in tilapia farming. Labour costs also contribute to about 30% of total expenses, exacerbating the financial vulnerability of small-scale systems, as noted by Omondi et al. [50]. Furthermore, the financial strain is worsened by the fact that a portion of farm output is consumed by the household, thus reducing potential revenue from market sales. Moreover, negative net farm income and low return on investment suggest that the financial sustainability of small-scale pond aquaculture is severely limited due to these high operational costs. This agrees with the findings of Okechi et al. [49] and Love et al. [35], who also reported high production costs as major challenges for small-scale aquaculture.

For small-scale cage aquaculture, the setup costs, which constitute 30% of fixed costs, are a major financial consideration. The initial investment in durable materials like frames, nets, and anchors is essential for long-term system sustainability, as emphasized by Cruz & Ridha [16, 17] and Beveridge [12]. Feed costs, which account for 22% of total expenses, also remain a concern. While the financial performance of cage aquaculture is positive with a net farm income of US$275 and a return on investment of 12%, it remains vulnerable to fluctuations in variable costs, particularly feed and labour. High labour costs, at 15% of total expenses, reflect the labour-intensive nature of cage farming. Although these systems can be profitable, managing these costs effectively is key to maintaining profitability. This is also supported by Narayanakumar [45], who found that labour and feed costs play a crucial role in determining profitability in aquaculture systems.

Aquaponics systems face financial barriers, primarily due to high infrastructure and operational costs. Setup costs represent 30% of total expenses, while variable costs, especially feed and nutrients, make up over 60%. The reliance on imported materials for nutrients further exacerbates these financial pressures, which is consistent with Bosma et al. [1, 13, 52]. Labour costs, which are influenced by local conditions, also contribute to high operational expenses, particularly for tasks like harvesting, as pointed out

by Asmah et al. [5]. Despite the challenges posed by high input costs, improving market access, sourcing locally produced inputs, and exploring alternative feeds could alleviate some of the financial strain and improve profitability in aquaponics systems. This is supported by the findings of Benjamin et al. [11], who highlighted the importance of improving input sourcing and market access.

4.2 Integrated analyses of the factors affecting gross margin

In pond aquaculture, larger ponds facilitate economies of scale, enhancing GM when effectively managed. Larger ponds reduce operational inefficiencies and increase profitability by optimizing space and resources. Similarly, cage aquaculture benefits from larger cage sizes, which support better yields; however, overcrowding can negatively impact GM if not managed appropriately. In aquaponics systems, a positive correlation is observed between system size and GM, with systems operating at optimal stocking densities benefiting from economies of scale and increased productivity. Nevertheless, the relationship between system size and GM is less pronounced in aquaponics due to the more integrated nature of the system [4]. Thus, while larger systems have a stronger effect on GM in pond and cage aquaculture, the relationship is more moderate in aquaponics.

In pond aquaculture, higher stocking densities generally lead to higher yields, contributing to increase GM. However, if density exceeds optimal levels, overcrowding increases disease and stress, negatively affecting GM [15, 46, 56]. Similarly, in cage aquaculture, stocking density correlates positively with GM, but excess density may result in increased stress and disease risks, undermining profitability [48, 55, 60]. In aquaponics, stocking density also correlates positively with GM, recycling affects water quality, and this reduces the potential stress factors. While stocking density remains an important factor across all systems, the negative effects of overcrowding are more pronounced in pond and cage systems than in aquaponics, due to the unique nutrient interactions within aquaponics.

In pond and cage aquaculture, feed costs comprise a substantial portion of operational expenses, and inefficiencies in feed management can severely undermine profitability [3, 21, 53]. This issue is particularly critical in cage systems, where high feed costs, coupled with inefficiencies, lead to increased financial losses. In aquaponics systems, feed costs have a slightly lesser impact on Gross Margin (GM). This reduced impact is largely due to the integrated nutrient recycling inherent in aquaponics, which decreases reliance on externally purchased feed. Nevertheless, effective feed management remains crucial across all systems to ensure profitability, as emphasized by Clark et al. [14, 28].

The role of contracted management varies across aquaculture systems. In none of the systems analyzed was the impact of contracted manager statistically significant. However, for pond-based systems, the correlation (r) was moderate, suggesting a potential benefit, especially in larger operations. This finding highlights the importance of operation scale: larger pond operations tend to have more complex management needs, and therefore, contracting a manager may be more necessary and beneficial. Whereas in smaller-scale pond operations, the costs associated with contracted manager may not outweigh the limited improvements in profitability, as smaller farms often do not have the same level of complexity that would require a professional manager. However, even for small-scale engaging contracted management can result into higher profit margins

due to sustainable intensification. For example, in pond aquaculture, contracting a farm manager can enhance operational efficiency and profitability, although the additional costs may not be feasible for smaller-scale operations [27, 32, 41]. In cage systems, the effect of contracted management is marginal, showing only a slight positive correlation with GM. This suggests that the added cost may not justify the benefits, particularly for smaller operations, as discussed by Daungsawasdi et al. [19]. In aquaponics, while contracted management can improve efficiency, the associated costs may not be justifiable for small-scale systems. However, similar findings were reported, in Myanmar for small-scale aquaculture households were adopting diversification practices significantly aquaculture yield and benefit-cost ratios due to contracted management [10, 63]. Furthermore, small-scale mariculture enterprises in India with contracted management, achieved higher profitability and economic viability. These findings underscore the potential of structured management approaches in enhancing the performance of small-scale aquaculture systems [62]. As with this study, contracted management is more impactful in pond aquaculture than in cage and aquaponics systems, where the costs may outweigh the benefits for smaller-scale farms.

Extension services and record-keeping are positively correlated with GM across all systems. These practices improve resource management, decision-making, and financial tracking, which are critical for maximizing profitability. In pond aquaculture, Ekesa et al. [20] highlighted the role of extension services in enhancing profitability by providing technical support and guidance. Similarly, in cage aquaculture, extension services contribute to better management practices and improved profitability, with a positive correlation between record-keeping and GM [48, 55]. Aquaponics systems also show a similar pattern, where access to extension services and organized financial management, including record-keeping, leads to better financial outcomes [31, 34, 57, 59]. Farmer experience plays a pivotal role in enhancing GM across all aquaculture systems. In pond aquaculture, Okechi et al. [49] found that experienced farmers can optimize management practices, leading to improved profitability. Similarly, in cage aquaculture, Opiyo et al. [8, 51], noted that experienced operators make more effective decisions and manage challenges, such as disease and overcrowding, more efficiently. In aquaponics, experienced farmers are better equipped to handle the complex interactions between fish and plants, ultimately improving GM, as noted by Veverica et al. [57].

Market conditions and harvest volume, influence GM in all aquaculture systems. In pond aquaculture, Clark et al. [14] emphasized that higher fish prices and larger harvests improve GM. This finding is echoed in cage aquaculture, where market dynamics such as fish prices and larger harvests are crucial for profitability, as discussed by Daungsawasdi et al. [6, 19, 54]. Similarly, in aquaponics, favourable market conditions, including higher fish prices, contribute to better financial outcomes, as highlighted by Opiyo et al. [51] and Veverica et al. [57]. Therefore, market conditions play a crucial role in influencing GM, with higher fish prices and larger harvests being key contributors to profitability across all systems.

Predator issues are especially important in pond and cage systems, where predators pose a significant threat to fish production and profitability. As noted by Munguti et al. [42], Ogello et al. [47] and [26], predators can lead to substantial financial losses in these systems [58]. While predator problems are less prominent in aquaponics systems, they remain a concern, especially in cases where external threats damage the system [9].

4.3 Limitations of the study

Four main weaknesses are highlighted. Firstly, the study utilized cross-sectional data to assess the association between various factors affecting aquaculture profitability. While this design allows for understanding correlations at a specific point in time, it does not establish causal relationships. Therefore, future studies should employ longitudinal designs to explore the causal-effect relationships between key variables and the long-term impacts of different aquaculture practices. Secondly, a stratified random sampling technique was used to select participants from different aquaculture systems. While this method ensured a diverse sample, the relatively small sample sizes in certain subgroups particularly for aquaponics and cage systems limit the generalizability of the results. Furthermore, the sampling approach could lead to unequal representation of certain groups, such as vulnerable populations or specific fish farming communities. Therefore, future studies could consider larger, more representative sample sizes, or apply alternative sampling methods, such as paired actors, where a respondent identifies relevant social connections to better capture network dynamics and ensure broader representation. Thirdly, the study mainly relied on data from fish farmers and did not incorporate the perspectives of other key stakeholders, such as policymakers, extension services, or industry experts. Including these additional stakeholders would provide a more holistic view of the aquaculture sector and enhance the understanding of the broader challenges and opportunities facing the industry. Therefore, future research should strive for a more inclusive approach, collecting data from a variety of stakeholders to capture a comprehensive range of insights.

5 Conclusions

The cost analysis of small-scale aquaculture systems across pond, cage, and aquaponics reveals financial challenges. Pond aquaculture, characterised by high variable costs for feed, labour, and fingerlings, results in negative gross margins and unprofitable financial outcomes, as total costs exceed revenues. This highlights the financial strain on fish farmers due to high input and labour costs, emphasising the need for strategies such as improved feed efficiency and better pond management practices. Cage aquaculture systems show better financial performance, despite high setup and operational costs, with positive net farm income and return on investment. Economies of scale, efficient feed management, and enhanced management practices contribute to profitability, although it remains sensitive to fluctuations in feed and labour costs. Qualitative insights from farmers in Uganda point to financial pressures and the need for financial support to sustain these systems. Aquaponics systems face financial bottlenecks due to high infrastructure and operational costs, resulting in negative gross margins. Correlation analyses indicate that system sizes and optimal stocking densities can improve profitability through economies of scale, while access to extension services and experienced management also correlate positively with profit performance. Overall, the findings suggest that interventions, including optimising input costs and improving management skills and market linkages, are necessary to ensure the long-term profitability of small-scale aquaculture systems in the Lake Victoria basin, Uganda.

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Author contributions
S.B. collected and analyzed the data and wrote the manuscript. M.L. reviewed the manuscript and provided supervisory guidance. S.R. also reviewed the manuscript and provided additional supervisory support. All authors reviewed the final version of the manuscript.

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Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study received authorization from the LUANAR Research Ethics Committee (LUANAR-REC). Verbal consent was obtained from all participants prior to data collection, with strict assurances of data confidentiality.

Consent for publication
Authors have approved the content of this manuscript, and it has been submitted for publication in the Journal of Discover Sustainability.

Competing interests
The authors declare no competing interests.

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