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Drivers of small-scale aquaculture systems adoption and sustainability in the Lake Victoria Basin, Uganda

Byabasaija Syliver^{1*}, Moses Limuwa² and Ronald Semyalo³

Abstract

Uganda's fisheries sector is vital for economic sustenance and food security but faces challenges due to declining fish stocks, necessitating the expansion of aquaculture systems to meet fish demand. This study investigated the factors influencing small-scale fish farmers' choice of aquaculture systems and assesses sustainability. Cross-sectional survey was conducted in November 2023 in the three district that were purposively selected districts (Buikwe, Wakiso, and Mpigi). 169 fish farmers as respondents were considered for data collection, through structured surveys, focusing on several variables. The Multivariate Probit Model (MVP) was used to assess determinants of aquaculture system choice. For system sustainability, data were analyzed using a weighted scoring method. Results indicate that aquaponics had the highest sustainability index (0.715), followed by pond farming (0.508) and cage farming (0.448), with socio-economic factors, including financial resources and technical knowledge, significantly influencing system choice. Findings revealed a male predominance (83.6%) in fish farming, with higher education levels favoring cage and aquaponics, whereas household with big sizes were associated with pond farming which is likely due to resource allocation dynamics. However, financial and technical constraints hindered aquaponics expansion despite its sustainability benefits. To enhance aquaculture system choice and sustainability, the study recommends strengthening access to credit, farmer training, and government support, alongside policies that empower women and improve financial services for farmers.

Keywords Lake Victoria Basin, Small-scale aquaculture systems, Sustainability, Household dynamics, Multivariate Probit Model, Sustainability index score

Introduction

Throughout history, fishing has proved essential to global food security and economic survival, especially for those whose livelihoods rely on capture fisheries [13]. However, unsustainable fishing methods have caused aquatic resources to be depleted, which has affected livelihoods and caused economic downturns [14]. Fish resources are essential to Uganda's economy, as water bodies occupy around 18% of the country's surface [37, 27]. Over 1.8 million people are supported by Uganda's fishing industry, which has great potential in both aquaculture and capture fisheries [25, 36]. Many of these people are

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strongly dependent on Lake Victoria and other smaller lakes [46]. This reliance is seriously threatened by diminishing fish stocks, nonetheless, underscoring the pressing need for calculated measures to guarantee sustainable fisheries management [25]. Fish farming is growing, especially in ponds, cages, and aquaponic systems, in order to meet the increasing demand for fish, that is brought on by population increase and changing dietary habits [14]. Although full-scale commercialisation is still a work in progress, the Ugandan government has taken steps to support small-scale aquaculture [25, 29]. Significantly, the 2022–2023 Ugandan government budget's \$518,919.19 (UGX 1.92 billion) expenditure highlights a dedication to bolstering the aquaculture industry, which presently accounts for about 3% of the country's GDP [45]. As a vital source of income and food security in the central region, small-scale aquaculture is intricately woven into the socioeconomic fabric of communities in the Lake Victoria basin [25]. With an estimated yearly per capita fish consumption of almost 13.6 kilos, this region is Uganda's largest fish-consuming area, underscoring the socioeconomic significance of aquaculture [28, 12]. Notwithstanding its potential for expansion, the industry continues to encounter obstacles such as restricted financing availability, insufficient training, and budgetary limitations [6, 34]. Growth is made more difficult by institutional and structural flaws, high upfront investment costs, a shortage of high-quality fish seed, and limited feed availability. The difficulties highlight the necessity of specific expertise and technical assistance for the successful setup and administration of aquaculture systems [37, 25]. For various aquaculture systems to function well, specialised technical knowledge is needed. For example, cage farming requires strict environmental impact studies and specialised licensing, and it must be located offshore to avoid interfering with other lake activities [14, 37]. Similar to this, aquaponics, a system that combines hydroponic plant growing and fish farming, grows best in regulated settings and needs thorough feasibility studies, regulatory permissions, and technological know-how to operate sustainably [34]. In contrast, pond fish farming necessitates site-specific licenses for sustainable management, environmental clearances, and thorough examinations of the soil and water quality [14, 6]. There is also a lack of knowledge regarding how socioeconomic and demographic aspects affect farmers' choices of aquaculture systems, despite earlier research [11] looking at the technological needs and obstacles in small-scale aquaculture [1].

This study examined the socioeconomic and demographic aspects that impact fish farmers' choices of aquaculture systems, such as pond, cage, and aquaponics, and to determine how these systems can be maintained. The Diffusion of Innovations Theory [43], which offers a

framework for comprehending how novel practices are embraced within a social system, serves as the foundation for our investigation. To determine the main determinants impacting aquaculture acceptance in Uganda, the theory's fundamental components relative benefit, compatibility, complexity, trialability, and observability are applied. Relative advantage, for instance, evaluates whether fish farmers consider one aquaculture system to be more advantageous than another, whereas compatibility looks at how well the system works with farmers' current resources and methods [43].

Additionally, this study considered variables that are believed to affect the selection and sustainability of different aquaculture systems in Uganda, such as age, education level, household size, access to credit, extension services, membership in farmer groups or associations, and geographic location (close to water bodies). It is important to understand how socio-economic factors influence farmers' choices of small-scale aquaculture systems in order to design targeted interventions that promote sustainable adoption and development in the sector. Complexity determines how easy or difficult the systems are to understand and use, trialability takes into account the ability to test the systems before full adoption, and observability examines how visible the benefits of the systems are to others in the community [43].

Materials and methods

Study area

Three districts were purposefully chosen for this study, which used a cross-sectional survey approach (Fig. 1). These districts Buikwe (0.761029 N, 33.040723 E), Wakiso (0.054163 N, 32.518079 E), and Mpigi (0.305544 S, 32.037822 E) were selected because of the small-scale aquaculture system they have built [31] and the fact that fish farming is common there [25]. In addition to small-scale aquaculture and capture fisheries, the Lake Victoria Basin supports a variety of other economic endeavours like agriculture, water transportation, and tourist, making it an essential ecological and economic zone [13, 35]. The region is suitable for agricultural techniques due to its moderate altitude and year-round significant rainfall [12]. Specifically, these selected are renowned for growing coffee, whilst Buikwe is noted for producing sugarcane [25]. In addition to horticulture products like tomatoes and other vegetables, farmers also grow other crops like bananas, cassava, potatoes, maize, beans, and pineapples [30]. Additionally, animal husbandry is widespread, with major livestock kinds including dairy and beef cattle, goats, and poultry [26].

Sample size determination

The study focused on farmers who had participated in 2019 training programs provided by government agencies

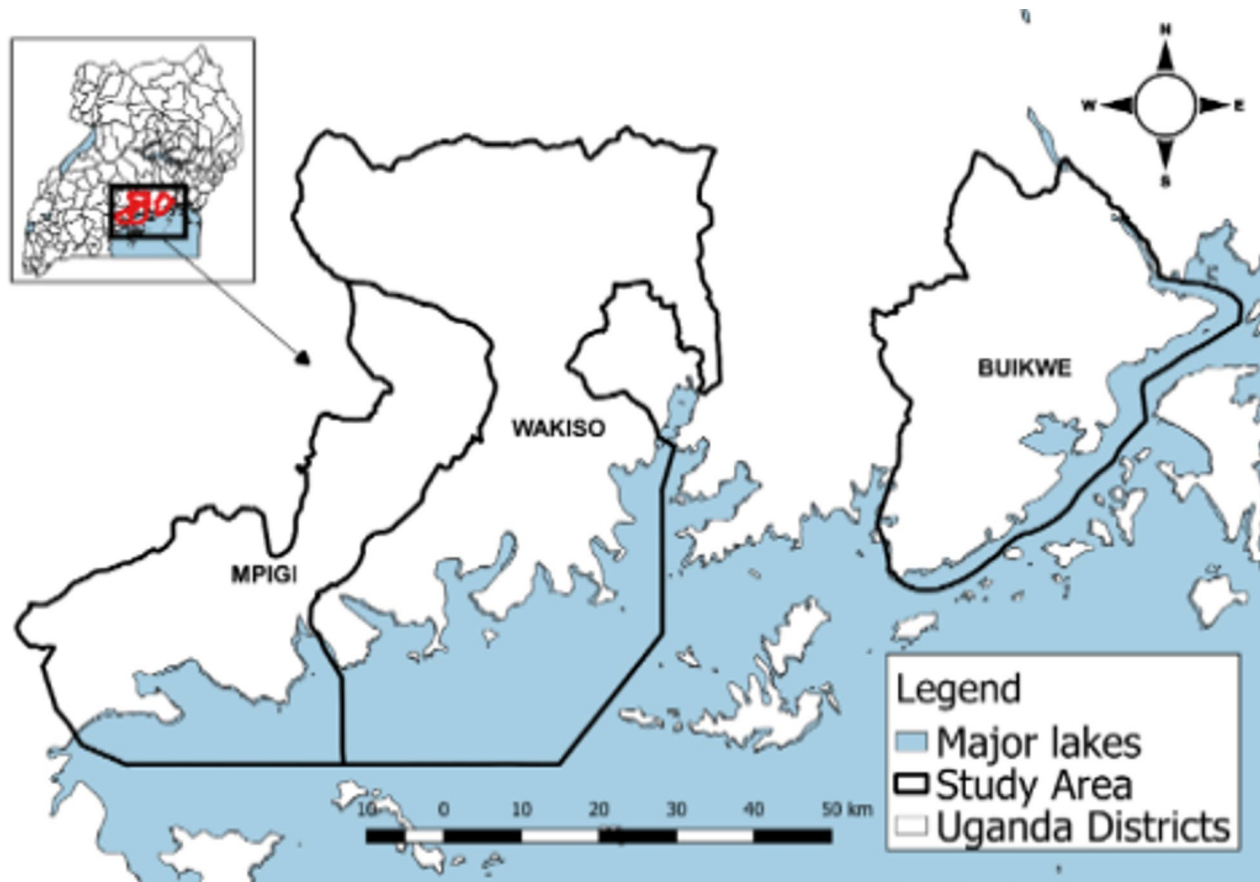


Fig. 1 Study area

such the Ministry of Agriculture, Animal Industry, and Fisheries, as well as development partners like CARI-TAS and World Vision [25]. 200, 130, and 127 fish farmers in Buikwe, Wakiso, and Mpigi, respectively, received training in small-scale aquaculture systems, according to data obtained from the relevant District Fisheries Offices. The sample size was determined using a modified version of the sample size calculation technique for population proportions [22, 40]. The sample consisted of 169 responders, 65 of whom were from Buikwe, 49 from Mpigi, and 55 from Wakiso. Making use of the formula n

$$= \frac{N Z^2 p(1-p)}{e^2(N-1) + Z^2 p(1-p)}.$$

Z is the Z-score corresponding to the confidence level (1.96 for a 95% confidence level), n is the necessary sample size, e is the margin of error (set at 0.05), and p is the estimated percentage of the population with the feature of interest (assumed to be 0.5 for maximum variability). Respondents were selected using a strict random sampling technique, ensuring proportionate representation from each district. Specifically, listings of certified farmers from the District Fisheries Offices used as sample frames. As part of the systematic random sample process, respondents were selected at predefined intervals. The

following formula was used to determine the sampling interval for each district.

$k = \frac{N}{n}$, where k is the sampling interval.

For Buikwe: $k = \frac{200}{65} \approx 3$
For Wakiso: $k = \frac{130}{55} \approx 2$ For Mpigi: $k = \frac{127}{49} \approx 3$.

This means that in Buikwe and Mpigi, every 3rd trained farmer on the list was selected, whereas in Wakiso, every 2nd trained farmer was selected. The starting point for selection was chosen randomly. To supplement the quantitative results, four Key Informant Interviews (KIIs) and eight Focus Group Discussions (FGDs) were used to gather qualitative data. Purposively chosen due to their experience and direct participation in fish farming training programs, the KIIs included district fisheries officers, aquaculture extension officers, community leaders, and representatives from training organisations. Based on the idea of data saturation, which states that more interviews are unlikely to produce fresh insights, just four KIIs were chosen. Key stakeholders with extensive expertise and first-hand experience in aquaculture training programs were represented by the chosen KIIs. Saturation was confirmed by meticulous theme analysis, which revealed no new codes or insights following the third and fourth

interviews. Additionally, the insights obtained from the KIIs were reinforced and given more depth by the usage of FGDs. In order to ensure representation from all small-scale fish farmers, the FGDs were arranged in each district and focused on trained fish farmers. Purposive and snowball sampling were used to choose participants for the FGDs, guaranteeing a range of viewpoints while concentrating on farmers with significant expertise and involvement in aquaculture operations.

Data collection

In November 2023, data was collected using a mixed-methods strategy that combined qualitative and quantitative techniques. In order to get quantitative data, 169 trained fish farmers were given organised surveys in person, and their answers were directly recorded. The surveys gathered data on socioeconomic factors including household income, access to aquaculture resources, and significant demographic characteristics like age, education level, and family size in order to evaluate the economic and demographic environment of small-scale aquaculture producers. A wide range of farmers, community leaders, and aquaculture stakeholders participated in in-depth qualitative interviews to investigate how social

networks, cultural norms, and community dynamics affect aquaculture decision-making. We also analysed the institutional structure that influences fish farming, including municipal laws, government assistance, and extension services. Additionally, surveys assessing the environmental, economic, and social aspects of sustainability in various fish farming systems were used to gather data for the sustainability index scores. The sustainability index ratings for each aquaculture system were calculated using a weighted scoring approach after respondents submitted percentage-based evaluations based on their observations and experiences.

Data analysis

We used STATA Version 13 for quantitative data analysis in order to understand the correlations between variables. To examine the variables influencing fish farmers' decisions across aquaculture systems (pond, cage, and aquaponics), we used a Multivariate Probit Model (MVP). This model takes into consideration the potential for farmers to choose multiple systems at the same time, such as integrating aquaponics with either system for sustainability or combining pond aquaculture with cage aquaculture. Using the MVP model, we calculated the odds of several binary outcomes (pond aquaculture: 1 = Yes, 0 = No; cage aquaculture: 1 = Yes, 0 = No; aquaponics: 1 = Yes, 0 = No) while taking possible correlations between these options into account.

The complexity and interdependence of decision are more accurately captured by this method. Variance inflation factors (VIF) were used to assess multicollinearity in order to guarantee model fidelity. The independent included comprised of a combination of continuous and categorical (Table 1). Model fit was assessed using Likelihood-ratio tests, pseudo R-squared values, and other post-estimation diagnostics. Age, years of education, household size, years of fish farming, sex, married status, group membership, household income, training access, and land ownership were among the socioeconomic and institutional factors that were analysed (Table 1). Thematic analysis was also used for qualitative data. A weighted scoring approach was used to analyse the system sustainability data, giving each sustainability factor a particular weight. The total sustainability index score for each agricultural system was determined by adding the weighted scores for each system after these parameters were normalised to a 0–1 scale.

Model specification

We developed a Multivariate Probit (MVP) Model, which takes into consideration the potential for farmers to concurrently select various aquaculture systems, in order to examine the variables impacting fish farmers' decisions among aquaculture systems. By allowing for correlation

Table 1 Description of independent variables included in the Model

Variable	Explanation	Measurement indicators	Expected influence
District location	Area where the fish farmer operates	1 = Buikwe, 2 = Wakiso, 3 = Mpigi	Positive (+)
Farmer gender	Sex of the aquaculture farmer	1 = Male, 0 = Female	Positive (+)
Marital category	Current marital condition of the farmer	1 = Married, 2 = Single, 3 = Widowed	Positive (+)
Farmer age	Number of years the farmer has lived	Recorded in years	Positive (+)
Educational attainment	Total years spent in formal schooling	Recorded in years	Positive (+)
Family size	Number of individuals living in the household	Actual count	Positive (+)
Aquaculture experience	Length of time engaged in fish farming	Measured in years	Positive (+)
Association membership	Participation in a farmer group or association	1 = Yes, 0 = No	Positive/Negative (+/-)
Household earnings	Total monthly income of the household	Measured in USD	Positive (+)
Training accessibility	Whether the farmer has access to aquaculture training	1 = Yes, 0 = No	Positive (+)
Land tenure status	Form of land ownership used for farming	1 = Owned, 2 = Rented	Positive (+)

in the unobserved factors influencing these decisions, this model depicts the interdependence among choices.

The dependent variables in this model were:

Y_1 : Pond aquaculture (1 = Yes, 0 = No)

Y_2 : Cage aquaculture (1 = Yes, 0 = No)

Y_3 : Aquaponics (1 = Yes, 0 = No)

The MVP model was specified as follows:

$$Y_j^* = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \epsilon_j, j = 1, 2, 3$$

Where:

Y_j^* is the latent variable representing the unobserved propensity to choose aquaculture system j (pond, cage, or aquaponics).

$X_1, X_2, \dots, X_k$ are independent variables (e.g., age, education level, household size, location...etc).

β_k are the estimated coefficients.

ϵ_j are the error terms, which are thought to have a variance-covariance matrix that permits correlation between choices and a multivariate normal distribution with a mean of zero.

$$\epsilon = (\epsilon_1, \epsilon_2, \epsilon_3) \sim MVN(0, \Sigma)$$

Where Σ is the variance-covariance matrix capturing potential correlations between the error terms of different aquaculture system choices.

The observed choice rule was given by:

$$Y_j = \begin{cases} 1, & \text{if } Y_j^* > 0 \\ 0, & \text{otherwise} \end{cases}$$

This implies that a farmer selects a particular aquaculture system if the latent propensity Y_j^* exceeds a certain threshold (normalized to zero). The MVP specification allowed for a flexible representation of farmers' decisions, capturing the interdependence between choices and improving the understanding of factors influencing aquaculture system selection.

Results

Respondents' economic and demographic characteristics

This section provides an overview of the study participants' demographic and economic characteristics. Gender, marital status, age, education level, family size, fish farming experience, group involvement, monthly income, and the choice of aquaculture technology were the main parameters that were examined (Table 2).

Male respondents predominated in small-scale aquaculture (83.6%), according to the demographic statistics (Table 2). With an average age of 47.5 years and an average of 11 years of education, indicating basic literacy, the

Table 2 Demographic and economic characteristics of the respondents

Variables	Buikwe (n = 65)	Mpigi (n = 49)	Wakiso (n = 55)	Pooled (n = 169)
Sex (%)	15.4 male / 84.6 female	13 male / 87 female	21.2 male / 78.8 female	16.4 male / 83.6 female
Marital Status (%)	83.1 married	77.8 married	71.2 married	77.8 married
Age (years)	43.2	49.1	50.2	47.5
Years in Education	11	11	11	11
Household Size (members)	4.3	3.5	3.9	3.9
Experience in Fish Farming (years)	3.1	3.6	3.1	3.3
Experience in Group Dynamics (years)	2.6	2.7	3.3	2.9
Monthly Income (USD)	318	299	301	306
Farming System (%)	Aquaponics: 4.6, Cage: 35.4, Pond: 60	Aquaponics: 0, Cage: 13, Pond: 87	Aquaponics: 19.2, Cage: 17.3, Pond: 63.5	Aquaponics: 7.6, Cage: 22.8, Pond: 69.6

Table 3 Results of assumption tests for the Multivariate Probit Model

Statistic	Value	p-value
Test statistic	4.53	0.095
Correlation range	0.35–0.60	-
VIF range	1.2–3.5	-
LR statistic	25.6	< 0.01
AIC value	238.5	-
BIC value	249.3	-
Wald statistic	19.3	< 0.05

majority (77.8%) are married. With an average household size of 3.9, Buikwe has rather larger houses (4.3 people). The responders had an average of 3.3 years of fish farming experience and 2.9 years of group dynamics experience. Farmers in Buikwe had the highest average monthly income, at USD 306. The most popular method is pond farming (69.6%), which is followed by aquaponics (7.6%) and cage farming (22.8%).

Assumption tests for the Multivariate Probit Model

The results of the assumption tests conducted to validate the Multivariate Probit Model (MVP) are presented in Table 3. Mardia's test for multivariate normality yielded a test statistic of 4.53 ($p = 0.095$), indicating that the error terms do not significantly deviate from the expected normal distribution, thereby supporting the assumption of multivariate normality. Significant off-diagonal correlations ranging from 0.35 to 0.60 were found in the variance-covariance matrix, supporting the application of the MVP model and proving the existence of

interdependencies across the aquaculture system selections (Pond, Cage, and Aquaponics). Multicollinearity between the independent variables is not a problem, according to the Variance Inflation Factor (VIF) values, which varied from 1.2 to 3.5. The Likelihood Ratio (LR) test yielded a result of 25.6 ($p < 0.01$), which further confirmed the MVP model's applicability and strongly rejected the null hypothesis that there was no link between the error components. Furthermore, the MVP model offers the best fit when compared to other models (AIC = 255.4, BIC = 268.1), according to the Akaike Information Criterion (AIC = 238.5) and Bayesian Information Criterion (BIC = 249.3) values. Ultimately, the Wald test produced a statistic of 19.3 ($p < 0.05$), indicating that the farmers' choice of aquaculture system is significantly influenced by the explanatory variables taken together.

Factors influencing choice of small-scale aquaculture system

Farmers in the Lake Victoria Basin choose small-scale aquaculture systems based on institutional, regional, and socioeconomic variables. The results from the Multivariate Probit Model (Table 4) highlight key determinants that shape farmers' decisions regarding pond, cage, and aquaponics systems.

Socioeconomic and demographic factors

Male farmers were more likely to select cage aquaculture (RRR = 2.52, $p = 0.087^*$) and aquaponics (Relative Risk Ratio [RRR] = 2.12, $p = 0.145$), indicating that gender differences affect risk preferences and technology selection in aquaculture investments. However, other demographic factors, included years of education, marital status, household size age, and farming experience, were not statistically significant across all three aquaculture systems, indicating that these characteristics may not be strong determinants in the selection of an aquaculture system.

Institutional and social support

Membership in farmers' groups significantly influences the choice of all aquaculture systems, with higher likelihoods of choosing pond (RRR = 0.56, $p = 0.039^{**}$), cage (RRR = 0.46, $p = 0.011^{**}$), and aquaponics (RRR = 0.82, $p = 0.011^{**}$) systems. This underscores the importance of collective knowledge, shared resources, and financial support in aquaculture decision-making. Conversely, access to training, despite being widely regarded as crucial for technology choice, was not statistically significant in this study, suggesting that informal knowledge-sharing through peer networks may have a greater influence on farmers' aquaculture choices.

Land and location constraints

Geographical location significantly influences the adoption of pond (RRR = 0.15, $p = 0.031^{**}$) and aquaponics (RRR = 0.42, $p = 0.047^{**}$) systems, while its effect on cage aquaculture is marginally significant (RRR = 0.8, $p = 0.055^*$), indicating that environmental factors and proximity to water sources play a crucial role in farmers' decisions. Additionally, land tenure security significantly reduces the likelihood of choosing cage aquaculture (RRR = 0.13, $p = 0.010^{**}$), suggesting that farmers with secure landholdings favor land-based systems such as ponds. This underscores the need for policy interventions to support farmers with limited land access who seek to engage in cage aquaculture.

Qualitative insights on small-scale aquaculture system choice

Gender barriers in aquaculture system choice

Participants emphasized that gender plays a crucial role in determining who engages in specific aquaculture systems. Male farmers were perceived as more likely to adopt aquaponics, a system described as requiring both advanced technical knowledge and financial input. An aquaculture officer in Buikwe stated, "Women often lack ownership of land and capital, making it difficult for them

Table 4 Results from the Multivariate Probit Model on the variables that affect farmers' selection of small-scale aquaculture systems

Variable	Pond (RRR)	p-value	Cage (RRR)	p-value	aquaponics (RRR)	p-value
Cons	4.15	0.603	3	0.123	6.72	0.675
Location	0.15	0.031**	0.8	0.055*	0.42	0.047**
Sex	0.72	0.097*	2.52	0.087*	2.12	0.145
Marital status	0.98	0.905	0.65	0.401	1.25	0.567
Age	1.03	0.582	1.03	0.31	1.1	0.311
Years in education	1.12	0.226	1.12	0.35	1.03	0.651
Household size	1.09	0.186	1.2	0.222	1.21	0.25
Experience (years)	0.94	0.659	1.04	0.265	0.98	0.85
Group membership	0.56	0.039**	0.46	0.011**	0.82	0.011**
Household income	1.02	0.285	0.98	0.434	0.98	0.434
Access to training	1.09	0.584	1.42	0.279	1.42	0.279
Land ownership	0.13	0.010**	0.2	0.112	1.53	0.398

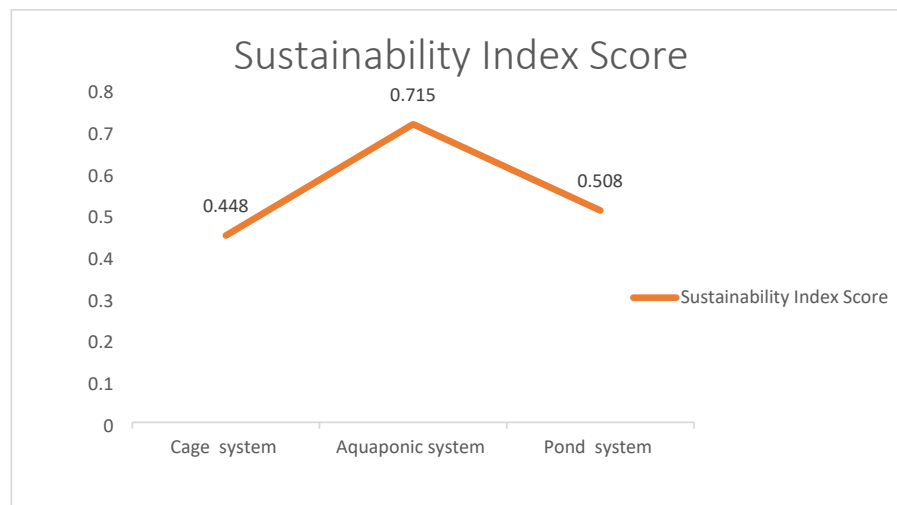


Fig. 2 Sustainability index scores for aquaculture farming systems

to participate fully in aquaculture.” Across discussions, women have limited access to resources for example land, credit, and training emerged as a consistent constraint, restricting their involvement in various aquaculture systems.

Financial and technical constraints as perceived barriers

The barriers to choosing certain aquaculture system differed depending on stakeholder perspective. Farmers consistently pointed to financial limitations particularly the lack of credit and the high initial cost of systems like aquaponics as a major constraint. One farmer in Wakiso noted, “The system [aquaponics] has potential, but the initial setup cost is beyond what most small-scale farmers can afford.” In contrast, extension officers placed greater emphasis on the importance of technical training and the availability of infrastructure. As one officer explained, “Hands-on demonstrations are crucial for farmers to fully grasp the potential of new systems like aquaponics.” These divergent views underscore how both financial and technical barriers interact to shape technology adoption.

Geographic context and access to water

Environmental conditions, particularly access to water, were frequently cited as key factors influencing system choice. In Buikwe, farmers highlighted the role of water bodies in making pond farming more feasible. One respondent explained, “Having access to water bodies is the primary factor that influences our decision to use ponds.” Such comments illustrate how the local physical environment strongly shapes aquaculture practices.

Group influence and cooperative support

Social structures also played a role in shaping adoption decisions. Group membership and participation in farmer cooperatives were identified as important

facilitators of access to knowledge, resources, and collective bargaining power. A cooperative leader in Mpigi remarked, “Through group membership, we can share costs, exchange knowledge, and collectively negotiate for better market prices.” For many participants, such networks were essential in navigating the challenges of aquaculture and in lowering individual risk when adopting new systems.

Sustainability index scores for aquaculture farming system

Results in Fig. 2 revealed aquaponic system emerges as the most sustainable method, with a high sustainability index of 0.715, due to resource efficiency, climate resilience, and social inclusivity, although it faces high initial costs and requires skilled labor [14]. Pond farming has a moderate sustainability score of 0.508, benefiting from strong community participation and cultural acceptance, but it struggles with lower water efficiency and higher climate vulnerability [35]. Cage system tend to, have lowest score of 0.448, faces significant environmental challenges, including water pollution concerns and climate vulnerability, while offering job creation and profitability, but lacks community involvement and gender inclusivity [20] (Fig. 2).

Discussion

Rogers’ Diffusion of Innovation (DOI) theory, which highlights five crucial characteristics that impact choice Relative Advantage, Compatibility, Complexity, Trialability, and Observability is used to understand the empirical results. The decision patterns of small-scale aquaculture systems are explained by each component.

The sociocultural barriers that prevent women from participating in aquaculture are shown by the male predominance (83.6%) in Buikwe, Mpigi, and Wakiso. Productivity and equity in the industry are decreased by

gender disparities in decision-making and resource access [8]. Women's participation is further hampered by structural obstacles such as unstable land tenure and restricted financial access [13]. However, integrating women into pond, cage, and aquaponics systems can improve household welfare, as evidenced in other regions [23, 32]. To address this, gender-inclusive training and improved credit access are essential [39]. Family labor plays a critical role in small-scale aquaculture. Married farmers, particularly in Buikwe, benefit from household labor support, while Wakiso faces labor shortages due to the prevalence of single-headed households. This is consistent with [2], who noted that single farmers face greater labor constraints.

The average age of farmers (47.5 years) suggests a moderate choice of aquaculture, with older farmers favoring traditional methods due to risk aversion and perceived high investment costs [16, 44] (Complexity). While younger farmers show greater enthusiasm for systems like aquaponics, they struggle with financing [47]. Despite an average of 11.3 years of education beyond primary level many farmers lack the technical knowledge needed for advanced systems. Bridging this gap requires practical training, demonstration farms, and robust extension services [21, 14] (Trialability).

Household size also influences labor availability. In Buikwe, larger families enhance aquaculture productivity, while Wakiso's smaller households experience labor shortages, an indication that household size with large number of active working age can provide labour for fish farming activities [2]. Establishing farmer cooperatives may alleviate labor constraints and promote knowledge sharing and resource access [33, 5].

Pond farming dominates (69.6%) across the study areas, particularly in Mpigi (87%), due to its accessibility, lower financial barriers, and ease of maintenance (Relative Advantage). This aligns with [14, 15], who emphasized the importance of traditional farming in resource limited settings (Compatibility). Its alignment with existing agricultural practices reduces perceived risk. Furthermore, Pond farming demonstrates high observability due to its widespread use in local communities particularly in Mpigi. Farmers can easily witness the outputs and practices of their peers, promoting knowledge transfer and trust in the system (trialability) [49, 51]. Cage farming, while less prevalent, offers moderate observability in areas with shared water resources, such as Buikwe, where communal or visible installations make outcomes more noticeable [24]. In contrast, aquaponics exhibits low observability, as its implementation is often confined to isolated, enclosed systems and remains uncommon across the study areas. This invisibility limits peer learning and contributes to misconceptions about its practicality, further impeding adoption [54]. Enhancing

aquaponics observability through demonstration farms, peer exchange programs, and community led pilots is essential to accelerate diffusion and build trust among potential adopters. Cage farming (22.8%) is more prevalent in Buikwe (35.4%), supported by better infrastructure and financial resources. However, high costs and technical demands constrain its growth [24] (Complexity). Aquaponics, with the lowest adoption (7.6%), but relatively higher uptake in Wakiso (19.2%), faces similar barriers due to its perceived difficulty and experimentation costs [20] (Trialability, Complexity).

The Multivariate Probit Model (MVP) results show that geographic location, group membership, land ownership, and gender significantly affect aquaculture system choice. Variables like age, education, household size, experience, and income showed no significant effects. Geographic factors influence the choice of pond and aquaponics systems due to water availability, infrastructure, and environmental conditions [7, 38]. Group membership enhances choice through knowledge sharing and financial support, especially in pond and cage systems [42, 10]. Secure land tenure supports long-term investment in pond systems but discourages cage farming, which suits farmers without land [9, 3]. Gender disparities are notable in aquaponics, where men are more likely to engage due to better access to training and credit [19]. While previous research emphasized education and experience [41], this study aligns with [18], showing that institutional mechanisms, such as land tenure policies and cooperatives, are more influential in system choice than individual attributes [17].

From a sustainability standpoint, aquaponics scores highest (0.715), driven by resource efficiency and environmental sustainability through its integrated, closed-loop system [53]. Its high climate resilience (85%) supports long-term viability [54], and it fosters social inclusivity [54]. However, its complexity and cost demand strong institutional and technical support [55] (Complexity, Trialability). Pond farming has a moderate sustainability score (0.508), characterized by strong community participation [49] but limited water efficiency (45%) and higher climate vulnerability (40%) [50]. Its compatibility with traditional farming methods sustains rural economies [51] (Compatibility, Observability). Cage farming, scoring lowest (0.448), offers profitability and job creation [48, 31, 4] but is hindered by environmental concerns, climate risks [52, 48], and low community and gender inclusivity [51].

Qualitative results highlights that gender plays a significant role in the choice of aquaculture systems. In particular, male farmers are more likely to engage in aquaponics, a system that requires both technical knowledge and financial investment. This is consistent with the quantitative findings, where men exhibited a higher

likelihood of choosing aquaponics ($RRR = 2.12$). As one aquaculture officer in Buikwe mentioned, “*Women often lack ownership of land and capital, making it difficult for them to participate fully in aquaculture.*” Women have limited access to land as well as resources, this hinders their involvement in all forms of aquaculture.

Farmers and extension officers highlighted different barriers to the choice of aquaculture technologies. Farmers were primarily concerned with access to credit and financial resources, while extension officers emphasized the need for technical training and infrastructure. A farmer from Wakiso mentioned, “*The system [aquaponics] has great potential, but the initial setup cost is beyond what most small-scale farmers can afford.*” In contrast, an extension officer in Buikwe noted, “*Hands-on demonstrations are crucial for farmers to fully grasp the potential of new systems like aquaponics.*” These differing perspectives highlighted that while financial constraints are critical for farmers, technical training and infrastructure development are also key enablers.

The quantitative results showed that geographic location ($RRR = 0.15$ for ponds, $p = 0.031^{**}$) significantly influences aquaculture system choice. The qualitative data supports this, as many farmers in Buikwe emphasized the role of proximity to water sources in their decision to choose pond farming. A farmer in Buikwe stated, “*Having access to water bodies is the primary factor that influences our decision to use ponds.*” Similarly, the model found that group membership ($RRR = 0.56$ for ponds, $p = 0.039^{**}$) influences system choice, which aligns with qualitative feedback from farmers who stressed the importance of cooperative networks in facilitating access to resources and shared knowledge. A cooperative leader in Mpigi mentioned, “*Through group membership, we can share costs, exchange knowledge, and collectively negotiate for better market prices.*”

Conclusion

The study analyzed the factors influencing small-scale aquaculture system choice and sustainability in Uganda's Lake Victoria Basin, focusing on pond aquaculture, cage aquaculture, and aquaponics. The findings revealed that location, group membership, land ownership, and gender significantly shape farmers' aquaculture system choice. Strong group membership enhances access to resources and knowledge exchange, whereas secure land ownership promotes long-term investments in aquaculture, particularly in cage aquaculture. Furthermore, disparities in gender in gender highlighted to have targeted system to support women's participation in aquaculture. The study recommends policy and practical system to promote small-scale aquaculture. Location-specific policies should address environmental challenges such as water accessibility. The need to strengthen fish farmer cooperatives,

this improves resource sharing, and technical knowledge transfer, thus, fostering sustainable aquaculture practices. Land reforms are needed to secure access resources, ensuring the viability of capital-intensive systems like cage farming. Gender-sensitive programs should be introduced to empower women in aquaculture by improving access to training, credit, and essential resources. Additionally, targeted training on aquaculture technologies as well as support mechanisms, in form of subsidies and credit facilities, these have to be implemented in order to enhance aquaculture, particularly for fish farmers with low income. Furthermore, Aquaponic farming stands out as a sustainable aquaculture system due to its resource efficiency and climate resilience, despite high initial costs. Pond farming supports rural economies but requires improved water efficiency and climate adaptation. Cage farming, while profitable, needs stricter environmental regulations and enhanced community engagement. Increased investment, training, and policy support can enhance sustainability across all systems.

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Author contributions

In addition to managing data collecting, doing data analysis and interpretation, leading focus groups and surveys, and developing the study design, SB also wrote the first draft of the manuscript. ML and SR gave the manuscript crucial oversight, direction, and important edits.

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Data availability

The authors' state that the information used to support the study's conclusions is readily available. The relevant author can provide any raw data files, in any format, upon reasonable request.

Declarations

Ethics approval and consent to participate

The study received ethics approval from Lilonwe University of Agriculture and Natural Resources' Research Ethic Committee (LUANAR-REC/23/11). The study was carried out in compliance with the 1964 Helsinki Declaration. Furthermore, our institution adopted the ethical criteria. For every individual involved. In order to conduct the study, the participants, their families, and local governments gave their oral informed consent. Additionally, the “Informed Consent section of the Helsinki Declaration (1964)” served as the basis for this consent. Clinical trial not applicable.

Consent for publication

All authors have reviewed and approved the content of this manuscript, which has been submitted for publication.

Competing interests

The authors declare no competing interests.

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