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ORIGINAL ARTICLE

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Implications of climate-smart aquaculture practices on households' income and food security in Mwanza and Mara, Tanzania's Lake Zone

Christopher N. Mdoe [1] **Christopher P. Mahonge** [2] **Edwin E. Ngowi** [3]

[1] Department of Rural Development and Regional Planning, Institute of Rural Development Planning-Lake Zone Centre, Mwanza, P O Box 11957 Mwanza, Tanzania. cmdoe@irdp.ac.tz
[2] Department of Policy Planning and Management, Sokoine University of Agriculture (SUA), P.O. Box 3000 Morogoro, Tanzania. mahonge@sua.ac.tz
[3] Department of Development and Strategic Studies, Sokoine University of Agriculture (SUA), P.O. Box 3000 Morogoro, Tanzania. ngowi@sua.ac.tz

ABSTRACT

Background: Climate-Smart Aquaculture (CSAq) practices present significant opportunity for the mitigation of climate-related challenges within the aquaculture sub-sector, particularly in the Lake Zone of Tanzania, where aquaculture and fisheries are central to household well-being.

Aims: This study aimed to evaluate the impact of three CSAq practices—integrated farming, polyculture, and monoculture—on household income and food security.

Methods: A cross-sectional study was conducted between November 2023 and February 2024, involving 384 aquaculture households across the Mara and Mwanza regions. Data were analyzed using descriptive and inferential statistical methods, including chi-square and t-tests, to determine the influence of CSAq practices on economic and food security outcomes.

Results: The findings revealed that integrated farming significantly enhanced both household income and food security, with participating households achieving a "Very Satisfactory" Household Food Security Index (HFSI) score. In Mara, where integrated farming was more prevalent, households reported significantly higher yields (3303 ± 155 kg) compared to those in Mwanza (2454 ± 146 kg; $t = 4.96$, $p < 0.001$). However, Mwanza exhibited significantly higher prices per kilogram (6719 ± 103 TSH) than Mara (5799 ± 122 TSH; $t = -5.29$, $p < 0.001$) attributed to superior market access and infrastructure. Polyculture practices, more frequently adopted in Mwanza (35.7%) than in Mara (21.8%), yielded variable impacts on income and food security. Chi-square analysis ($\chi^2 = 9.269$, $p = 0.010$) indicated significant regional disparities in CSAq adoption, with Mara exhibiting higher adoption rates of integrated farming (69.3%) compared to Mwanza (56.0%).

Conclusions: This study confirmed that integrated aquaculture-agriculture systems significantly improve household income and food security, while monoculture increases vulnerability. Regional variations indicate higher yields in Mara, associated with the widespread adoption of integrated farming, whereas Mwanza benefited from enhanced market access and elevated fish prices. Strengthening financial access, training programs, and institutional support is crucial for enhancing CSAq adoption. Key recommendations include the expansion of extension services, the improvement of market infrastructure, and the fortification of cooperative support systems to ensure sustainable aquaculture.

Keywords: Climate-Smart Aquaculture (CSAq), Income, Food Security, Household Well-being, Tanzania's Lake Zone.

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Corresponding author: Christopher N. Mdoe
E-mail: christmdoe@gmail.com / cmdoe@irdp.ac.tz
Tel. +255 (715 124 320)

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1 INTRODUCTION

Climate change poses significant challenges to ecosystems and livelihoods globally, with disproportionate effects on regions that rely heavily on natural resources for sustenance and economic activity. Tanzania's Lake Zone, including regions such as Mwanza and Mara, is particularly vulnerable due to its dependence on aquaculture and fisheries as primary sources of both income and food security. Rising temperatures, erratic rainfall patterns, and increased climatic variability have led to declining fish production, compromised ecosystem health, and heightened risks for smallholder aquaculture farmers. In Lake Victoria, temperature fluctuations have become more pronounced, with maximum monthly temperatures ranging from 27°C to 29°C, and July recording the lowest temperatures around 15°C (Mdoe *et al.*, 2025).

More critically, water temperature variations directly affect the growth, health, and reproductive cycles of key aquaculture species such as tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*). Cooler water temperatures slow fish metabolism, reduce feed efficiency, and ultimately decrease yields, while higher temperatures can increase disease prevalence and stress, further threatening production (Berg *et al.*, 2021; Abd El-Hack *et al.*, 2022). These environmental changes not only jeopardize the sustainability of aquaculture systems but also exacerbate pre-existing socio-economic challenges, including poverty, resource depletion, and food insecurity in the region (Tran *et al.*, 2021; Ojo *et al.*, 2024). Climate-induced risks have been found to significantly increase household food insecurity in Tanzania, reinforcing the need for climate-resilient agricultural and aquaculture systems (Kitole *et al.*, 2024).

Addressing these intertwined challenges aligns with several United Nations Sustainable Development Goals (SDGs), including SDG 1.1 (eradicate extreme poverty), SDG 2.1 (end hunger and ensure access to nutritious food), and SDG 13.1 (strengthen resilience and adaptive capacity to climate-related hazards) (NU-CEPAL, 2019). Aquaculture, as one of the fastest-growing sub-sectors of agriculture, has the potential to play a dual role in Tanzania's economy: enhancing nutritional outcomes and generating household income. However, traditional aquaculture practices, such as monoculture systems, are increasingly inadequate in addressing the climate-related risks faced by smallholder farmers. Monoculture systems, characterized by the cultivation of a single fish species, are highly vulnerable to disease outbreaks, environmental shocks, and market fluctuations, leading to unstable productivity and limited resilience (Okoko *et al.*, 2020; United Nations Development Programme [UNDP], 2022).

One such approach is Climate-Smart Aquaculture (CSAq), grounded from Climate-smart agriculture (CSA) introduced by FAO in 2010, aiming to enhance agricultural productivity while promoting resilience to climate change and reducing greenhouse gas emissions (Food Agriculture Organisation [FAO], 2013). Building on this framework, Climate-Smart Aquaculture (CSAq) has emerged as an extension of CSA, specifically tailored to the unique challenges and opportunities within aquaculture systems. CSAq integrates climate adaptation, mitigation, and sustainable resource management into aquaculture practices, emphasizing the need for environmentally sound, economically viable, and socially equitable solutions (Asiedu *et al.*, 2017; Julius, 2023).

CSAq encompasses a range of practices designed to optimize resource use and minimize environmental impacts while maintaining or enhancing productivity. Key strategies include integrated aquaculture-agriculture systems, polyculture, and Recirculating Aquaculture Systems (RAS). Integrated farming combines fish production with crop cultivation and/or livestock rearing, creating synergies that maximize resource efficiency, reduce waste, and improve environmental outcomes (Ajeigbe & Ganda, 2024). Polyculture systems, which involve farming multiple fish species, offer advantages in terms of diversifying outputs, mitigating risks associated with environmental shocks, and improving household dietary diversity. These approaches not only contribute to environmental sustainability but also enhance household income and food security, aligning with broader global sustainability goals (UNDP, 2022; Bhattacharyya *et al.*, 2020).

In Tanzania's Lake Zone, CSAq presents a critical opportunity to address the intertwined challenges of poverty, food insecurity, and climate vulnerability. However, despite its potential, the adoption of CSAq practices remains uneven and limited. Factors such as socio-economic disparities, limited access to training, resource constraints, and weak market linkages continue to hinder widespread implementation (Rukanda, 2018). Moreover, while CSAq is widely promoted in policy frameworks, empirical evidence on its localized socio-economic impacts, particularly in freshwater systems like Lake Victoria, is scarce. Existing studies primarily focus on marine aquaculture, theoretical models, or technical aspects such as fish feed management and disease control, leaving a gap in understanding the real-world impacts of CSAq on household income and food security in Tanzania's inland regions (Sène-Harper *et al.*, 2019; Mmanda *et al.*, 2020; Rahman *et al.*, 2021).

This study seeks to address this gap by providing region-specific empirical evidence on the socio-economic implications of CSAq practices in the Mwanza and Mara regions. These regions were selected due to their distinct aquaculture environments: Mwanza, with its established fisheries sector and better market integration, contrasts with Mara, where integrated farming is more prevalent, but market access is limited. By comparing these two regions, the study aims to examine how localized factors such as resource availability, market accessibility, and environmental conditions influence CSAq adoption and its impacts on household income and food security. The findings will provide valuable insights into the scalability and adaptability of CSAq practices across diverse socio-economic and ecological contexts in Tanzania, contributing to the development of targeted interventions to improve livelihood resilience and strengthen food systems in vulnerable communities.

1.1 Theoretical review

The Sustainable Livelihood Framework (SLF), developed by the Department for International Development (Department for International Development [DFID], 1999), is widely applied in analyzing how households utilize their assets, manage risks, and adopt livelihood strategies to enhance well-being. The framework identifies five key livelihood assets natural, human, financial, social, and physical capital that influence a household's capacity to engage in productive activities. Additionally, SLF recognizes the role of vulnerability contexts (shocks, trends, and seasonality) and transforming structures and processes (institutions, policies, and regulations) in shaping livelihood strategies and outcomes.

In the context of Climate-smart aquaculture (CSAq), SLF provides a structured lens to assess how smallholder farmers leverage their available assets to adopt CSAq practices (integrated farming, polyculture, and monoculture) while responding to environmental and economic shocks. Households with greater access to financial capital (credit, savings), physical capital (storage facilities, transport infrastructure), and human capital (education, skills training) are more likely to adopt integrated CSAq practices, leading to improved household income and food security. However, external shocks such as climate variability, fluctuating fish prices, and market access challenges create vulnerabilities that influence farmers' decisions and outcomes. Similar approaches have been used in rural livelihoods studies, including Kitole & Sesabo (2024), who applied SLF to analyze tourism-driven livelihood strategies in Tanzania. Their study underscores how external shocks and institutional frameworks shape livelihood decisions, reinforcing SLF's relevance in examining how CSAq adoption is influenced by household assets and broader socio-economic factors.

Despite its strengths, SLF has limitations. Scholars argue that the framework does not adequately capture power relations, policy enforcement barriers, and macroeconomic factors that influence livelihood strategies (Natarajan *et al.*, 2022). Furthermore, SLF assumes rational decision-making, overlooking behavioral and cultural factors in household adaptation strategies. To address these gaps, this study modifies the SLF framework by incorporating institutional and market-based factors that impact CSAq adoption, ensuring a more holistic understanding of income and food security outcomes in aquaculture-based livelihoods. This approach aligns with Kitole & Sesabo (2024), who emphasized the importance of policy and institutional interventions in supporting sustainable rural livelihoods.

1.2 Conceptual framework

This study adopts the Sustainable Livelihood Framework (SLF) to analyze how CSAq practices influence household income and food security in Tanzania's Lake Zone. SLF provides a structured approach to understanding how households leverage their assets, respond to shocks, and navigate institutional and policy structures to achieve sustainable livelihoods (DFID, 1999). The modified framework in this study incorporates institutional and market-based factors to better explain the challenges and opportunities influencing CSAq adoption.

Households' ability to adopt CSAq practices depends on access to livelihood assets, including natural (water, fish species), human (skills, education), financial (credit, savings), social (cooperative networks), and physical (storage, transport, and market infrastructure) capital. However, these assets alone do not determine outcomes—they are shaped by external and internal shocks, such as climate variability, fluctuating fish prices, and input costs, which affect resource availability and decision-making.

The framework positions CSAq adoption as a key livelihood strategy, with households engaging in integrated aquaculture-agriculture, polyculture, or monoculture. The livelihood outcomes (income and food security) are influenced by both the chosen CSAq practice and the enabling environment, which includes market access, extension services, aquaculture policies, and cooperative support. Studies such as Kitole & Sesabo (2024) highlight the role of institutional and policy interventions in shaping rural livelihoods, reinforcing the need for strong governance structures to enhance CSAq sustainability.

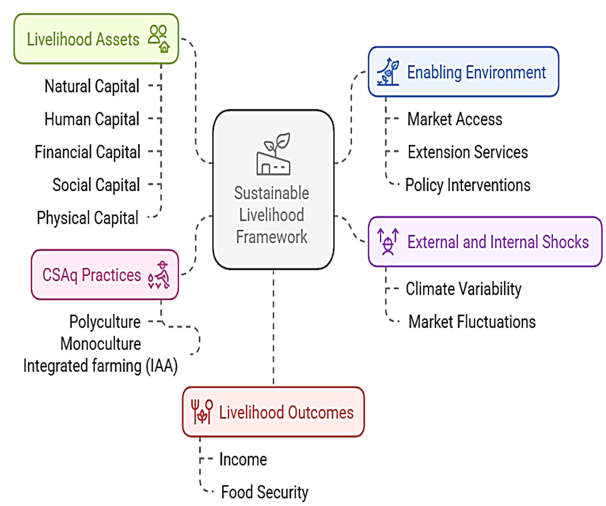

Figure 1. Conceptual Framework model of the Study on CSAq Practices (*Modified from SLF)*

This conceptual model modifies SLF by explicitly incorporating institutional barriers and policy interventions as key variables affecting CSAq adoption and its impact on livelihoods. Integrating these dimensions, the study provides a holistic framework for understanding the socio-economic dynamics of CSAq practices, ensuring that policy recommendations address both household-level constraints and structural challenges.

2 Material and Methods

The study was conducted in Tanzania's Lake Zone, focusing on Mwanza and Mara regions along the southern shores of Lake Victoria. These regions are renowned for their significant contributions to aquaculture and fisheries, which play a pivotal role in enhancing food security and economic development in Tanzania (Nyboer *et al.,* 2022). Lake Victoria, as one of the largest freshwater lakes globally, serves as a critical resource for aquaculture practices, providing livelihoods to many households. Figure 1 illustrates the map of Mwanza and Mara regions in relation to Lake Victoria.

2.1 Sample procedures and sample size

A cross-sectional survey design was employed, utilizing a multistage sampling technique to ensure a representative sample from the two regions. Initially, districts within Mwanza and Mara regions were purposively selected based on their prominence in aquaculture activities. From these districts, villages were selected based on the aquaculture database register provided by aquaculture extension officers from each council, ensuring a representative sample of aquaculture households. Random sampling was then applied within the selected villages to capture a broad aquaculture population. Subsequently, households were randomly sampled within the selected villages. The sample size was determined using Cochran's formula to achieve statistical reliability with a 95% confidence level and a 5% margin of error:

$$n_0 = \frac{Z^2 P(1-P)}{e^2} \quad (Eq1)$$

Whereby Z=1.96, representing the critical value for a 95% confidence level, P=0.5, the assumed proportion of the population practicing aquaculture =0.05, the allowable margin of error. Substituting these values in equation 1 the estimation will be;

$$n_0 = \frac{(1.96)^2 0.5(1-0.5)}{0.05^2} = 384$$

The final sample was distributed proportionally between the regions based on their population and aquaculture activity levels. Mara accounted for 202 households, while Mwanza included 182 households. In each selected village, 30 households were surveyed. This sample size ensured robust data collection and representation of aquaculture households in the Lake Zone.

For the purposes of this research, food security is operationally defined according to the Food and Agriculture Organization (FAO) as a condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life. This definition encompasses three critical dimensions that are crucial for our analysis:

i. *Availability*: This dimension assesses the presence and adequacy of food supplies within the regions, analyzed through data on local food production, imports, and availability in markets.

ii. *Access*: This aspect evaluates both the economic means and physical capabilities of households to obtain food. It includes an analysis of income levels, market prices, and the proximity of food sources to assess how easily individuals can acquire the foods they need.

iii. *Utilization*: Concerns about the proper dietary use of food, focusing on the nutritional quality and adequacy of the food consumed by individuals. This is measured through surveys on dietary diversity, meal frequency, and nutritional status of households.

2.2 Data types, methods, and tools for data collection

This study utilized a mixed approach method where by quantitative and qualitative data were used to collect data on climate-smart aquaculture (CSAq) practices, food security, and household socio-economic characteristics. Structured household questionnaires were administered using a

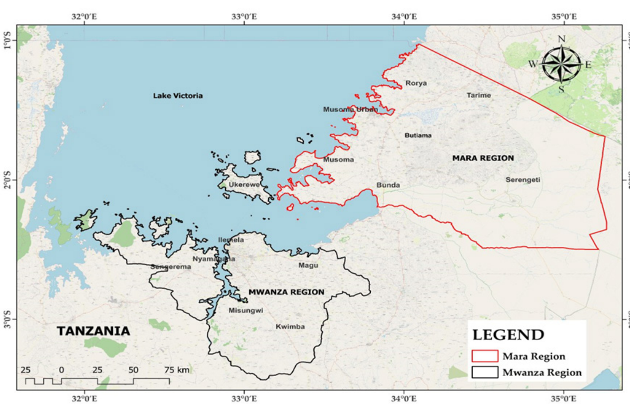

Figure 2. Map of the study area

Computer-Aided Personal Interviewing (CAPI) tool called KOBO-COLLECT, enhancing data accuracy and minimizing errors during data entry. The tool was pre-tested in a pilot study conducted in Busega District to ensure reliability, and enumerators underwent standardized training to maintain consistency and ensure uniform data collection across regions. Data collection focused on assessing CSAq practices adopted by households, food security indicators, and socio-economic variables such as income, education, and employment. The study emphasized three major CSAq practices: integrated farming, monoculture, and polyculture, to explore their prevalence and impact.

Qualitative data were collected through Key Informant Interviews (KIIs) to provide deeper insights into Climate-Smart Aquaculture (CSAq) practices and their impacts on income and food security. A total of 39 key informants were purposefully selected for their expertise and relevance to the study's objectives. Participants included government officers, researchers, extension officers, private sector representatives, and aquaculture-based institutions, ensuring diverse perspectives. The interviews followed a semi-structured format, using an Interview Checklist with open-ended questions designed to explore themes such as the socio-economic and contextual factors influencing CSAq practices.

2.3 Study variables

The variables analyzed in this study are categorized into key components that address food security and aquaculture practices. These variables provide a framework for understanding the impacts of Climate-Smart Aquaculture (CSAq) on household well-being. A detailed summary of the key variables is presented in Table 1.

2.4 Data analysis

Quantative data analysis was conducted using SPSS Version 27 and Microsoft Excel to process, summarize, and interpret the collected data effectively. Descriptive statistics, including frequencies, percentages, and mean scores, were employed to provide a detailed overview of key variables such as household food security status, nutritional diversity, and the adoption of CSAq practices. Dimensional analysis was performed to calculate weighted scores for critical subcomponents, including food consumption, stability of food access, and nutritional diversity. These scores were rescaled to a 10 – 100 scale to enhance clarity and interpretability. Inferential statistical methods, specifically chi-square tests, were utilized to assess the associations between CSAq adoption and food security outcomes. This combination of descriptive and inferential approaches ensured a robust and comprehensive evaluation of the data.

The qualitative data collected from Key Informant Interviews (KIIs) were analyzed using thematic analysis, a systematic and flexible approach for identifying, organizing, and interpreting patterns within qualitative data. This method was chosen for its ability to uncover diverse stakeholder perspectives and contextual nuances critical to understanding the socio-economic and environmental factors influencing household well-being. The analysis began with systematic coding of transcribed interviews to identify recurring patterns and insights related to income generation, food security, and the adoption of Climate-Smart Aquaculture (CSAq) practices. These codes were then grouped into broader themes.

Thematic analysis was particularly effective in this study as it allowed for the integration of qualitative insights with quantitative findings, providing a richer and more comprehensive understanding of how CSAq practices impact household well-being. Focusing on key proxies' income and food security this approach illuminated actionable themes that were directly relevant to policy and practice recommendations. It also offered clarity and depth in interpreting the socio-economic and environmental dynamics shaping CSAq adoption, enhancing the study's implications for sustainable development.

2.5 Computational of indices

In this study food and nutritional security are conceptualized as derivatives of three dimensions: food consumption, stability of food access, and nutritional diversity. These dimensions are aggregated to calculate an overall food security score using weighted methods, enabling multidimensional analysis. Each subcomponent was computed using a weighted arithmetic average formula (Eq. 2) and converted into a 10 – 100 scale for enhanced resolution:

$$Y_{jk} = \sum_{i=1}^{n} W_{ii} \, . \, x_{ijk} \quad \text{(Eq. 2)}$$

Whereby yjk = score for household j in subcomponent k, Wij = weight assigned to question i in subcomponent k, xijk = scaled score for household j in question i of subcomponent k.To compute the overall food and nutritional security score, the weighted geometric mean formula was applied (Eq. 3):

$$Y_{jk} = \prod_{i=1}^{n} x_{ijk}^{w_i} \quad \text{(Eq. 3)}$$

These formulas enabled the calculation of scores for each household, categorized into four groups based on performance thresholds proposed by IFAD (2014) and the scales are, below 30: Very Unsatisfactory, 30–60: Unsatisfactory, 60–80: Satisfactory, above 80: Very Satisfactory. These satisfaction levels were derived using objective criteria based on standardized scoring thresholds proposed by IFAD (2014). The scores incorporate quantitative indicators of food security and nutritional diversity, minimizing subjective bias in household responses as indicated in Table 2.

Table 1. Key Variables Analyzed in the Study

Category	Variable Name	Measurement Definition
CSAq Practices	CSAq Practice Adopted	Specific aquaculture practices used, are categorized as "*Integrated Farming, Monoculture, or Polyculture*".
Household Experience in Food Security	Food and Nutritional Security	Household experience is categorized into *"Very Unsatisfactory," "Unsatisfactory," "Satisfactory,"* and *"Very Satisfactory."*
	Frequency of Hunger	Frequency of household members going to sleep hungry (e.g., Never, Once or Twice, Most Days).
	Food Sufficiency	The proportion of households experiencing periods without enough food (e.g., one full day, more than two weeks).
Food Consumption and Sufficiency	Food Consumption Frequency	Frequency of consuming seven food groups (e.g., grains, roots, dairy, meat) daily, weekly, or monthly.
	Food Group Consumption	The proportion of households consuming food groups (e.g., grains, vegetables, dairy) every day.
Stability of Food Access	Stability in Food Access	Duration of food instability, including periods without sufficient food for more than two weeks or missing meals.
Household Nutritional Diversity	Nutritional Diversity	The proportion of households consuming a balanced variety of food groups (e.g., grains, fruits, vegetables) by frequency.
Socio-Economic Variables	Household Size	Number of household members.
	Age	Age of the household head.
	Education	Education level of the household head.
	Employment	Employment status of the household head.
	Housing	Quality of housing based on construction materials.
	Asset Ownership	Ownership of assets such as land, livestock, and durable goods.
	Gender	Gender of the household head.
	Income	Household income categories

Table 2. Thresholds for Evaluating Food Security Status Based on Household Scores (IFAD 2014)

S/No.	Category	Category Label
1.	Below 30	Very unsatisfactory
2.	30 – 60	Unsatisfactory
3.	60 – 80	Satisfactory
4.	Above 80	Very satisfactory

3 Results and Discussion

3.1 Socio-demographic and economic characteristics of the study participants

The socio-demographic and economic characteristics (Table 3) of respondents in Tanzania's Lake Zone regions exhibit significant variations that shape the adoption of Climate-Smart Aquaculture (CSAq) practices. The predominance of male participants (85.7%) is consistent with findings by Munguti *et al.* (2021), indicating that aquaculture continues to be a male-dominated sector. This disparity is often

Table 3. Socio-Demographic Characteristics of Respondents (n=384)

Variable	Category	Mara		Mwanza		Total		Pearson Chi-Square Tests		
		Freq	Per (%)	Freq	Per (%)	Freq	Per (%)	Chi-square	df	Sig.
Gender	Female	37	18.3%	18	9.9%	55	14.3%	5.54	1	.019*
	Male	165	81.7%	164	90.1%	329	85.7%			
Age category	18 – 25 years	10	5.0%	0	0.0%	10	2.6%	63.255	4	.000*
	26 – 35 years	81	40.1%	30	16.5%	111	28.9%			
	36 – 45 years	51	25.2%	29	15.9%	80	20.8%			
	45 – 60 years	55	27.2%	120	65.9%	175	45.6%			
	Above 60 years	5	2.5%	3	1.6%	8	2.1%			
Marital Status	Single	28	13.9%	2	1.1%	30	7.8%	22.578	3	.000*
	Married	145	71.8%	152	83.5%	297	77.3%			
	Widow/Widower	18	8.9%	14	7.7%	32	8.3%			
	Divorced/Separated	11	5.4%	14	7.7%	25	6.5%			
Education level	Primary	110	54.5%	59	32.4%	169	44.0%	43.353	5	.000*
	Secondary	49	24.3%	40	22.0%	89	23.2%			
	Certificate	4	2.0%	1	0.5%	5	1.3%			
	Diploma	13	6.4%	30	16.5%	43	11.2%			
	University	13	6.4%	45	24.7%	58	15.1%			
	Informal	13	6.4%	7	3.8%	20	5.2%			
Household size	Below 3	3	1.5%	0	0.0%	3	0.8%	7.529	2	.023*
	3 – 5 members	127	62.9%	96	52.7%	223	58.1%			
	Above 5 members	72	35.6%	86	47.3%	158	41.1%			
Primary source of income	Both	52	25.7%	16	8.8%	68	17.7%	31.094	2	.000*
	Fish Farming	75	37.1%	115	63.2%	190	49.5%			
	Off- fish farming	75	37.1%	51	28.0%	126	32.8%			
Extension Officer	No	83	42.6%	88	50.9%	171	46.5%	2.541	1	0.111
	Yes	112	57.4%	85	49.1%	197	53.5%			
Training	No	61	31.3%	72	41.6%	133	36.1%	4.244	1	.039*
	Yes	134	68.7%	101	58.4%	235	63.9%			

** The Chi-square statistic is significant at the .05 level.*

attributed to socio-cultural norms that position aquaculture and fisheries as labor-intensive activities traditionally reserved for men. Additionally, limited access to resources, training, and decision-making opportunities further restricts female participation in the sector (Uduji & Okolo-Obasi, 2020). Age distribution further reveals a concentration of respondents within the 45-60 age group (45.6%), particularly in Mwanza, emphasizing the value of experience in aquaculture. However, this age pattern also suggests potential barriers for younger participants, who may face challenges such as limited access to resources or capital, as highlighted by Stankus, (2021). These socio-demographic dynamics underscore the importance of targeted strategies to promote inclusive participation and sustainability in CSAq adoption.

Education levels further illustrate disparities, with Mwanza having a higher proportion of diploma and university graduates, which aligns with literature showing that higher education levels correlate with greater adoption of innovative aquaculture practices (FAO, 2024). The larger household sizes in Mwanza (47.3% above 5 members) may reflect socio-economic pressures influencing labor availability and household dependence on aquaculture income. Fish farming as the primary income source for 49.5% of respondents, particularly in Mwanza, supports evidence that regions with greater access to resources and markets are more inclined to specialize in aquaculture (Jettah *et al.*, 2024).

Additionally, access to extension officers (53.5%) and training programs (63.9%) highlights the importance of capacity-building initiatives in promoting CSAq adoption. However, disparities in training access between regions emphasize the need for targeted support to bridge knowledge gaps and encourage uniform uptake of CSAq practices (Rukanda, 2018). These findings underscore the critical interplay of socio-demographic factors, education, and institutional support in unlocking the potential of CSAq practices for food security and economic resilience in Tanzania.

The economic characteristics of respondents reveal significant differences in harvest outcomes and prices between the Mara and Mwanza regions as indicated in Table 4, underscoring regional disparities in aquaculture performance. Farmers in Mara produced significantly higher harvests (3303±155 kg) compared to Mwanza (2454±146 kg), with a difference of 849 kg. Mara's higher yields are attributed to favorable environmental conditions, including abundant water resources, less urban pollution, and greater land availability for aquaculture. Additionally, strong community-based farming practices and traditional knowledge contribute to efficient resource use and productivity (Nyboer *et al.,* 2022; Rukanda, 2018). However, despite these advantages in production, Mara farmers face challenges in accessing lucrative markets due to logistical constraints and remoteness.

Table 4. Economic characteristics of farmers involved (n=384)

Variables	Mara	Mwanza	Difference	T-stat	*p*-value
Harvest amount (Kg)	3303 ± 155	2454 ± 146	849	4.96	< 0.001
Price of your harvest per kg (TSH / Kg)	5799±122	6719±103	-920	-5.29	< 0.001

In contrast, Mwanza farmers achieved higher prices per kilogram (6719±103 TSH) compared to Mara (5799±122 TSH), thanks to superior market infrastructure, including cold storage facilities, ice flakes, and efficient transportation networks. Mwanza's accessibility via direct flights and proximity to major urban centers reduces transportation costs and enhances market reach. The city's strategic location near Burundi and Uganda facilitates cross-border trade, while its urban branding attracts high-value buyers from outside the region (Mulokozi *et al.*, 2020; Munguti *et al.*, 2024). This combination of infrastructure, market access, and branding gives Mwanza a competitive pricing advantage despite lower yields. This finding, supported by a highly significant t-statistic (t = 4.96, $p < 0.001$), suggests that Mara may have more favorable conditions or better resource utilization for aquaculture productivity.

The adoption of Climate-Smart Aquaculture (CSAq) practices across Tanzania's Lake Zone regions demonstrates notable regional disparities, with integrated farming being the most prevalent practice overall, adopted by 63.0% of respondents. Mara shows a higher adoption rate of integrated farming (69.3%) compared to Mwanza (56.0%), which may reflect differences in access to inputs, technical knowledge, or infrastructure for implementing diversified aquaculture systems. Integrated farming is widely recognized for its ability to enhance productivity and resilience by combining fish farming with agriculture, effectively utilizing resources and minimizing environmental impacts (Chan *et al.*, 2019).

Polyculture adoption is more prominent in Mwanza (35.7%) than Mara (21.8%), with significant regional variation in CSAq adoption. This higher adoption rate in Mwanza is likely influenced by favorable environmental factors, such as optimal water temperatures and the availability of diverse, compatible fish species suited for polyculture systems. Additionally, Mwanza's better market infrastructure and higher demand for varied fish species provide economic incentives for farmers to diversify production. The presence of extension services and training programs in Mwanza also facilitates the adoption of polyculture practices (Aloo *et al.*, 2017; Munguti *et al.*, 2021). The significant chi-square result ($\chi^2 = 9.269$, $p = 0.010$) underscores the regional variation in CSAq adoption, highlighting the role of local socio-economic and ecological factors in influencing farming choices.

3.2 Economic impact of CSAq practices

Significant regional disparities in the economic impact of Climate-Smart Aquaculture (CSAq) practices were identified in the study (Table 5), encompassing more than just income generation. While the findings from Mara and Mwanza show distinct differences in annual, seasonal, and monthly revenues integrated farming in Mara generated significantly higher income compared to other practices, with annual revenues reaching approximately 11,200,000 TZS, as opposed to 7,500,000 TZS in Mwanza where polyculture and monoculture are more prevalent. These differences are part of a broader economic picture.

Table 5. Adoption of Climate-Smart Aquaculture (CSAq) Practices Across Regions (n=384)

Variable	Category	Mara		Mwanza		Total		Pearson Chi-Square Tests		
		Freq	Per (%)	Freq	Per (%)	Freq	Per (%)	χ^2	df	Sig.
CSAq Practice adopted	Integrated farming	140	69.3%	102	56.0%	242	63.0%	9.269	2	.010*
	Monoculture	18	8.9%	15	8.2%	33	8.6%			
	Polyculture	44	21.8%	65	35.7%	109	28.4%			

*Note. * The Chi-square statistic is significant at the .05 level*

In addition to revenue disparities, the economic analysis considered the role of CSAq practices in fostering employment within the communities, reducing costs through more efficient resource use, and encouraging sustainable farming practices that contribute to long-term economic stability (Bisht *et al.*, 2020; Abegunde & Obi, 2022). For instance, integrated farming not only increases revenue but also enhances resource utilization and lowers input costs over time. Furthermore, these practices may stimulate local economies by increasing demand for related goods and services, thus extending economic benefits beyond direct farm incomes (Imran *et al.*, 2019; Mizik, 2021). As one aquaculture extension officer explained,

"Integrated systems allow farmers to earn from multiple sources fish, vegetables, and livestock all year round, reducing risks and boosting their income."

(KII, Musoma DC, December 2024).

These comprehensive economic impacts are underpinned by statistically significant disparities, with t-values indicating strong regional variations ($p < 0.001$), as detailed in Table 6. Such an expanded discussion of economic impacts provides a deeper understanding of how CSAq practices influence regional economic landscapes, highlighting their potential to contribute to broader economic development.

The superior economic performance of integrated farming systems in Mara can be attributed to the diversification of agricultural products and reduced vulnerability to market and climatic fluctuations, suggesting that diversification within CSAq practices not only stabilizes but also enhances income (Rogerson 2018; Zheng *et al.*, 2024). Additionally, the proximity of Mwanza to larger markets likely influences the relatively higher incomes from polyculture systems, benefiting from better market access and infrastructure.

The economic implications of these findings are critical for policy and practice. The data supports the promotion of integrated and polyculture practices, which have proven effective not only in improving food security but also in increasing economic returns. Such insights are invaluable for policymakers, suggesting that investments in CSAq training, infrastructure, and market access can yield substantial returns (Alokpaï & Harris, 2024). Specifically, policies should focus on subsidizing initial investments in integrated farming and enhancing market access to maximize the economic benefits of CSAq (Mulokozi *et al.*, 2020; Rahman *et al.*, 2021b).

Table 6. Annual, Seasonal, and Monthly Revenue from CSAq Practices Across Regions

CSAq Practice	Revenue Frame	Mara (TSHS)	Mwanza (TSHS)	t-value	*p*-value
Integrated Farming (IAA)	Annual	11,200,000 ± 1,500,000	7,500,000 ± 1,200,000	9.62	< 0.001
	Seasonal	5,600,000 ± 1,000,000	3,750,000 ± 800,000	8.34	< 0.001
	Monthly	1,500,000 ± 400,000	1,250,000 ± 350,000	3.72	< 0.001
Polyculture	Annual	5,600,000 ± 1,000,000	3,750,000 ± 800,000	8.34	< 0.001
	Seasonal	2,800,000 ± 500,000	1,875,000 ± 400,000	6.58	< 0.001
	Monthly	933,333 ± 166,667	625,000 ± 133,333	5.75	< 0.001
Monoculture	Annual	1,500,000 ± 400,000	1,250,000 ± 350,000	3.72	< 0.001
	Seasonal	750,000 ± 200,000	625,000 ± 175,000	2.88	< 0.001
	Monthly	250,000 ± 66,667	208,333 ± 58,333	2.34	< 0.001

The economic analysis within this study confirms that CSAq practices, particularly integrated farming, significantly contribute to higher households' incomes in Tanzania's Lake Zone. These practices, by enhancing both economic and food security, represent a sustainable pathway forward for the region's aquaculture sector. This economic advantage underscores the need for targeted interventions that promote these practices to foster broader socio-economic development (Rogerson 2018; Elpisah, 2023). Moreover, understanding the economic impacts of CSAq practices is pivotal for assessing their role in the sustainable development of Tanzania's Lake Zone regions, hence analysis focuses on how different CSAq practices influence the financial outcomes for households engaged in aquaculture, which is crucial for evaluating their viability and sustainability.

3.3 Food consumption across regions

Table 7 reveals notable differences in food consumption frequency between Mara and Mwanza regions, highlighting regional variations in dietary diversity. For grains, Mara leads with 73.3% of respondents consuming grain 'always,' while Mwanza follows with 63.3%, a significant difference (χ^2 = 5.87, p = 0.015). This suggests that Mara residents have a higher reliance on grains in their daily diets compared to Mwanza, possibly due to regional differences in agricultural practices or food availability, as supported by findings from (Nyboer *et al.,* 2022), who noted regional dietary variations linked to local crop production and food preferences in rural Tanzania. However, this higher reliance on grains in Mara may limit protein intake and reduce overall nutritional diversity, potentially leading to micronutrient deficiencies. In contrast, Mwanza's higher consumption of protein-rich foods, such as meat and fish, may contribute to better nutritional outcomes, including improved dietary balance and nutrient intake (Eyayu *et al.*, 2023; Mzula *et al.*, 2021). An extension officer revealed this during the interviews,

"Farmers practicing integrated farming often grow staple grains alongside fish, vegetables, and livestock, ensuring a steady supply for household consumption."

(KII, Buchosa DC, February, 2024).

For roots and tubers, although Mara (12.4%) leads in 'always' consumption, the difference is not as pronounced as in grains, and the statistical result (p = 0.073) is marginally above the 0.05 threshold, indicating no strong regional difference in this food group (Figure 3). However, both regions show similar consumption patterns across monthly and weekly categories, aligning with trends reported by Eyayu *et al.* (2023), which emphasize the variability in root and tuber availability across different agricultural zones.

Table 7. Food consumption intensity for dietary diversity (n=384)

Food Group	Frequency of Consumption	N	Mara (n=202)	Mwanza (n=182)	χ^2	*p*-value
Grains	Always	300	73.3%	63.3%	5.87	0.015
	Often	53	14.9%	16.0%		
	Occasionally	31	11.9%	20.7%		
Roots and Tubers	Always	35	12.4%	8.7%	3.22	0.073
	Often	198	47.5%	53.8%		
	Occasionally	151	40.1%	37.5%		
Vegetables and Greens Fruits	Always	186	46.5%	50.5%	0.34	0.845
	Often	106	28.7%	26.4%		
	Occasionally	92	24.8%	23.1%		
	Always	64	17.6%	15.8%	0.11	0.947
	Often	255	67.6%	65.3%		
	Occasionally	65	14.8%	18.8%		
Meat and Fish	Always	153	46.2%	38.7%	6.42	0.041
	Often	93	23.6%	24.8%		
	Occasionally	138	30.2%	36.5%		
Dairy Products and Eggs	Always	43	9.9%	12.4%	2.62	0.105
	Often	268	72.5%	67.3%		
	Occasionally	73	17.6%	20.3%		
Nuts and Legumes	Always	118	33.0%	28.7%	0.45	0.798
	Often	148	40.7%	36.6%		
	Occasionally	118	26.4%	34.7%		

** The Chi-square statistic is significant at the .05 level.*

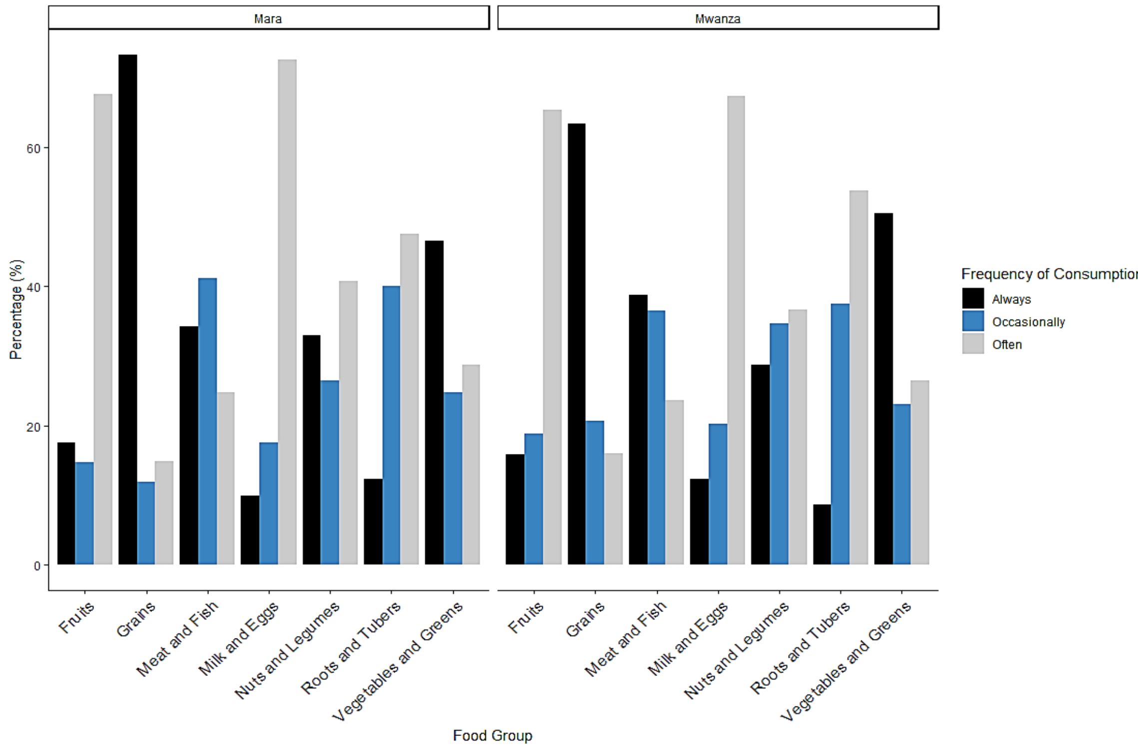

Figure 3. Food Consumption Frequency by Region and Food Group

On the other hand, meat and fish consumption show a significant difference, with Mwanza leading in 'always' consumption (46.2%) compared to Mara (38.7%), with the chi-square statistic reaching significance ($\chi^2 = 6.42$, $p = 0.041$) (Figure 3). This suggests that meat and fish are more frequently consumed in Mwanza, likely reflecting differences in access to protein sources or local dietary preferences, consistent with findings by Mzula *et al.* (2021).

These initial findings point to underlying differences in CSAq practices between the regions. Integrated farming practices in Mara, which include a strong focus on crop production alongside aquaculture, may explain the higher grain consumption. In contrast, Mwanza, with its emphasis on polyculture and monoculture systems, likely benefits from better access to fish and meat, underlining the region's capacity to leverage aquaculture for enhanced protein intake, as suggested by (Obiero *et al.*, 2024).

These patterns are not only reflective of the direct outcomes of CSAq practices but also interact with broader socio-economic factors and market accessibilities that influence food availability and dietary preferences. For instance, the availability of grains in Mara could be bolstered by better integration of crop and fish farming practices, while Mwanza's proximity to major markets and water bodies might facilitate greater access to fish and meat, supporting the observed dietary trends, as documented in various studies (Ambikapathi *et al.*, 2022; Muhie, 2022).

Analyzing these food consumption trends in the context of CSAq practices, the study provides insights into how aquaculture can differentially impact food security across regions. This analysis not only highlights the importance of tailoring aquaculture practices to regional needs and capacities but also underscores the need for context-specific policies that enhance food security through diversified and integrated farming approaches.

3.4 Food Security Index across adopted CSAq practices

The findings highlight the Household Food Security Index (HFSI) across different Climate-Smart Aquaculture (CSAq) practices integrated farming, monoculture, and polyculture in the Mara and Mwanza regions of Tanzania's Lake Zone. Integrated farming consistently recorded the highest mean HFSI scores, classified as "Very Satisfactory," demonstrating its effectiveness in improving food security through diversified and resilient production systems. Polyculture achieved "Satisfactory" scores, showcasing its contribution to food security by diversifying outputs and mitigating risks associated with single-species farming. In contrast, monoculture exhibited the lowest HFSI scores, categorized as

"Unsatisfactory," indicating its limited ability to address food security challenges in the context of climate and market vulnerabilities. The results of the Chi-square tests (*p*-value < 0.05) further confirm that the differences in food security outcomes among the CSAq practices are statistically significant as indicated in Table 8. These findings underscore the importance of promoting integrated and polyculture farming systems as sustainable strategies to enhance food security in rural communities.

Integrated farming, which combines tilapia and/or catfish farming with poultry, other livestock, and crop cultivation, is ranked as "Very Satisfactory" in both regions, with Mara achieving a slightly higher mean HFSI score of 84.2 compared to Mwanza's 81.4. This diversified approach provides a more stable source of food and income for rural households, enhancing overall food security and resilience. The integration of multiple farming activities allows households to buffer against the risks associated with environmental shocks and market fluctuations (Mulokozi *et al.*, 2020; Mzula *et al.*, 2021). Similarly, polyculture, which involves farming more than one fish species, was ranked as "Satisfactory" in both regions, with Mara scoring 69.5 and Mwanza 71.8. Polyculture contributes to food security by diversifying agricultural outputs and reducing vulnerabilities to diseases and environmental stresses, offering a balance between yield stability and market opportunities (Mulokozi *et al.*, 2020).

In contrast, monoculture farming, which focuses on growing a single fish species or crop, received the lowest HFSI scores 48.7 in Mara and 43.9 in Mwanza ranking 'Unsatisfactory' in both regions. This is primarily due to the higher reliance on a single species, increasing susceptibility to environmental shocks and disease outbreaks. The lack of species diversification limits income streams and food variety, reducing household resilience to both market fluctuations and climatic changes (Sène-Harper *et al.*, 2019; Nyamete, 2021). Despite its simplicity, monoculture adoption remains low across both regions (8.6%), reflecting farmers' awareness of its inherent risks. These systems are particularly vulnerable to water quality fluctuations and climate variability, often leading to total stock loss in the event of disease outbreaks. The lack of diversification in monoculture practices limits not only economic stability but also household food security (Peart *et al.*, 2021; Rahman *et al.*, 2021a). This evidence underscores the importance of promoting CSAq practices, such as integrated farming and polyculture, as essential components of Tanzania's rural development strategies to strengthen food systems and improve resilience against climate change (FAO, 2024; Jettah *et al.*, 2024) as indicated in Table 8.

Table 8. Food Security Index Across CSAq Practices by Region

Region	CSA Practice	Mean HFSI	Standard Deviation	Ranking	χ^2	*p*-value
Mara	Integrated Farming (IAA)	84.2	4.1	Very Satisfactory	18.45	0.000*
	Monoculture	48.7	11.3	Unsatisfactory		
	Polyculture	69.5	9.2	Satisfactory		
Mwanza	Integrated Farming (IAA)	81.4	3.8	Very Satisfactory	20.67	0.000*
	Monoculture	43.9	9.8	Unsatisfactory		
	Polyculture	71.8	11.7	Satisfactory		

*Note. * The Chi-square statistic is significant at the .05 level.*

The bar plot in Figure 4 shows the Food Security Index across different CSAq practices Integrated Farming, Monoculture, and Polyculture highlight significant variations in food security outcomes based on these practices. Integrated Farming shows the highest mean score (82.8), categorized as "Very Satisfactory," which aligns with findings from studies that demonstrate the benefits of diversified farming systems in enhancing food security through improved resilience and productivity (Stankus, 2021)). Monoculture, with a lower score of 45.3, falls under the "Unsatisfactory" category, and shows an increased vulnerability to environmental shocks, lower nutritional diversity, and food insecurity risks (Ahmed *et al.*, 2019; Lundeba *et al.*, 2023), Polyculture, at 68.2, is classified as "Satisfactory" and shows that polyculture can promote food security by diversifying crop more than 1 species usage in the aquaculture farming like catfish and tilapia thus reducing dependency on single outcomes and enhancing nutritional diversity (Neori *et al.*, 2017; Thomas *et al.*, 2021). These findings reinforce the notion that integrating multiple CSAq practices can contribute significantly to sustainable food security in agricultural systems.

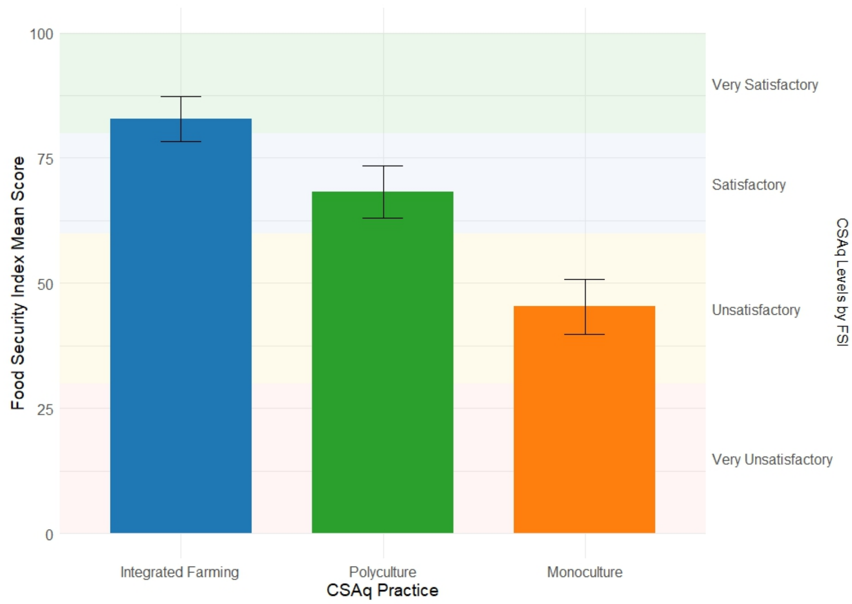

Figure 4. Food Security Index Across CSAq Practices with performance bands

3.5 Theoretical contribution

This study advances the Sustainable Livelihoods Framework (SLF) by integrating Climate-Smart Aquaculture (CSAq) practices as key livelihood strategies, demonstrating their role in enhancing income, food security, and resilience in smallholder aquaculture. It refines SLF by distinguishing between internal (economic) and external (climatic) shocks, showing how these factors influence CSAq adoption. Additionally, the study strengthens SLF's transforming structures and processes component by empirically demonstrating the role of policies, regulations, extension services, and market infrastructure in moderating CSAq effectiveness.

Furthermore, it expands the concept of livelihood assets by emphasizing aquaculture-specific resources such as water access, fish breeding technology, and cooperative networks. Lastly, the study enhances understanding of the CSAq-livelihood outcomes nexus by providing empirical evidence on how different CSAq strategies impact household income and food security, highlighting regional variations that underscore the importance of localized institutional support. Integrating these dimensions, this study extends the SLF's applicability to aquaculture-based livelihoods, offering a more comprehensive theoretical foundation for analyzing climate-smart rural development.

4 Conclusions

This study assessed the implication of Climate-Smart Aquaculture (CSAq) practices in integrated farming (IAA), polyculture, and monoculture on household income and food security in Mara and Mwanza, Tanzania's Lake Zone, revealing that integrated farming provides the highest economic and food security benefits, while monoculture increases household vulnerability. Findings indicate regional disparities, with Mara achieving higher fish yields due to widespread integrated farming, whereas Mwanza benefits from higher market prices and better infrastructure. The study highlights the importance of access to financial support, training, and institutional policies in enhancing CSAq adoption, particularly for smallholder farmers. Addressing barriers such as limited infrastructure, weak cooperative structures, and policy enforcement gaps are critical for ensuring the long-term sustainability of CSAq practices. The study recommends expanding extension services, improving market linkages, increasing access to credit, and strengthening institutional frameworks to maximize the benefits of CSAq for rural livelihoods, enhance climate resilience, and promote food security in Tanzania's aquaculture-dependent communities.

Based on the study's findings, the following key recommendations are proposed to enhance the adoption and impact of Climate-Smart Aquaculture (CSAq) practices on household income and food security in Tanzania's Lake Zone:

Firstly, promoting integrated aquaculture-agriculture systems should be prioritized, as they have been found to provide the highest economic and food security benefits. Policies should encourage farmers to adopt this practice by increasing access to extension services, training, and financial incentives. Given that integrated farming yields higher fish production and diversified income sources, targeted programs should focus on scaling up adoption in both Mara and Mwanza regions.

Secondly, region-specific interventions should be developed to address the different challenges and opportunities in Mara and Mwanza. While Mara exhibits higher fish yields due to widespread integrated farming, Mwanza benefits from stronger market access and infrastructure, leading to higher fish prices. To optimize CSAq benefits, Mwanza needs enhanced production capacity, while Mara requires improved market linkages and storage infrastructure to reduce post-harvest losses and increase profitability.

Thirdly, financial support and capacity-building programs should be strengthened to improve CSAq adoption, particularly among smallholder farmers. Limited access to credit, aquaculture inputs, and technical knowledge hinders the effectiveness of CSAq practices. Expanding microfinance opportunities, cooperative-based credit schemes, and structured training programs will enhance farmers' ability to invest in sustainable aquaculture.

Finally, strengthening institutional frameworks and policy enforcement is critical to ensuring the sustainability of CSAq practices. The study highlights gaps in aquaculture policies, weak cooperative structures, and inadequate extension services as key barriers to CSAq adoption. Government and stakeholders should focus on improving policy implementation, enhancing cooperative support systems, and investing in infrastructures such as ice flakes production centers, cold rooms for storage and transportation especially in Mara to make CSAq more viable and profitable.

Limitations of the study and area for further research

This study provides valuable insights into the implications of CSAq practices on household income and food security in Mara and Mwanza, Tanzania's Lake Zone. However, it has certain limitations. First, the study relied on cross-sectional data, which captures findings at a single point in time and may not fully account for seasonal variations in aquaculture production and income fluctuations. Future research could adopt longitudinal studies to track CSAq adoption and its impacts over time. Additionally, while the sample size was statistically determined, the study was limited to two regions, Mwanza and Mara, which may affect the generalizability of the findings to other aquaculture-dependent areas in Tanzania. Expanding the geographical scope in future studies would provide a more comprehensive understanding of CSAq adoption patterns and regional disparities.

Furthermore, the study employed descriptive and inferential statistical methods, which, while effective in identifying relationships between variables, do not establish causality. Advanced econometric models or experimental research designs could provide deeper insights into the causal effects of CSAq on income and food security. The study was also guided by the Sustainable Livelihoods Framework (SLF), which, although useful for analyzing household assets, shocks, and livelihood strategies, may not fully capture the influence of broader macroeconomic and policy factors. Future research could integrate institutional or behavioral economics frameworks to better understand policy impacts and farmer decision-making in CSAq adoption. Addressing these limitations will strengthen the body of knowledge on CSAq and support evidence-based policymaking for sustainable aquaculture development.

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