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RESEARCH PAPER

Quantifying Post-Harvest Fish Losses in Central Kenya: Implications for Small-Scale Aquaculture Sustainability

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Abstract

Post-harvest fish losses (PHLs) significantly hinder the growth and sustainability of Kenya's aquaculture sector, contributing to economic losses and reduced food security. This study aimed to quantify transit-related fish losses, identify contributing factors, and assess the effectiveness of storage and refrigeration practices among small-scale aquaculture farmers in Central Kenya. A cross-sectional survey was conducted between September and October 2023, involving 227 fish farmers from Kirinyaga, Nyeri, and Meru counties. Data were collected using structured questionnaires and analyzed using descriptive and inferential statistics. The findings revealed that tilapia was the most cultivated species, predominantly in polyculture systems with African catfish. Kirinyaga County had the highest adoption of polyculture practices (58%) compared to Nyeri (24%) and Meru (16.3%). Despite higher per-farmer production, Meru County experienced the most significant post-harvest losses, with an average of 7.0 kg lost per farmer, representing 37% of total production. The high losses in Meru were associated with inadequate refrigeration during transit, with 81% of farmers not using any cooling methods, compared to 56% in Kirinyaga and 51% in Nyeri. Transportation times also contributed to losses, with Meru reporting the longest average transport duration (3 hours, 23 minutes). The study recommends investing in affordable and accessible refrigeration technologies, such as solar-powered ice makers and insulated containers, alongside improving transportation efficiency. The findings provide valuable insights for policymakers, development agencies, and stakeholders in the fisheries sector to develop targeted interventions that enhance post-harvest practices, reduce losses, and strengthen the aquaculture value chain. These efforts align with Sustainable Development Goals 2 (Zero Hunger) and 12 (Responsible Consumption and Production) by promoting food security and reducing food losses in the aquaculture sector.

Introduction

The Fish and other aquatic animal foods are central to global diets and nutrition. In 2021, approximately 3.2 billion people obtained at least 20% of their animal protein intake from aquatic foods, underscoring their role in food and nutrition security, especially in low- and middle-income countries (FAO, 2024). Fisheries and aquaculture also underpin livelihoods, with approximately 61.8 million people employed directly in the primary sector and roughly 600 million people's livelihoods depending on the wider value chain (FAO, 2024). Small-scale fisheries contribute about half of global fish catches and comprise around 90% of people directly dependent on capture fisheries, highlighting their importance for inclusive rural economies (Tran et al., 2019). In Sub-Saharan Africa, approximately 200 million people regularly consume fish, and in several countries, fish provides 20–50% of animal-protein intake, emphasizing the sector's relevance for regional food security and resilience (FAO, 2016). Despite this importance, post-harvest fish losses (PHLs) remain a persistent constraint on sector sustainability.

Post-harvest fish losses, defined as the degradation, spoilage, or physical loss of fish during handling, storage, and transportation, have far-reaching consequences on food security, economic viability, and public health (Ikbal et al., 2023). These losses are often driven by poor storage infrastructure, inadequate preservation methods, and improper handling practices, especially during transit (Masette, 2023). PHLs can take various forms, including physical damage, loss of nutritional value, quality deterioration, and market force losses, where fish are sold at heavily discounted prices or diverted to alternative uses such as animal feed or fertilizers (Abelti & Teka, 2024). Moreover, the consumption of deteriorated fish poses significant food safety risks, which are particularly concerning in low- and middle-income countries (Freitas et al., 2020). The World Bank estimates that unsafe food results in an annual cost of $110 billion in medical expenses and lost productivity, with a considerable portion attributed to inadequate fish handling and storage (World Bank Group, 2018; Abelti & Teka, 2024).

Globally, PHLs are estimated at 10–12 million tons annually, representing approximately 10% of total fish production from capture fisheries and aquaculture (Abelti & Teka, 2024). These losses translate into significant economic setbacks, with annual financial losses estimated between $10 billion and $20 billion. In SSA, the situation is particularly dire, where the region faces a growing demand for fish but struggles to meet this need due to inefficiencies in its fisheries value chains (Akande & Diei-Ouadi, 2010). For instance, Nigeria, the leading importer of fish in the region, had a net import value of USD 770.4 million in recent years, underscoring the region's inability to harness its aquaculture potential (FAO, 2016). PHLs not only reduce the availability of fish for consumption but also undermine the livelihoods of fishers, processors, distributors, and retailers, creating a ripple effect across the value chain (Bawa et al., 2024).

In Kenya, the aquaculture sector has shown significant growth, with production reaching 32 thousand tons valued at KES 10 billion in 2023 (KeFS, 2024). However, post-harvest losses continue to impede the sector's contribution to food security and economic development. Quality deterioration accounts for the largest share of these losses (60%), followed by market force losses, while physical losses are comparatively lower (Abelti & Teka, 2024). These losses are exacerbated by seasonal fluctuations, with peak periods for losses varying by fish species. For instance, sardine dealers experience the highest losses from the months of March to August, while tilapia and Nile perch traders report significant losses during other months (Samuel, 2020). Based on Akande & Diei-Ouadi (2010), the overall quality loss of tilapia and sardine was reported at 27% and 7% in Kenya, respectively. The growing demand for fish in Kenya—estimated at 600 thousand tons annually compared to a production capacity of 400 thousand tons—further highlights the urgency of addressing PHLs to close the supply gap (Kubasu, 2024). Despite these challenges, the fisheries and aquaculture sector remains a vital component of Kenya's economy (Ndanga et al., 2013), contributing 4.7% to the country's GDP and supporting approximately 1.5 million people directly and indirectly (Odoli et al., 2019).

Central Kenya has become a key area for aquaculture development, benefiting from its suitable climatic conditions and substantial government support. Programmes like the Aquaculture Business Development Programme (ABDP), jointly funded by the Kenyan government and the International Fund for Agricultural Development (IFAD), have played a significant role in advancing inland aquaculture in this region (Gichuki et al., 2025). These efforts have positioned Central Kenya as a key player in the country's aquaculture industry. However, despite this progress, the region faces persistent challenges that undermine its potential, with post-harvest losses being a significant impediment. Small-scale farmers who dominate the sector often lack access to modern refrigeration facilities, efficient transportation systems, and adequate market infrastructure (Ochieng et al., 2024). As a result, fish spoilage during transit remains a critical issue, leading to economic losses and reduced fish availability for consumption.

Although post-harvest fish losses are widely recognized, there is limited information regarding their magnitude, underlying causes, and the extent to which they compromise food security, reduce farmer incomes, and weaken the sustainability of aquaculture value chains in Central Kenya. This lack of data hampers the formulation of targeted strategies and policies to effectively address these losses. Additionally, post-harvest activities within the fisheries value chain have not been adequately prioritized in development initiatives and food security policies, despite their vital role in ensuring the sustainability and profitability of the aquaculture sector (Ward, 2022). Tackling these losses is crucial for improving food security and maximizing the economic benefits of aquaculture, especially for small-scale farmers who rely on the industry for their livelihoods.

Therefore, this study addresses the lack of information about the cause and extent of post-harvest fish losses in Kenya. Specifically, it aims to quantify transit-related losses, identify the main contributing factors, and assess the availability and effectiveness of refrigeration systems used by small-scale farmers. These insights will inform strategies to reduce losses and enhance fish contributions to per capita protein intake, which currently accounts for about 10% of animal protein consumption in Kenya.

Materials and Methods

Study area

The study focused on three counties in Central Kenya—Kirinyaga, Nyeri, and Meru (Figure 1)—which are prominent aquaculture hubs in the country (KeFS, 2024). These counties were chosen for their substantial contributions to aquaculture production in the region, driven by supportive climatic conditions, government initiatives, and active participation by small-scale fish farmers. Further, Meru, Nyeri and Kirinyaga counties rank highest in aquaculture production with over 2 thousand tons and over 340 registered fish farmers (KeFS, 2024). This notable output underscores the critical role these counties play in Kenya's aquaculture sector. Their close proximity to major urban centers such as Nairobi, combined with well-developed transportation infrastructure, enhances their strategic importance in the fish supply chain by enabling the efficient distribution of aquaculture products to both local and regional markets. Furthermore, the region has greatly benefited from government and institutional support through programmes like the Economic Stimulus Programme (ESP), the ABDP, and other aquaculture development initiatives (Munguti et al., 2023). These efforts have significantly accelerated the adoption and growth of aquaculture in these counties.

Development and Validation of the Survey Instrument

The survey instrument was developed through a collaborative process involving aquaculture experts, fisheries extension officers, and local stakeholders to ensure its relevance and comprehensiveness. The structured questionnaire included sections on socio-demographic characteristics, fish production practices, storage and transportation methods, and challenges related to post-harvest fish losses. Questions were designed based on established methodologies from previous studies on aquaculture and post-harvest loss assessments (e.g., Akande & Diei-Ouadi, 2010; Ochieng et al., 2024).

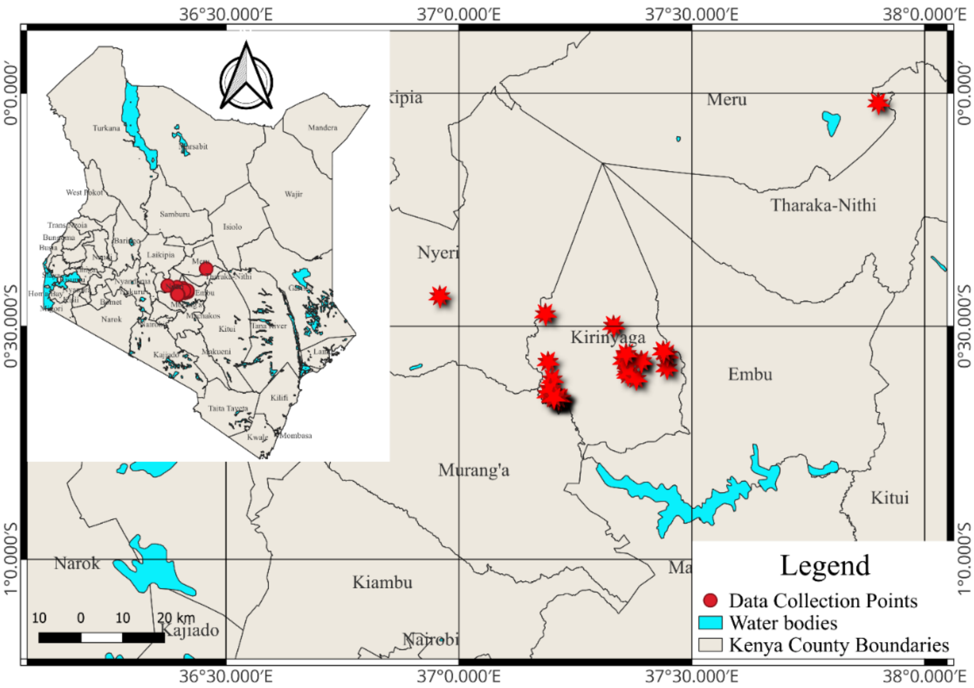

Figure 1. Kenyan Map showing the data collection points in red

Validation Process

The survey instrument underwent a two-step validation process:

a) *Content Validation*: The draft questionnaire was reviewed by a panel of five experts in fisheries and aquaculture, including researchers from the Kenya Marine and Fisheries Research Institute (KMFRI) and representatives from local fish farmers' associations. This review ensured the instrument's content validity, verifying that all relevant aspects of post-harvest losses were covered adequately. Suggestions from this review were incorporated to improve the clarity and relevance of the questions.

b) *Pre-Testing and Pilot Study*: The questionnaire was pre-tested with a sample of 30 fish farmers in Murang'a county. The pilot study aimed to assess the clarity of the questions, the feasibility of the data collection method, and the reliability of the responses. Based on the pilot results, some questions were rephrased to avoid ambiguity, and additional response options were included in multiple-choice questions. The reliability of the instrument was measured using Cronbach's alpha, which yielded a score of 0.82, indicating a high level of internal consistency.

Research Design

This study employed a cross-sectional research design to collect primary data from aquaculture farming households in Kirinyaga, Nyeri, and Meru counties, Central Kenya. A structured household survey was conducted between September and October 2023, using mobile-based digitized questionnaires designed to gather detailed information about fish farm and household characteristics, fish production, marketing practices, and the adoption of aquaculture technologies.

A multistage sampling procedure was utilized to ensure the representativeness of the selected households. In the first stage, the three counties were purposively selected due to their prominence as aquaculture hubs in Central Kenya. In the second stage, fish farming households within each county were stratified into two groups: those actively engaged in structured aquaculture programmes (e.g., Aquaculture Business Development Programme - ABDP) and those not participating in such programmes. This stratification allowed for a balanced representation of both groups in the sample, facilitating a comparative analysis of outcomes.

Registered fish farmers within each stratum were identified using lists provided by County Departments of Fisheries under the State Department for Blue Economy and Fisheries and aquaculture cooperatives. The sample size for each county was determined proportionally to the total fish farmer population in that county, ensuring fair representation across the study area. Random sampling was then conducted within each stratum using a random number generator applied to the household lists. This method ensured that every registered fish farming household had an equal chance of selection, enhancing the sample's representativeness. A total of 227 households were sampled across the three counties.

Data Collection Procedure

The data collection was carried out by a trained team of 15 enumerators under the supervision of the lead researchers. The enumerators received a three-day training session covering survey administration techniques, ethical considerations, and the use of the Kobo Toolbox platform for data entry. Data were collected through face-to-face interviews with household heads or key fish farming decision-makers. Where in-person interviews were not feasible, telephone interviews were conducted as an alternative. The digitized questionnaires facilitated real-time data capture and automatic uploading to a secure cloud-based server, ensuring data accuracy and reducing the risk of data loss.

The survey instrument included both closed and open-ended questions, collecting quantitative data on demographics, fish production volumes, storage and transportation methods, refrigeration practices during transit, and market channels used by farmers. Qualitative insights were also gathered on challenges faced in fish handling, storage, and transportation.

Target Population

The target population for this study comprised fish farmers and fish traders operating in Meru, Nyeri and Kirinyaga counties. This included individual farmers managing their own fish farms, members of community or group-operated fish farms, and entrepreneurs engaged in fish trading within key trading centres across the three counties. The study specifically focused on farmers who had successfully harvested and sold their fish at least once, as well as those facing challenges related to post-harvest storage and transportation of fish produce.

Data Analysis

Data cleaning and analysis were conducted using R software (R Foundation for Statistical Computing, version 4.3). The analysis included both descriptive and inferential statistics. Descriptive statistics were used to summarize the socio-demographic characteristics of the respondents. Measures of central tendency (mean) and dispersion (standard deviation) were calculated for continuous variables, including harvested fish volumes (kg), fish losses during transit (kg), storage duration before transit (hours), and transportation times (hours). Categorical data were presented as frequencies and percentages. Data visualization tools, including bar graphs and boxplots, were utilized to illustrate key trends and distributions effectively.

To examine the differences in aquaculture practices and outcomes across the counties, inferential statistical methods were employed. A one-way analysis of variance (ANOVA) was used to test for statistically significant differences among the counties regarding fish production volumes, post-harvest losses, storage times, and transportation times. Where the ANOVA indicated significant differences, post-hoc analyses using Tukey’s Honest Significant Difference (HSD) test were conducted to determine which specific county pairs differed significantly.

Chi-square tests of independence were applied to assess the association between categorical variables, such as county of residence and fish species reared, storage methods, market channels, and refrigeration practices during transit. All statistical tests were conducted using a significance threshold of 0.05. Results with p-values less than 0.05 were considered statistically significant, indicating meaningful differences or associations relevant to the study objectives.

RESULTS

Socio-Demographic Information of Respondents

227 respondents were sampled across the three counties: Kirinyaga (71), Nyeri (75), and Meru (81). The gender distribution showed that male respondents constituted the majority in all counties, with proportions of 68.0% in Kirinyaga, 65.0% in Nyeri, and 70.0% in Meru. Female respondents accounted for 32.0%, 35.0%, and 30.0%, respectively. The mean age of the respondents was 43.0 years in Meru, 42.3 years in Kirinyaga, and 41.2 years in Nyeri, reflecting a relatively mature demographic engaged in aquaculture. The larger male proportion is culturally not uncommon, as the men have more presence and handle fishing, while women are more active in post-fishing and marketing.

Regarding education, the proportion of respondents with at least secondary education was 42.0% in Meru, 40.0% in Kirinyaga, and 38.0% in Nyeri, while tertiary education levels were highest in Meru at 30.0%, followed by Nyeri at 28.0%, and Kirinyaga at 25.0%. The average household size was consistent across the counties, ranging from 5.2 to 5.5 persons. Fish farming experience averaged 4.2 years in Kirinyaga, 4.5 years in Nyeri, and 4.7 years in Meru, showing a moderate level of expertise among the respondents.

Species Reared

Most of the farmers were observed to practice polyculture systems, particularly cultivating Nile tilapia (*Oreochromis niloticus*) and catfish (*Clarias gariepinus*) together (Figure 2). Tilapia emerged as the most dominant species under cultivation, followed by African catfish. Ornamental fish farming was only noted in Kirinyaga County, where species such as goldfish and koi carp were reared. The findings revealed a significant correlation between the county of residence and the species cultivated ($\chi^2 = 45.67$, df = 6, n = 227, $p < 0.001$), indicating that fish species distribution differed considerably among the counties.

The analysis identified a significant variation in polyculture practices among the counties ($F(2, 224) = 32.15$, $p < 0.001$). Post-hoc analysis using Tukey's test indicated that Kirinyaga had a significantly higher polyculture rate (M = 58%) compared to Nyeri (M = 24%) and Meru (M = 16.3%), with Meru exhibiting the lowest levels.

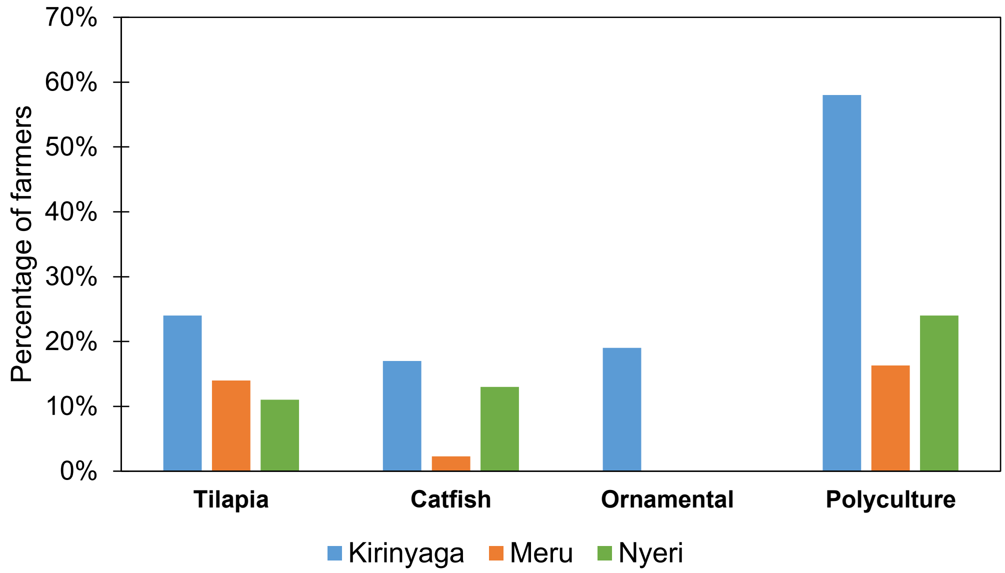

Figure 2. Fish species produced by Aquaculture farmers in Central Kenya

Tilapia production was highest in Kirinyaga County at 1,112 kilograms, followed by Meru County with 1,052 kilograms, and Nyeri County recorded the least production at 728 kilograms (Figure 3). On average, Meru County exhibited the highest individual farm production, followed by Nyeri and Kirinyaga counties. In terms of catfish production, Nyeri County led significantly with 2,260 kilograms, followed by Kirinyaga County with 603 kilograms, while Meru County reported the lowest production at 87 kilograms.

An analysis of variance (ANOVA) showed no statistically significant difference in tilapia production among the counties, $F(2, 224) = 2.27$, $p = 0.11$. However, a similar ANOVA test for catfish production revealed a statistically significant difference among the counties, $F(2, 224) = 5.67$, $p = 0.004$. Post-hoc Tukey comparisons showed that Nyeri's catfish production was significantly higher than that of Kirinyaga and Meru, while the difference between Kirinyaga and Meru was not statistically significant.

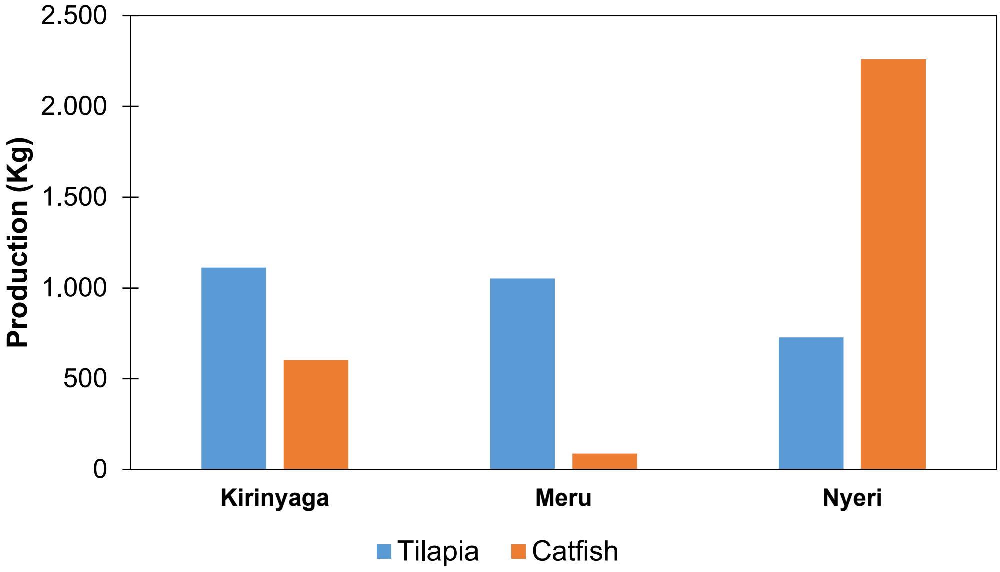

Figure 3. Production of fish species by farmers in central Kenya.

Market

The distribution of fish marketing channels utilized by farmers varied significantly across Kirinyaga, Meru, and Nyeri counties. Farmers primarily sold their produce within their community and neighbors (37%), hotels and restaurants (33%), and free street markets (28%) (Figure 4). A small percentage of farmers sold to specialized markets (1.3%), such as aquaculture cooperative outlets, supermarket chains, and institutional buyers (e.g., schools and hospitals), while an even smaller fraction engaged with export markets (0.4%), highlighting the untapped potential for export-oriented aquaculture.

The results indicated a significant association ($\chi^2 = 46.82$, df = 8, $p < 0.001$), suggesting that the market channels utilized by farmers depended on their county of residence. Kirinyaga showed the highest engagement in free street markets (18%), followed by Nyeri (7.5%) and Meru (2.2%). Similarly, hotels and restaurants were a dominant market for farmers in Kirinyaga (18%) compared to Nyeri (8.4%) and Meru (7.5%). Farmers in Meru had a small but unique participation in export markets (0.4%), reflecting the early adoption of opportunities for regional and international trade.

The ANOVA results revealed significant differences in using market channels among the counties ($F(4, 222) = 12.38$, $p < 0.001$). Post-hoc Tukey tests indicated that Kirinyaga significantly differed from Meru in the proportion of farmers utilizing free street markets, while Meru and Nyeri showed similar patterns.

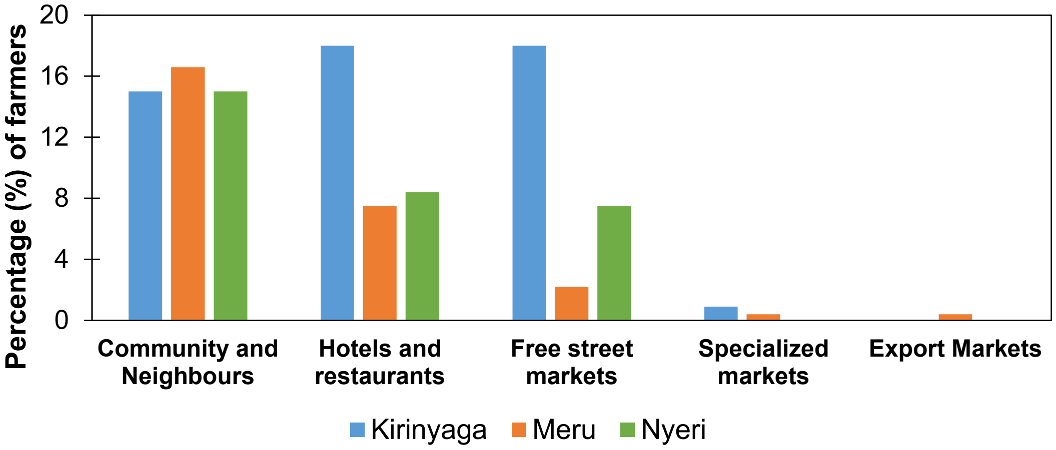

Figure 4. Market for fish produced by farmers in central Kenya.

Storage Before Transit

Buckets and troughs were the most commonly used storage method in all counties, with 41% in Nyeri, 37% of farmers in Kirinyaga, and 33% in Meru, using this method. Personal freezers, mostly powered by grid electricity, were also prevalent, utilized by 56% in Meru, 37% in Nyeri, and 27% of farmers in Kirinyaga. Polythene carrier bags were frequently used in Kirinyaga (29%) and Nyeri (20%) but not in Meru. County regional storage facilities and community freezers were less frequently used, accounting for less than 11% in all cases (Figure 4).

The results indicated a statistically significant association (χ^2 = 24.67, df = 6, p = 0.006), suggesting that the choice of storage method was influenced by the county. Meru had a significantly higher proportion of farmers using personal freezers compared to the other counties, while Kirinyaga and Nyeri showed greater reliance on buckets and troughs and polythene bags, which jeopardize the catch quality.

The mean storage time before transit also varied among the counties, with Meru reporting the longest mean storage time (3 hours 31 minutes), followed by Nyeri (2 hours 29 minutes) and Kirinyaga (2 hours 15 minutes) (Figure 5). A one-way ANOVA showed no statistically significant difference in mean storage times (F(2, 224) = 0.79, p = 0.5) across the three counties, showing the commonality in fish handling practice across the sector in Kenya.

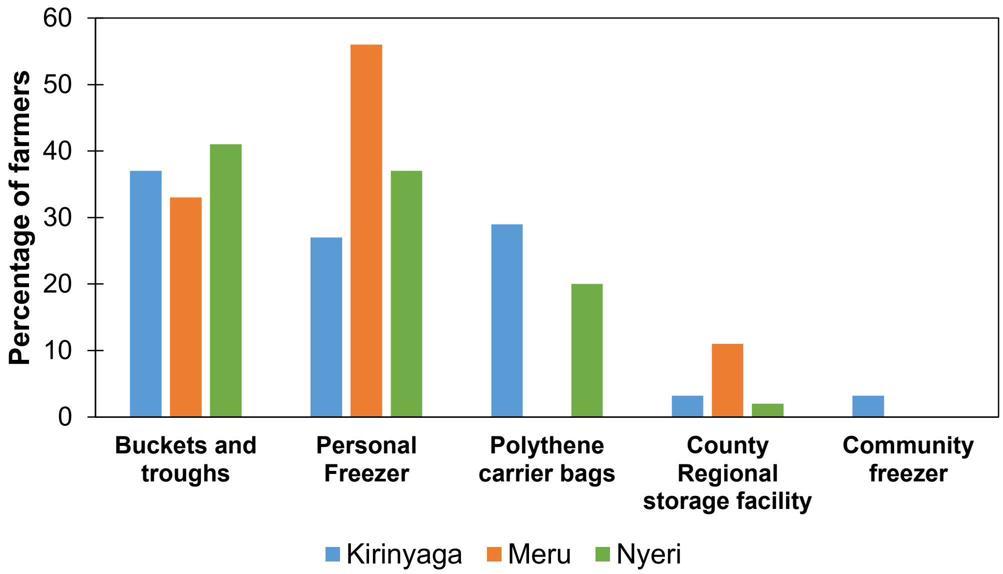

Figure 4. Storage methods used by farmers.

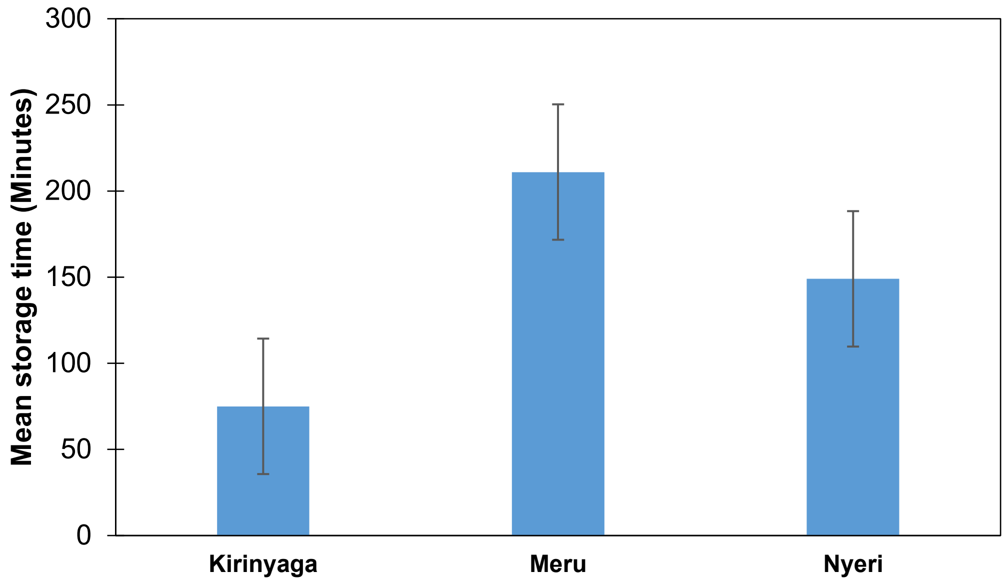

Figure 5. Mean storage time for fish.

Refrigeration During Transport

Most farmers in Nyeri (33%) and Kirinyaga (42%) used ice as a refrigeration method, whereas only 15% of farmers in Meru used ice. A notable proportion of farmers in Nyeri (16%) used cool boxes without ice, relying instead on the insulation properties of the boxes to maintain relatively lower temperatures during transit. This method, while less effective than using ice, may have been used due to limited access to ice or as a cost-saving measure, as purchasing ice can be expensive and logistically challenging for some farmers. The use of refrigerated fish transport vehicles was minimal, with only 2.3% of farmers in Kirinyaga and 3.8% in Meru adopting this method, reflecting the high costs and limited availability of such infrastructure. However, a majority of farmers in Meru (81%) and a significant proportion in Kirinyaga (56%) and Nyeri (51%) did not refrigerate their fish during transit. This was largely attributed to the high cost of refrigeration equipment or ice, inadequate access to cooling facilities, and a lack of awareness about the importance of refrigeration in preserving fish quality. The absence of refrigeration led to significant quality deterioration, highlighting a critical gap in cold chain logistics within the aquaculture sector. Therefore, investing in affordable and accessible refrigeration technologies, such as solar-powered ice makers or insulated containers, could help reduce the post-harvest fish losses.

The results indicated a statistically significant association ($\chi^2 = 18.67$, df = 6, $p = 0.002$), suggesting that refrigeration methods differed significantly across counties. Nyeri exhibited a more diversified use of refrigeration methods compared to Kirinyaga and Meru. Transportation time also varied among the counties, with Meru reporting the longest average transport time of 3 hours 23 minutes, followed by Kirinyaga at 3 hours 16 minutes, and Nyeri at 2 hours 20 minutes. This establishes a 2-4-hour time bracket as the industry average transportation time. The ANOVA results revealed a statistically significant difference in transport times among the counties ($F(2, 224) = 3.84$, $p = 0.042$). Post-hoc Tukey tests indicated Nyeri had significantly shorter transport times compared to Meru, while the difference between Kirinyaga and the other two counties was not statistically significant.

Fish losses on transit

Fish losses during transit varied across the three counties, with Kirinyaga reporting an average loss of 5.1 kilograms per farmer from an average production of 40 kilograms. Meru experienced the highest average loss at 7.0 kilograms from an average production of 100 kilograms, while Nyeri reported the lowest average loss of 3.1 kilograms from an average production of 60 kilograms. These variations were partly influenced by proximity to major urban markets. Kirinyaga and Nyeri farmers are relatively closer to Nairobi and other regional towns (average distance 100–150 km), while Meru farmers must cover longer distances, averaging over 200 km to reach comparable markets. The longer transit distance and time in Meru expose fish to higher risks of spoilage

A one-way analysis of variance (ANOVA) results showed a significant difference in fish losses across the counties (F(2, 224) = 4.58, p = 0.011). Post-hoc Tukey tests revealed Meru had significantly higher losses compared to Nyeri (p < 0.05), while the difference between Kirinyaga and the other two counties was not statistically significant.

The standard deviation of fish losses varied considerably, with Meru showing the highest variability (SD = 14.2 kilograms), reflecting significant disparities among farmers in the county. Kirinyaga and Nyeri had lower standard deviations of 3.9 kilograms and 3.0 kilograms, respectively, indicating more consistent losses across the sampled farmers.

Percentage loss from production

Meru County reported the highest proportion of fish lost during transit (37%), followed by Kirinyaga County at 14%, and Nyeri County at 11%. Despite having the highest percentage loss, Meru's total production (1,139 kilograms) was lower compared to Nyeri (2,988 kilograms) and Kirinyaga (1,715 kilograms) (

Table 1). Post-harvest losses as a percentage of production in Meru were significantly higher compared to the other counties.

A one-way analysis of variance (ANOVA) results revealed a statistically significant difference in percentage losses across the counties (F(2, 224) = 6.85, p = 0.003). Post-hoc Tukey tests showed Meru had significantly higher percentage losses compared to Kirinyaga (p < 0.01) and Nyeri (p < 0.01), while the difference between Kirinyaga and Nyeri was not statistically significant. In terms of production volume, an ANOVA showed no statistically significant differences among the counties (F(2, 224) = 0.22, p = 0.8), indicating that production levels were relatively comparable. However, an ANOVA comparing post-harvest losses in kilograms across the counties showed a significant difference (F(2, 224) = 4.58, p = 0.011). Post-hoc Tukey tests indicated Meru experienced higher absolute losses compared to Nyeri, with no significant differences between Kirinyaga and the other two counties.

Table 1. The proportion of fish lost on transit as a percentage of total production

Particulars	Kirinyaga (kg)	Meru (kg)	Nyeri (kg)	p-value
Production	1,715	1,139	2,988	0.8
Post-harvest losses	240.0	421.0	329.0	0.011
Percent loss	14%	37%	11%	0.003

Discussion

The findings of this study illuminate several critical aspects of small-scale aquaculture in Central Kenya, particularly concerning socio-demographic characteristics, species reared, production levels, market dynamics, storage practices, refrigeration during transport, and post-harvest fish losses during transit. The aquaculture sector in Central Kenya is predominantly male-dominated, with male respondents constituting the majority across all counties. This finding is consistent with prior research showing that aquaculture in Kenya is largely male-dominated due to cultural norms and the physically demanding nature of fish farming (Abwao et al., 2021). Similarly, Awuor (2021) points out that aquaculture is often mistakenly viewed as a male-oriented industry, limiting women's involvement. This is partly due to the high capital investment and technological demands associated with the sector. Although women are involved in various aspects of the aquaculture value chain, their opportunities have not advanced at the same pace as the industry's growth.

The mean age of respondents, ranging from 41.2 to 43.0 years, suggests that aquaculture is primarily undertaken by middle-aged individuals who may have more resources and experience to invest in fish farming. This demographic is crucial for the adoption of innovative practices aimed at reducing post-harvest losses (Cascante et al., 2022). The relatively high educational attainment among respondents, with substantial proportions having at least secondary education and notable percentages possessing tertiary qualifications, is significant. Higher education levels are associated with better management practices and openness to adopting new technologies in aquaculture (Amankwah & Quagrainie, 2019; Prodhan & Khan, 2018). This indicates a potential for effective implementation of strategies to mitigate post-harvest losses if adequate training and resources are provided. The consistency in household size across the counties suggests similar social structures, which may influence labor availability for fish farming activities. The average fish farming experience of over four years reflects a moderate level of expertise essential for understanding the complexities of aquaculture production and post-harvest handling. Supporting this, Osmundsen et al. (2017) emphasize the importance of experience as a critical tool in managing uncertainties and unforeseen challenges in fish farming, with farmers relying heavily on their practical knowledge to make informed decisions.

Regarding the species reared, the study found that tilapia and African catfish are the predominant species cultivated, consistent with national trends due to their adaptability to local conditions and market preference (KeFS, 2024). As warm-water fish, they thrive under the region's climatic conditions and have been recommended and promoted by the Kenyan government as ideal species for aquaculture (Obiero et al., 2014). The significant association between county of residence and the species reared may be attributed to variations in environmental conditions, market demands, and extension services across the counties. The prominence of tilapia and catfish in polyculture systems indicates farmers' strategies to maximize yield and resource efficiency by combining species with different ecological niches. Kirinyaga County's significantly higher adoption of polyculture (58%) may result from better access to extension services and training programmes that promote integrated farming techniques (Waithanji et al., 2020). This practice enhances productivity and income diversification, which is crucial for small-scale farmers. Contrarily, Wanja et al. (2020) reported that tilapia-catfish polyculture was less common in Kirinyaga, practiced by only 10% of fish farmers, while Mwangi et al. (2017) found that most farmers kept tilapia in monoculture, with polyculture being the second most common method. The lower rates of polyculture in Meru County (16.3%) could be due to limited technical knowledge or a preference for monoculture systems perceived as less complex to manage.

The higher production of catfish in Nyeri County could be linked to targeted promotion and training programmes, as catfish are known for their hardiness and fast growth rates (Mulei et al., 2021). This is supported by Mavuti et al. (2017), who noted that African catfish is one of the most important species cultured in Nyeri due to its resistance to parasites and diseases, as opposed to tilapia, which consumes a wide variety of feed materials and feeds low in the food chain. The exclusive occurrence of ornamental fish farming in Kirinyaga County suggests diversification driven by proximity to urban markets and higher-income consumers interested in ornamental species like goldfish and koi carp. The emerging ornamental fish market in Kenya (Munguti et al., 2024b) has encouraged farmers in Kirinyaga to venture into the culture of these species. This niche market offers higher profit margins but requires specialized knowledge and initial investment, which may not be accessible to farmers in other counties. These findings align with those of Murugami et al. (2017), who reported that ornamental fish was among the main species farmed in Kirinyaga County. Mwangi et al. (2017) also reported that 11.4% of respondents kept ornamental fish, consistent with the present study. The significant association between county and fish species reared underscores the need for region-specific aquaculture development strategies.

The observed disparities in fish production among the counties suggest that regional factors significantly influence aquaculture outputs in Central Kenya. While tilapia production was highest in Kirinyaga County, the lack of statistically significant differences among the counties indicates that tilapia farming practices and environmental conditions may be relatively uniform across the region, possibly due to the widespread adoption of tilapia and its strong market demand (Abwao et al., 2023). In contrast, the significantly higher catfish production in Nyeri County implies that specific local factors, such as targeted extension services or market preferences, promote catfish farming in this area. Catfish's hardiness and high growth rates make them particularly suitable for conditions in Nyeri. The higher average individual farm production in Meru County suggests that farmers there may have access to larger ponds, better resources, or more intensive farming techniques, possibly due to greater investment capacity or more effective aquaculture training programmes.

Market dynamics revealed significant variations in fish marketing channels among the counties, underscoring the influence of regional factors on market access and sales strategies. The reliance on local markets—selling within the community and to neighbors (37%), as well as hotels and restaurants (33%)—reflects a common trend among small-scale aquaculture producers who often lack resources to access distant or larger markets (Penca et al., 2021). Kirinyaga's notably higher engagement in free street markets (18%) and sales to hotels and restaurants (18%) compared to Nyeri and Meru may be attributed to its proximity to urban centers and better-developed infrastructure, facilitating easier access to diverse and potentially more lucrative market outlets. The significant association between county of residence and choice of market channel suggests that geographical location and infrastructural development play critical roles in determining market opportunities for farmers. The minimal participation in export markets, with Meru exhibiting a small yet unique involvement (0.4%), highlights the challenges small-scale farmers face in accessing international markets due to stringent quality standards, lack of market information, and logistical constraints (Munguti et al., 2024a). These findings are consistent with previous research indicating that smallholder farmers often struggle to penetrate export markets due to limited capacity and support (Ababouch et al., 2023). The significant differences in market channel utilization among the counties imply that targeted interventions—such as improving infrastructure, enhancing market information systems, and providing training on meeting export requirements—are necessary to expand market access.

Also, improving the cold chain logistics would enhance the local and regional market sales of the locally cultured fish, which prolong its shelf life and minimize the damage. The observed differences in storage methods before transit among the counties reveal significant disparities in access to cold storage facilities and preservation practices among small-scale fish farmers. The predominant use of buckets and troughs, as well as polythene carrier bags in Kirinyaga and Nyeri counties, suggests limited access to adequate refrigeration infrastructure, predominantly due to economic constraints or insufficient electricity access (Sivagnanam, 2016). In contrast, the significantly higher utilization of personal freezers in Meru County indicates better access to electricity and a higher socioeconomic status that allows farmers to invest in refrigeration equipment. This variation is critical because proper cold storage is essential for maintaining fish quality and reducing post-harvest losses (Gupta et al., 2024). Similar findings have been reported in other developing countries where inadequate cold chains contribute to increased spoilage and economic losses among small-scale fish farmers (Ochieng et al., 2024; Marigu et al., 2023). The lack of significant differences in mean storage times across the counties suggests that, despite varying storage methods, farmers face similar time constraints in delivering their products to market. However, those without proper refrigeration are more susceptible to quality degradation during this period, potentially leading to higher post-harvest and monetary losses.

The prevalent use of non-refrigerated methods for fish storage and transportation, such as buckets, troughs, and polythene bags, exposes fish to spoilage agents, leading to quality deterioration

(Alam et al., 2012). The limited use of ice and refrigerated transport vehicles, especially in Meru County, where only 15% of farmers used ice during transit, exacerbates post-harvest losses. These findings are consistent with those of Marigu et al. (2023), who emphasized that the lack of cold chain facilities is a major contributor to fish spoilage in Kenya. According to Marigu et al. (2023), the main contributors to post-harvest losses were the lack of necessary cold-chain infrastructure and equipment, such as freezers, cooler boxes, and ice-making machines, in addition to the prohibitively high cost of electricity bills from cold-chain facilities connected to the national grid. These findings concur with those of Diei-Ouadi et al. (2011) and Acharjee et al. (2021), who reported that most small-scale fish farmers lack refrigeration facilities to store their fish during harvesting and transportation. Consequently, farmers are often compelled to sell their fish immediately after harvest, sometimes at significantly reduced prices, to avoid spoilage. In the present study, 20% of farmers reported using ice in cool boxes during fish transportation, while the majority (75%) used buckets, troughs, and polythene bags.

The higher utilization of ice by farmers in Nyeri (33%) and Kirinyaga (42%) suggests better access to cooling resources or greater awareness of preservation techniques, e.g., pre-cooling and cold storage, essential for maintaining fish quality during transit. In contrast, the low use of ice in Meru (15%) and the fact that a majority did not refrigerate their fish (81%) highlight potential constraints such as limited or no access to ice facilities, economic barriers, or lack of awareness, leading to increased spoilage and post-harvest losses. The statistically significant association between refrigeration methods and county underscores how regional differences impact preservation practices. Nyeri's diversified use of refrigeration, including cool boxes without ice (16%), may indicate adaptive strategies to overcome resource limitations, aligning with findings from Ntzimani et al. (2023), who reported that farmers employ alternative methods when conventional refrigeration is inaccessible. Additionally, the longer transportation times in Meru (average 3 hours 23 minutes) exacerbate the risk of spoilage when refrigeration is inadequate, as prolonged exposure to ambient temperatures accelerates microbial growth and fish deterioration (Nie et al., 2022). The significant difference in transport times suggests infrastructural challenges that not only affect timely market access but also compromise product quality, similar to observations in other developing regions where transportation inefficiencies contribute to post-harvest losses (Acharjee et al., 2021).

Fish losses during transit varied across the three counties, with Meru County experiencing the highest average loss per farmer, which was statistically greater than the losses in Nyeri County. This disparity may be attributed to factors such as longer transportation times—averaging about 4 hours from Meru to Nairobi compared to roughly 2 hours from Kirinyaga or Nyeri—inadequate refrigeration during transit, and inferior infrastructure in Meru, which exacerbates spoilage and degradation of fish quality (Akande & Diei-Ouadi, 2010). The high standard deviation in fish losses in Meru (SD = 14.2 kg) suggests significant inconsistencies among farmers, possibly due to varying access to preservation technologies or differences in post-harvest handling practices. In contrast, Kirinyaga and Nyeri exhibited lower variability and more consistent losses, indicating more uniform adoption of preservation methods or better collective management strategies. These findings align with previous research by Acharjee et al. (2021), who reported that inadequate transportation and lack of cold chain facilities contribute significantly to post-harvest losses in small-scale fisheries. Moreover, the total losses being highest in Kirinyaga despite lower average losses per farmer may reflect higher aggregate production, pointing to systemic issues affecting the entire supply chain.

The significantly higher percentage of fish lost during transit in Meru County (37%) compared to Kirinyaga (14%) and Nyeri (11%) underscores critical inefficiencies in post-harvest handling and transportation systems within Meru. Despite having a lower total production, Meru's disproportionate losses suggest that factors such as inadequate cold chain infrastructure, longer transportation times, and poor handling practices are contributing to elevated spoilage rates. The statistical significance of these losses underscores the urgent need to address these issues. Abelti and Teka (2024) have demonstrated that post-harvest losses are exacerbated by insufficient refrigeration during transit and extended time to market, leading to quality deterioration and economic losses for farmers. The absence of significant differences in production volumes among the counties indicates that the high percentage loss in Meru is not due to lower production capacity but systemic challenges in the supply chain. Acharjee et al. (2021) emphasize that enhancing post-harvest practices, such as improved handling, storage, and transportation, can substantially reduce losses.

Conclusion

This study assessed post-harvest fish losses during transit to markets in Central Kenya and found that small-scale aquaculture in the region suffers from significant physical and economic losses related to fish harvesting and transportation. These losses pose an immediate concern for food and nutritional security and are a major impediment to increasing the earning potential for various actors in the fish value chain. Given the high costs associated with aquaculture production, particularly for seeds and feeds, it is imperative to optimize production and minimize wastage to ensure sustainability. While traditional refrigerated transport vehicles may not be feasible for small-scale operations, adapting refrigeration technologies to smaller vehicles or motorbikes could significantly reduce losses during fish transit and transform the sector. Further, training programmes that educate farmers on the importance of cold chain management and proper handling techniques could significantly reduce spoilage rates. Additionally, investing in affordable and accessible refrigeration technologies, such as solar-powered ice makers or insulated containers, could provide practical solutions for small-scale farmers. The government's role is pivotal in facilitating these changes through policy support, subsidies for refrigeration equipment, and infrastructure development to reduce transportation times. Collaborations with non-governmental organizations and private sector partners could also enhance the availability of resources and expertise required to implement effective post-harvest loss reduction strategies. This study provides valuable insights that enable policymakers and stakeholders in the fisheries sector to make informed decisions on supporting the cold chain infrastructure and adopting technological innovations.

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Ethical Approval

The study was conducted within the scope of Kenya Marine and Fisheries Research Institute's (KMFRI's) ethical provisions. The institute is mandated to conduct studies on fisheries and aquaculture in the country and abides by the KMFRI Research Policy and the KMFRI Social Science Research Ethics.

Informed Consent

All respondents voluntarily participated in the survey after being fully informed of the study's objectives and procedures. Informed consent was obtained from each participant prior to the interview.

Conflict of Interest

The authors declare that there is no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to ethical restrictions, raw survey responses are not publicly available to protect participant confidentiality.

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