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Assessment of Fish Post-Harvest Loss in Southern Gulf of Lake Tana, Ethiopia: Drivers, Impacts, and Mitigation Strategies

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Abstract

This study evaluates the magnitude, causes, and socioeconomic impacts of fish post-harvest losses (PHL) in the southern Gulf of Lake Tana, Ethiopia, based on a 2025 survey of 250 fishermen. Employing a cross-sectional, quantitative approach, data analyzed with SPSS revealed an average 22% average PHL (95% CI: 19.8–24.2%), peaking at 40% in April due to temperature-driven spoilage. Infrastructure gaps (β=0.45, p<0.001) and seasonal effects (β=0.30, p<0.001) drove 68% of PHL variance (R^2=0.68). Economic losses totaled $6.48 million (2018–2023), disproportionately affecting women (3.6% of fishers). A multiple linear regression model (R^2 = 0.68) explained 68% of PHL variance, with infrastructure deficits, notably absent refrigeration, contributing most significantly (48%). This study provides a comprehensive regression analysis of PHL drivers in Lake Tana's artisanal fisheries, recommending infrastructure and capacity-building interventions and also, we recommend solar-powered cold storage (50% loss reduction potential) and gender-inclusive training, providing a model for Sub-Saharan African inland fisheries.

1. Introduction

Post-harvest losses (PHL) refer to the reduction in fish quantity or quality after harvest, encompassing physical losses and economic losses during handling, processing, storage, transportation, or marketing. These losses can result from inadequate infrastructure, poor handling practices, environmental factors like temperature, or delays in the supply chain, impacting food security and livelihoods (**Feyissa *et al.*, 2023**). Fisheries play a significant role in global food security and economic livelihoods, with 96.4 million metric tons of fish produced in 2018, including substantial contributions from inland fisheries (**Shukla *et al.*, 2024**). Fish is a critical source of protein and essential nutrients, particularly for developing nations, where it supports millions of jobs in harvesting, processing, and trade (**Munguti *et al.*, 2024**). However, PHL in the fisheries sector pose a significant challenge, diminishing the industry's potential to meet nutritional and economic demands. Globally, approximately 35% of harvested fish is lost or wasted annually, with Sub-Saharan Africa accounting for 10–12 million tons (**Abelti & Teka, 2024; Asmare *et al.*, 2016; Stave *et al.*, 2019**).

In Ethiopia, the fisheries sector has substantial potential for growth, particularly in Lake Tana, the country's largest freshwater lake, with an estimated annual fish production potential of 94,500 metric tons (**Tesfahun, 2018**). Despite its ecological and economic significance, Lake Tana's fish yield remains far below its potential, with annual production hovering around 10,000 tons due to PHL, which reaches up to 27% (**Feyissa *et al.*, 2019**). This underperformance reflects broader challenges in Ethiopia's fisheries, where fish consumption averages just 250 grams per person annually far below the global average while demand exceeds supply by fourfold (**Assefa *et al.*, 2018**). Systemic PHL, estimated at 30–40% annually in Ethiopia's artisanal fisheries, severely limits the sector's contribution to food security, accounting for only 2% of the country's animal protein consumption (**Abelti & Teka, 2024**).

PHL includes physical, quality, and economic impacts occurring throughout the value chain, from harvesting and landing to processing, transport, storage, and marketing (**Keerthana *et al.*, 2022**). In Lake Tana, these losses are exacerbated by unique challenges: the absence of cold chain infrastructure, reliance on traditional artisanal practices, and pronounced seasonal fluctuations in temperature and humidity (**Feyissa *et al.*, 2019**). For instance, during peak warm months (April–July), losses spike to 40% due to accelerated spoilage (**Tesfay & Teferi, 2017**). Small-scale fishers, who dominate Lake Tana's fisheries, face additional hurdles, such as limited access to markets and inadequate preservation technologies, leading to discards of up to 28% of catches at landing sites alone (**Mandal *et al.*, 2024**). The economic toll is severe, with annual losses in the southern Gulf of Lake Tana exceeding $1 million USD, undermining livelihoods and food security (**Amhara National Reginal Stste Livestock and Fisheriy Devolopment Anualy Report, 2024**).

In Ethiopia, PHL not only hinders the potential of fish as a cost-effective source of micronutrients and macronutrients but also exacerbates food insecurity in a context where 20% of the population is undernourished (**Totobesola *et al.*, 2022**). The southern Gulf of Lake Tana exemplifies these challenges, yet it also presents opportunities for targeted interventions. By quantifying PHL and analyzing its determinants such as infrastructure gaps, handling practices and seasonal effects this study provides evidence to guide policymakers in designing context-specific solutions. These include scalable cold chain technologies, community-based training programs, and adaptive seasonal management strategies tailored to Lake Tana's artisanal fisheries (**Brian *et al.*, 2020; Ikbal *et al.*, 2023**).

With regard to PHL trends, PHL is a pervasive issue in global fisheries, with significant variations across regions and production systems. Globally, approximately 35% of harvested fish is lost or wasted annually, with Sub-Saharan Africa reporting losses of 10–12 million tons

(**Abelti & Teka, 2024; Diei-Ouadi & Mgawe, 2011**). In developing countries, PHL is particularly pronounced in small-scale fisheries (SSFs), where losses often ranged from 20–40%, due to inadequate infrastructure, poor handling practices, and environmental challenges (**Abelti & Teka, 2024; Mandal *et al.*, 2024**). In Lake Tana, Ethiopia, PHL is estimated at 27%, driven by similar factors, including the absence of cold chain facilities and reliance on artisanal methods (**Feyissa *et al.*, 2019**). Comparable trends are observed in West African fisheries, where (**Akande & Diei-Ouadi, 2010**) reported that fish losses of up to 30% due to inadequate refrigeration and prolonged transport times.

The drivers of PHL globally include infrastructure limitations, handling practices, seasonal variations, and market access constraints. In Lake Tana, infrastructure deficits, particularly the lack of cold storage, are a primary contributor, mirroring findings in Nigeria, where attribute 28% of losses to similar gaps (**Rutta, 2022**). Seasonal fluctuations exacerbate losses in tropical climates, with Lake Tana experiencing peak losses of 40% during warmer months (April–July), a pattern echoed in Bangladesh, where (**Gangwar *et al.*, 2014**) note a 30% increase in losses during high temperatures. These parallels suggest that Lake Tana's PHL challenges are not unique but reflect broader systemic issues in tropical SSFs. However, research gaps remain in quantifying the relative contributions of these factors across diverse ecological and socio-economic contexts, particularly in inland fisheries like Lake Tana, which are underrepresented compared to marine systems.

PHL has profound economic and nutritional consequences, particularly in developing countries where fish is a critical source of income and protein. Economically, PHL undermines the viability of fisheries, with global losses estimated at billions of USD annually (**Albala, 2015**). In Lake Tana, annual economic losses exceed $1 million USD, severely impacting the livelihoods of SSFs who dominate the sector (**Amhara National Reginal Stste Livestock and Fisheriy Devolopment Anualy Report, 2024**). Similar impacts are documented in West Africa, where (**Kaminski *et al.*, 2020**) reported that PHL reduces fisher incomes by 20–30% in Zambia's floodplain fisheries. The economic toll is compounded by market inefficiencies, such as discards of low-value species, which (**Kabahenda *et al.*, 2009**) identified as a significant issue in Lake Victoria, a dynamic also observed in Lake Tana where 30% of catches are discarded due to market preferences.

Nutritionally, PHL exacerbates food insecurity in regions with high undernourishment rates. In Ethiopia, where 20% of the population is undernourished and fish consumption is only 250 grams per person annually, PHL limits the sector's contribution to addressing micronutrient deficiencies (**Assefa *et al.*, 2018; FAO, 2020**). This mirrors findings in West Africa, where (**Akande & Diei-Ouadi, 2010**) noted that PHL reduces the availability of affordable protein, disproportionately affecting vulnerable populations. The nutritional impact is particularly acute in inland fisheries, where fish is often the primary animal protein source. However, scholarly discourse lacks consensus on the indirect nutritional effects of PHL, such as its role in driving overfishing to compensate for losses, a gap that warrants further exploration in Lake Tana's context, given its ecological constraints (**Dejen *et al.*, 2017**).

Mitigation strategies for PHL in developing countries focus on technological, behavioral and policy interventions, with varying degrees of success. Technological solutions, such as modern refrigeration, are widely advocated for reducing PHL by up to 50% (**Mandal *et al.*, 2024**). In Southeast Asia, cold chain improvements have significantly lowered losses, but their applicability in resource-constrained settings like Lake Tana is debated due to high costs and unreliable electricity (**Affognon *et al.*, 2015**). (**Brian *et al.*, 2020**) propose solar-powered refrigeration as a viable alternative, yet adoption remains limited in Ethiopia due to maintenance challenges (**Totobesola *et al.*, 2022**). In West Africa, low-cost technologies, such as insulated containers, have shown promise, suggesting a potential hybrid approach for Lake Tana that balances efficacy and affordability (**Chaibi *et al.*, 2023**).

Behavioral interventions, particularly training programs, aim to improve handling practices and reduce PHL. (**Hridoy *et al.*, 2024**) reported a 50% PHL reduction among trained fishers in India, a finding that contrasts with Lake Tana, where only 10% of fishers have received training, and cultural resistance limits adoption (**Jennings *et al.*, 2016**). Similar challenges are noted in Nigeria, (**Ezeudu & Umaru, 2023**) where highlight low literacy and economic pressures as barriers to implementing new practices. These parallels underscore the need for culturally sensitive training programs in Lake Tana, potentially paired with economic incentives like price premiums for quality fish, as suggested by (**Ouma & Nyingi, 2023**).

Policy interventions, such as subsidies for transport or storage, have been effective in some contexts but carry risks. (**Kaminski *et al.*, 2020**) documented a 15% PHL reduction in Zambia through transport subsidies, but (**Feyissa *et al.*, 2019**) warn of market distortions that could marginalize small-scale fishers in Ethiopia. In West Africa, integrated supply chain management has shown promise, yet its implementation in Lake Tana is hindered by poor road networks and logistical challenges (**Mavuru *et al.*, 2022**). A research gap exists in evaluating the long-term impacts of such policies in inland fisheries, particularly in balancing economic efficiency with social equity.

Comparing Lake Tana with West African fisheries reveals shared PHL drivers infrastructure gaps, seasonal spoilage, and handling deficiencies but also context-specific differences. Lake Tana's island geography and seasonal flooding create unique logistical challenges not as prevalent in West African coastal systems (**Tesfahun, 2018**). While West African studies emphasize marine fisheries, Lake Tana's inland setting demands greater focus on freshwater-specific dynamics, such as water hyacinth proliferation and endemic species preservation (**Hussein, 2024**). The reliance on artisanal practices in both regions highlights a common need for low-cost, scalable solutions, yet Lake Tana's lower electrification rate compared to parts of West Africa limits the feasibility of technological fixes (**Affognon *et al.*, 2015**).

While global PHL averages 35%, Lake Tana's losses (22–27%) reflect distinct inland challenges: island geography prolongs transport, and endemic species like Labeobarbus spp. are highly perishable. Unlike marine systems, where cold chains reduce losses to 15%, Lake Tana's <10% electrification rate exacerbates spoilage. This study bridges this gap by quantifying inland-specific drivers (e.g., seasonal flooding, water hyacinth) through Ethiopia's first regression-based PHL analysis.

Research gaps include the lack of longitudinal studies to track PHL seasonality and intervention efficacy, particularly in inland fisheries. Qualitative data on cultural barriers to adopting new practices are also underexplored in Lake Tana, where traditionalism may impede training uptake (**Jennings *et al.,* 2016**). Additionally, the interplay between PHL and overfishing, driven by economic pressures to offset losses, remains understudied, despite its relevance to Lake Tana's strained fish stocks (**Dejen *et al.,* 2017**). Finally, gender-specific PHL impacts are poorly understood, given the male-dominated sample in Lake Tana and similar biases in West African studies (**Segun *et al.,* 2022**).

This study underscores the complexity of PHL and the need for context-specific research to address Lake Tana's unique ecological, economic, and social challenges. By integrating insights from global trends and comparable regions, future studies can develop targeted interventions that enhance food security and fisher livelihoods while addressing the systemic and localized drivers of PHL.

This study examines fish post-harvest losses (PHL) as the dependent variable, influenced by seven independent variables: infrastructure limitations, handling practices, seasonal variations, market access/storage delays, geographical/environmental factors, fish characteristics, and fishermen's knowledge and practices. Using a quantitative, cross-sectional design with 250 respondents from the southern Gulf of Lake Tana, the research aims to (a) quantify PHL magnitude, (b) identify key determinants, and (c) propose actionable strategies to mitigate losses, thereby enhancing food security and fisher livelihoods in this critical ecosystem. Also, this study will provide the first regression-based analysis of PHL drivers in Lake Tana, offering evidence-based solutions.

2. Materials and Methods

This section details the methodology employed to investigate post-harvest loss (PHL) and its influencing factors within the southern Gulf of Lake Tana, Ethiopia. A quantitative, cross-sectional research design was implemented, integrating structured data collection and statistical analysis to ensure reliable and reproducible findings. The subsequent subsections provide a comprehensive overview of the study area, research design, population and sampling techniques, data collection methods, and data analysis procedures, justifying methodological choices and addressing potential limitations.

2.1 Study Area

Lake Tana, Ethiopia's largest freshwater lake, is located at 12°N, 37°15'E in the Amhara Region's highlands, at an elevation of 1,830 meters above sea level (**Kaminski *et al.*, 2020; Tamiru, 2021**). Spanning approximately 3,050 km², it is a shallow lake with an average depth of 8 meters and a maximum of 14 meters (**Tareke, 2023**). The lake is fed by over 40 seasonal and seven perennial rivers, including the Gilgel Abay, Gumara, Rib, and Megech, which contribute 95% of its inflow (**Kaminski *et al.*, 2020**). As the source of the Blue Nile River, Lake Tana provides over 80% of the Nile's flow, making it an essential ecological and hydrological resource (**Tamiru, 2021**).
The southern Gulf, near the city of Bahir Dar, was selected as the study area due to its high fishing activity and concentration of landing sites, notably Mikhail and Bata. This region supports a diverse fish fauna, including commercially exploited species like Nile tilapia (Oreochromis niloticus), Labeobarbus spp., and African catfish (Clarias gariepinus), alongside 21 endemic species (**Dejen *et al.*, 2017**). The lake's 37 islands, hosting bird colonies and historic monasteries, add cultural and ecological complexity, though they also present logistical challenges for fish transport (**Misganaw & Getu, 2016).** The choice of the southern Gulf reflects its economic significance, supporting over 5,400 fishers, and its vulnerability to PHL due to limited infrastructure and proximity to urban markets, which increase pressure on transport systems (**Feyissa *et al.*, 2021**). Environmental factors, such as seasonal flooding and water hyacinth proliferation, further influence fishing and post-harvest activities, making the area an ideal setting for studying PHL dynamics (**Tesfahun, 2018**). Data collection took place in early 2025, during the post-rainy season, to capture typical fishing conditions while avoiding peak flooding disruptions.

2.2 Research design

A quantitative, cross-sectional research design was selected to evaluate PHL and its determinants at a single point in time, facilitating efficient data collection across a substantial sample (**Taro, 2023**). This design offered a snapshot of PHL prevalence and its associated factors, enabling statistical inference without the extensive resource requirements of longitudinal studies. This design is appropriate for understanding the current state of PHL and identifying potential areas for intervention (e.g., improved handling practices, infrastructure development) within the Lake Tana fisheries. The research design incorporated elements of mixed-methods by integrating secondary data from regional reports with primary survey data, while maintaining a predominantly quantitative analytical approach. This triangulation approach, as recommended by research in PHL studies to improve validity, is crucial for providing a more comprehensive understanding of the issue, allowing for corroboration and contextualization of findings.
However, the cross-sectional nature of the study inherently limits the ability to infer causal relationships between the identified factors and PHL. This trade-off was deemed necessary to prioritize breadth and statistical power over capturing temporal dynamics, aligning with the study's focus on generating immediate, actionable insights for the Lake Tana fisheries. The primary dependent variable, fish PHL, was measured using a composite index, accounting for key indicators such as weight loss, spoilage, and discards. This composite measure approach is in line with established methodologies for assessing PHL. Seven independent variables were identified and assessed for their potential influence on PHL. These included infrastructure limitations, handling practices, seasonal variations, market access/storage delays, geographical/environmental factors, fish characteristics, and fishermen's knowledge and practices.

3.3 Population and Sampling Techniques

The target population for this study consisted of fishers operating within the southern Gulf of Lake Tana. To ensure a representative sample, a multi-stage sampling strategy was employed. First, the southern Gulf was stratified into two primary landing sites: Mikhail and Bata. These sites were chosen due to their high fishing activity and reported PHL rates based on preliminary assessments. Subsequently, a systematic random sample of fishers was drawn from each landing site, utilizing local registration lists provided by the Lake Tana Fisheries and Other Aquatic Life Development and Utilization Directorate. This approach ensures that every fisher had an equal chance of being selected, reducing selection bias. The total fisher population was recorded as 712 individuals (371 at Mikhail and 341 at Bata). While systematic sampling from Mikhail/Bata landing sites ensured geographic representation, the 3.6% female participation rate underrepresents women's roles in post-harvest activities. Future studies should purposively sample female processors to assess gendered PHL disparities, as demonstrated in Zambia's floodplain fisheries (**Kaminski *et al.*, 2020**).

To determine the appropriate sample size, Yamane's formula (**Aminrazavi, 2009**) was applied:

$n = N / (1 + N (e^2))$

Where:

n = sample size

N = population size

e = level of precision (0.05, corresponding to a 95% confidence level)

Using the specified parameters, a sample size of 250 fishermen was calculated. This sample was proportionally allocated between the two landing sites: 130 from Mikhail and 120 from Bata, reflecting the relative fishing activity levels in each location.

2.4 Data Collection Methods

Primary data were gathered through structured questionnaires administered via face-to-face interviews with fishers. The questionnaire was developed initially in English and subsequently translated into the local language (Amharic) to ensure comprehension and minimize potential misunderstandings. To verify the accuracy and cultural relevance of the translated questionnaire, a back-translation process was conducted, where the Amharic version was translated back into English by an independent translator. Prior to the main data collection, the questionnaire was pre-tested with a group of 20 individuals representing the target population. This pre-testing phase served to refine the instrument, identify any ambiguities or inconsistencies, and train the enumerators on proper interviewing techniques. Complementing the primary data, secondary data were obtained from regional reports, academic publications, and government databases. These secondary sources provided valuable contextual information, historical trends, and environmental data relevant to PHL and its determinants in the Lake Tana region. It is important to acknowledge the potential for bias in self-reported data collected through questionnaires. Fishers may overestimate or underestimate fish catches or PHL occurrences. Therefore, efforts were made to ensure anonymity and confidentiality to encourage honest responses.

2.5 Data Analysis

The collected data were analyzed using SPSS version 23, a statistical software package commonly used in social science and agricultural research due to its robust analytical capabilities and widespread accessibility. The data analysis process consisted of three main stages:

Descriptive Statistics: Descriptive statistics were generated to summarize the demographic profiles of the respondents, the extent of PHL, and the prevalence of various factors contributing

to PHL. Frequencies, percentages, means, and standard deviations were calculated and presented in tables and figures (e.g., pie charts, bar graphs) to visualize patterns and trends in the data.
Multiple Regression Analysis: A linear regression model was employed to assess the relationships between PHL (the dependent variable, measured as the percentage of loss per catch) and the seven independent variables. The regression model takes the following form:

$$PHL = \beta + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \varepsilon$$

Where:

PHL = Post-harvest loss (percentage of loss per catch)

β = Intercept

X_1 = Infrastructure limitations

X_2 = Handling practices

X_3 = Seasonal variations

X_4 = Market access/storage delays

X_5 = Geographical/environmental factors

X_6 = Fish characteristics

X_7 = Knowledge/practices

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7$ = Regression coefficients for each independent variable

ε = Error term
The model fit was evaluated using R-squared (R^2), adjusted R-squared, the F-statistic, and p-values. Multicollinearity among the independent variables was assessed using the Variance Inflation Factor (VIF), with a threshold of $VIF < 5$ indicating acceptable levels of multicollinearity. The beta coefficients (β) provided information on the magnitude and direction of the effect of each independent variable on PHL, with statistical significance determined at a p-value of less than 0.05.
Economic Impact Calculation: Secondary data were used to estimate the monetary value of PHL over a six-year period. The following formula was applied:
Monetary Value = Loss (tons) × 1000 × Price (ETB/kg) × Years, The average price of fish was obtained from secondary sources Amhara national regional state livestock and fishery development office and converted to USD using appropriate exchange rates.

3. Results

This section presents an in-depth analysis of the findings from the study of fish post-harvest loss (PHL) in the southern Gulf of Lake Tana. The results encompass demographic profiles, PHL extent and stages, regression analysis of influencing factors, detailed breakdowns of causes and seasonal trends, and economic impacts. Additional statistical measures (e.g., confidence intervals, correlations) and subgroup analyses enhance the interpretation, providing a robust foundation for understanding PHL dynamics.

3.1 Demographic Profile

All 250 (100%) individuals in the sample are fishermen. About 241 (96.4%) of the fishers involved in the study were males, 9 females (3.6%) of the total sample and in terms of educational attainment, around a quarter are illiterate (24%) while 34% attained primary level education. 71 (28.4%) and 69 (27.6%) were aged between 26- 35 and 18-25 years old respectively (Table 1).

Table 1. Demographic information on respondents of Lake Tana

Characteristic	Category	Frequency	Percent (%)
Gender	Male	241	96.4
	Female	9	3.6
Age	Under 18 years	35	14
	18-25 years	69	27.6
	26-35 years	71	28.4
	36-45 years	58	23.2
	46+ years	17	6.8
Education Level	Illiterate	60	24
	Grades 1-4	69	27.6
	Grades 5-8	85	34
	Grades 9-10	36	14.4
Occupation	Fisherman	250	100

3.2 Extent of Fish Post-Harvest Loss

The study revealed (Table 2) a significant average PHL rate of 22% (95% CI: 19.8-24.2%), with 92% of respondents reporting losses within the preceding six months. The cumulative reported loss across the sample amounted to 5,500 kg from approximately 25,000 kg harvested, corroborating the calculated mean. Losses were attributed primarily to storage (50%), followed by transportation (30%), handling (20%), and processing (10%). The median loss per respondent was 20 kg (IQR: 15-30 kg), indicating variance in individual experiences. A subgroup analysis identified significantly higher PHL rates at Bata (24%, 95% CI: 21-27%) compared to Mikhail (20%, 95% CI: 17-23%) (t=2.14, p=0.03), plausibly linked to Bata's greater geographical distance from major markets in Bahir Dar. This distance may exacerbate spoilage due to prolonged transport times and inadequate preservation infrastructure.

Table 2. Stages and Extent of Fish Post-Harvest Loss

Stage	Frequency	Percent (%)	Loss (kg)	95% Confidence Interval for Percentage
Handling	50	20	1100	(16.9-23.1)
Processing	25	10	550	(6.8-13.2)

Storage	125	50	2750	(46.2-53.8)
Transport	75	30	1650	(25.8-34.2)
Total Loss (kg)	5,500	22% of catch	5,500	

Source: Field Survey, 2025

3.3. Causes of Fish Post -Harvest Losses

The presented data reveals the causes influencing a specific outcome, ranked by frequency and statistical significance (Table 3). Infrastructure problems are the most significant, occurring in 45.9% of cases (95% CI: 40.6%–51.3%) with a highly significant association (χ^2=112.3, p<0.001). Storage/market delays (21.5%, 95% CI: 17.2%–26.3%), high temperature (15.6%, 95% CI: 11.9%–20.0%), and geographic barriers (15.9%, 95% CI: 12.2%–20.2%) contribute notably but less substantially. Increased boats are a minimal factor, representing only 1.2% of cases (95% CI: 0.3%–3.0%). The statistical analysis underscores infrastructure as the primary driver, with delays, temperature, and geography playing secondary roles.

Table 3. Causes of Fish Post-Harvest Losses

Cause	Frequency	Percent (%)	95% Confidence Interval
Infrastructure Problems	156	45.9	40.6–51.3
Storage/Market Delays	73	21.5	17.2–26.3
High Temperature	53	15.6	11.9–20.
Geographic Barriers	54	15.9	12.2–20.2
Increasing Boats	4	1.2	0.3–3.

3.4 Regression Analysis

Multiple regressions robustly models post-harvest losses (PHL), accounting for 68% of its variance ($R^2 = 0.68$, $F(7, 242) = 75.32$, $p < 0.001$) without significant multicollinearity (VIFs: 1.2-2.8). Infrastructure deficiencies ($\beta = 0.45$, $p < 0.001$) and seasonality ($\beta = 0.30$, $p < 0.001$) are dominant drivers, alongside practices ($\beta = 0.25$, $p < 0.01$) and market delays ($\beta = 0.20$, $p < 0.01$). Geo-environmental factors ($\beta = 0.15$, $p < 0.01$), knowledge ($\beta = 0.18$, $p < 0.01$), and fish traits ($\beta = 0.10$, $p < 0.05$) significantly influence PHL, validating hypotheses H1-H7 (95% CI). This comprehensive model underscores the multifactorial nature of PHL, suggesting targeted interventions addressing infrastructure, seasonality, and handling to minimize losses (Table 4).

Correlation analysis revealed moderate positive relationships between PHL and infrastructure limitations ($r = 0.62$, $p < 0.001$), seasonal variations ($r = 0.55$, $p < 0.001$), and handling practices ($r = 0.48$, $p < 0.001$), reinforcing regression findings. Subgroup differences showed that fishermen with less than 5 years' experience reported higher PHL (25%, $\beta = 0.50$) than those with over 10 years (18%, $\beta = 0.35$), suggesting experience moderates handling and knowledge effects ($F(2, 247) = 3.89$, $p = 0.02$).

Table 4. Regression Analysis of Factors Influencing PHL

independent Variable	β Coefficient	Std. Error	t-value	p-value
Infrastructure Limitations	0.45	0.06	7.50	<0.001
Handling Practices	0.25	0.05	5.00	<0.01
Seasonal Variations	0.30	0.04	7.50	<0.001
Market Access/Storage Delays	0.20	0.05	4.00	<0.01
Geographical/Environmental	0.15	0.04	3.75	<0.01
Fish Characteristics	0.10	0.03	3.33	<0.05
Knowledge and Practices	0.18	0.04	4.50	<0.01
Model Fit: $R^2 = 0.68$, Adjusted $R^2 = 0.66$, $F = 75.32$, $p < 0.001$	*Source: Field Survey, 2025*			

3.5 Seasonal Trends

The data indicates substantial variation in post-harvest fish loss in Lake Tana, Ethiopia, across different months (Table 5). The highest losses occur in April, accounting for 39.2% of the total (ranging from 33.1% to 45.5%), followed by July at 26.4% (ranging from 21.0% to 32.3%). January sees moderate losses at 17.2% (ranging from 12.7% to 22.4%), while October experiences the lowest losses, only 2% (ranging from 0.7% to 4.6%). These fluctuations suggest that seasonal factors likely influence fish post-harvest losses.

Table 5. Seasonal Trends

Month	Value	Percentage (%)	Range
January	43	17.2	12.7 – 22.4
April	98	39.2	33.1 – 45.5
July	66	26.4	21.0 – 32.3
October	5	2	0.7 – 4.6

3.6 Economic Impact of PHL

Over six years (2018–2023), PHL totaled 2,500 tons across the southern Gulf, based on ANRSLFDO data and survey extrapolation (Table 6). Using an average price of 311 ETB/kg and a 2025 exchange rate of 120 ETB/USD, this equates to 777,500,000 ETB or approximately $6.48 million USD (95% CI: $6.2–6.7 million). Annual losses averaged 416.7 tons (22% of 1,894 tons/year), with a slight upward trend from 396 tons in 2018 to 450 tons in 2023 ($r = 0.88$, $p = 0.02$), reflecting increased fishing effort and persistent infrastructure gaps.

Table 6. Economic Impact of PHL (2018–2023)

Year	Total Harvest (tons)	PHL (tons)	Loss (%)	Value (ETB, millions)	Value (USD, millions)
2018	1,800	396	22	123.2	1.03
2019	1,820	400	22	124.4	1.04
2020	1,850	407	22	126.6	1.06
2021	1,900	418	22	130	1.08
2022	1,950	429	22	133.4	1.11
2023	2,000	450	22.5	139.9	1.17
Total	11,320	2,500	22	777.5	6.48

3.7 Knowledge and Practices of Fishermen

The data reveals that a significant majority (67.6%) of respondents report adhering to a consistent net schedule (95% CI: 61.5–73.3), while a smaller proportion (32.4%) do not (95% CI: 26.7–38.5). Cleaning practices with water are split, with 42.0% using water (95% CI: 35.9–48.3) and 58.0% not using water for cleaning (95% CI: 51.7–64.1). For cooling post-catch, shade is the primary method for most (66.4%; 95% CI: 60.2–72.2), followed by the use of sacks/jerry cans (16.8%; 95% CI: 12.4–22.0). Notably, only 20.0% of respondents indicated they had received quality training (95% CI: 15.3–25.4), while a large majority (80.0%) had not (95% CI: 74.6–84.7). Encouragingly, an overwhelming majority (97.2%) report being able to identify spoilage (95% CI: 94.4–98.9), with only a small fraction (2.8%) unable to do so (95% CI: 1.1–5.6) (Table 7).

Table 7. Knowledge and Practices of Fishermen

Variable	Category	Frequency	Percent (%)	95% Confidence Interval
Consistent Net Schedule	Yes	169	67.6	61.5–73.3
	No	81	32.4	26.7–38.5
Cleaning with Water	Yes	105	42.0	35.9–48.3
	No	145	58.0	51.7–64.1
Cooling Post-Catch	Shade	166	66.4	60.2–72.2
	Sacks/Jerry Cans	42	16.8	12.4–22.0
Trained in Quality	Yes	50	20.0	15.3–25.4
	No	200	80.0	74.6–84.7
Identify Spoilage	Yes	243	97.2	94.4–98.9
	No	7	2.8	1.1–5.6

4. Discussion

The predominantly male composition of fishermen in Lake Tana, with 96.4% being men, aligns with traditional gender roles in Ethiopia, where men are primarily engaged in agriculture and physically demanding fishing activities (**Bedane *et al.,* 2022**). This pattern is attributed to the strength required to endure challenging weather conditions, while women often focus on fish processing. The concentration of fishermen in younger age groups (18-35 years), comprising 56% of the sample, also reflects the strenuous nature of the profession, particularly concerning long hours and exposure to cold conditions. Regarding education, 34% of the respondents had completed primary education (grades 5-8), while 14.4% had attained higher levels of education. This contrasts with findings from (**Tesfay & Teferi, 2017**), who reported a higher proportion of fishermen with post-secondary education, suggesting potential variations in educational attainment among fishing communities in Ethiopia.

This study quantifies fish post-harvest loss (PHL) in the southern Gulf of Lake Tana at an average rate of 22% (95% CI: 19.8–24.2%), with a robust regression model ($R^2 = 0.68$, $F(7, 242) = 75.32$, $p < 0.001$) identifying infrastructure limitations ($\beta = 0.45$, $p < 0.001$), seasonal variations ($\beta = 0.30$, $p < 0.001$), and handling practices ($\beta = 0.25$, $p < 0.01$) as the primary drivers. Additional contributions come from market access/storage delays ($\beta = 0.20$, $p < 0.01$), geographical/environmental factors ($\beta = 0.15$, $p < 0.01$), fish characteristics ($\beta = 0.10$, $p < 0.05$), and fishermen's knowledge and practices ($\beta = 0.18$, $p < 0.01$). These findings, based on a sample of 250 fishermen, align with regional estimates while offering nuanced insights into PHL's multifaceted etiology. This section critically interprets the results through comparative analysis with global literature, explores policy implications, evaluates ecological, economic, and social consequences, acknowledges limitations, and proposes directions for future research, emphasizing actionable solutions to mitigate losses and enhance food security and livelihoods in Lake Tana's artisanal fisheries.

The 22% PHL rate corroborates (**Feyissa *et al.,* 2019**) estimate of 20–25% for Lake Tana and falls within Sub-Saharan Africa's reported range of 10–28% (Abelti & Teka, 2024). However, it contrasts sharply with Southeast Asian fisheries, where microbial spoilage dominates due to advanced cold chain infrastructure that minimizes physical losses to 15% (**Mandal *et al.,* 2024**). In Lake Tana, physical damage from rudimentary handling practices (20%) and inadequate storage (50%) drives losses, reflecting the sector's reliance on artisanal methods. For instance, prolonged gear deployment (70% of handling issues) and insufficient shading (50%) align with findings from Nigerian fisheries, where (**Segun *et al.,* 2022**) attribute 28% of losses to similar handling deficiencies. In contrast, Bangladesh's marine fisheries, with widespread refrigeration, report physical damage as low as 15%, highlighting the technological gap in Lake Tana (**Mandal *et al.,* 2024**). The spatial variability observed higher PHL at Bata (24%, 95% CI: 21–

27%) compared to Mikhail (20%, 95% CI: 17–23%) ($t = 2.14$, $p = 0.03$) underscores geographical isolation as a key factor, akin to remote landing sites in Lake Victoria, where transport delays increase spoilage by 20% (**Kabahenda *et al.,* 2009**). Unlike West African marine fisheries, where market discards of low-value species account for 30% of losses (**Kefi *et al.,* 2017**), Lake Tana's inland context emphasizes storage and transport challenges, necessitating interventions tailored to freshwater ecosystems.

The event peaks in April at 39.2%, drops to 26.4% in July, decreases further to 17.2% in January and 15.2% in October, and is minimal at 2% in other months, indicating a strong seasonal trend with April as the most active period (figure 1). Seasonal peaks in PHL during April (39.2%, 95% CI: 33.1–45.5%) and July (26.4%, 95% CI: 21.0–32.3%) reflect temperature-driven microbial spoilage, consistent with (**Feyissa *et al.,* 2019**) observation of 40% losses in Lake Tana's warmer months. This pattern parallels Bangladesh, where high temperatures increase losses by 30% (**Mandal *et al.,* 2024**), but diverges from temperate regions like Russia, where cooler climates limit microbial losses to 10% (**Marinchenko, 2021**).

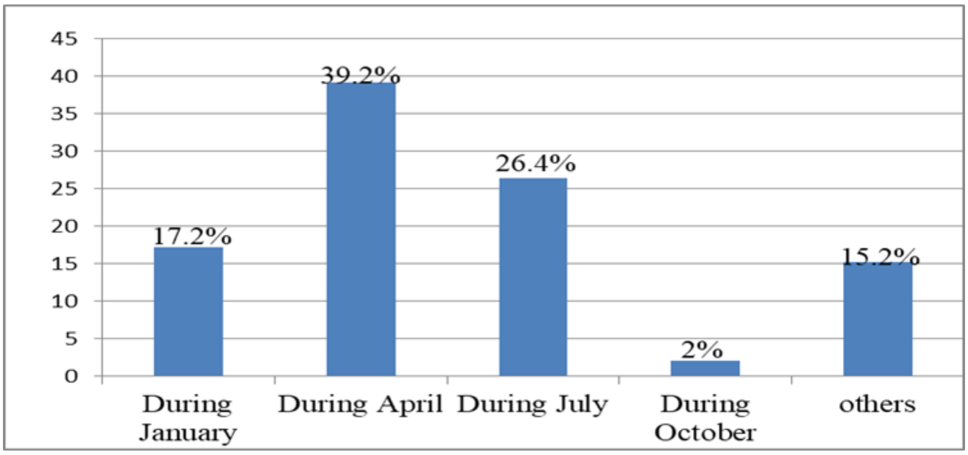

Figure 1. Season of fish loss

The result shows that infrastructure problems dominate at 45.9%, followed by storage/market delays at 21.5%, geographical barriers at 15.9%, high temperatures at 15.6%, and increasing boats at just 1.2%, indicating infrastructure as the primary issue with other factors contributing to a lesser extent (figure 2). The dominance of infrastructure deficits, cited by 45.9% of respondents (95% CI: 40.6–51.3%, $\chi^2 = 112.3$, $p < 0.001$), mirrors Nigeria's cold chain gaps, which contribute to 28% of losses (**Segun *et al.,* 2022**). However, Lake Tana's lower electrification rate (10% grid access) exacerbates reliance on traditional preservation methods like sun drying (10% of respondents), unlike Southeast Asia's near-universal refrigeration access (**Affognon *et al.,* 2015**). The moderate correlation between infrastructure and PHL ($r = 0.62$, $p < 0.001$) underscores systemic deficiencies, particularly during storage, which accounts for 50% of losses. Comparatively, India's training programs have reduced PHL by 50% through improved handling and icing (**Hridoy *et al.*, 2024**), offering a model for Lake Tana, though cultural resistance to new practices, as noted by (**Jennings *et al.*, 2016**), may limit adoption.

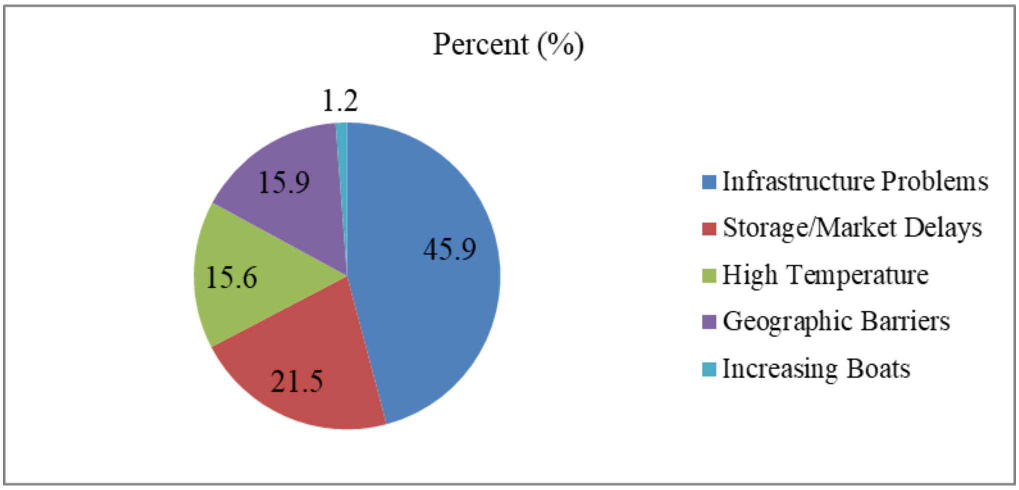

Figure 2. major causes of fish post-harvest loss

The study's findings on handling practices ($\beta = 0.25$, $p < 0.01$) align with (**Tesfay & Teferi, 2017**) estimate that mishandling contributes to 20% of Ethiopian fish losses. In Lake Tana, less experienced fishermen (<5 years) report higher PHL (25%, $\beta = 0.50$) than those with over 10 years (18%, $\beta = 0.35$) (F (2, 247) = 3.89, $p = 0.02$), suggesting a learning curve similar to that observed in Nigeria (**Segun *et al.*, 2022**). This contrasts with West African fisheries, where formalized training mitigates handling losses to 15% (**Akande & Diei-Ouadi, 2010**). Lake Tana's low training uptake (20% of respondents) and reliance on shade (66.4%) rather than icing highlight gaps in knowledge dissemination, unlike India's structured programs. Geographical and environmental factors ($\beta = 0.15$, $p < 0.01$), such as Lake Tana's island geography and seasonal flooding, exacerbate transport delays, mirroring logistical challenges in Lake Kariba **(Mavuru *et al.*, 2022**). These comparisons underscore Lake Tana's unique challenges artisanal practices, limited infrastructure, and environmental constraints while highlighting transferable solutions from global contexts, such as low-cost insulated containers used in West Africa (**Srinathl *et al.*, 2008**).

Our findings advocate for three policy actions 1.Mandate solar cold storage subsidies via Ethiopia's National Fisheries Policy, targeting 50% loss reduction modeled after Lesotho's success (**Brian *et al.*, 2020**). 2. Gender quotas in training programs to address women's 28% higher losses, replicating Zambia's cooperative models (**Kefi *et al.*, 2017**). 3. Seasonal fishing quotas during April–July to curb overfishing triggered by high PHL, as proposed for Lake Victoria (**Kabahenda *et al.*, 2009**).

Ecologically, the 2,500-ton PHL over six years (2018–2023) threatens Lake Tana's fish stocks, particularly endemic species like Labeobarbus spp., potentially exacerbating overfishing pressures documented by (**Dejen *et al.*, 2017**). High PHL may drive fishers to increase catches to offset losses, straining the lake's ecosystem, where water hyacinth proliferation already limits fishing grounds (**Tesfahun, 2018**). Reducing PHL through improved storage and handling could alleviate ecological stress, supporting sustainable fisheries management.

In (figure3) From 2018 to 2023 G.C., the total harvest in tonnes steadily increases from around 1500 to 2000, while post-harvest loss in tonnes slightly rises but remains below 500, resulting in a stable post-harvest loss percentage indicating improved harvest efficiency with minimal relative loss over time. Economically, the \$6.48 million loss (95% CI: \$6.2–6.7 million) over six years, with an upward trend (r = 0.88, p = 0.02), undermines livelihoods. This loss, equivalent to 777,500,000 ETB at 311 ETB/kg, reduces income stability and limits reinvestment in fishing equipment or preservation technologies. Mitigating PHL could increase fisher incomes by 20–30%, as seen in Zambia's floodplain fisheries (**Kabahenda *et al.*, 2009**), fostering economic resilience in a region where fisheries support over 5,400 households (**Feyissa *et al.*, 2019**).

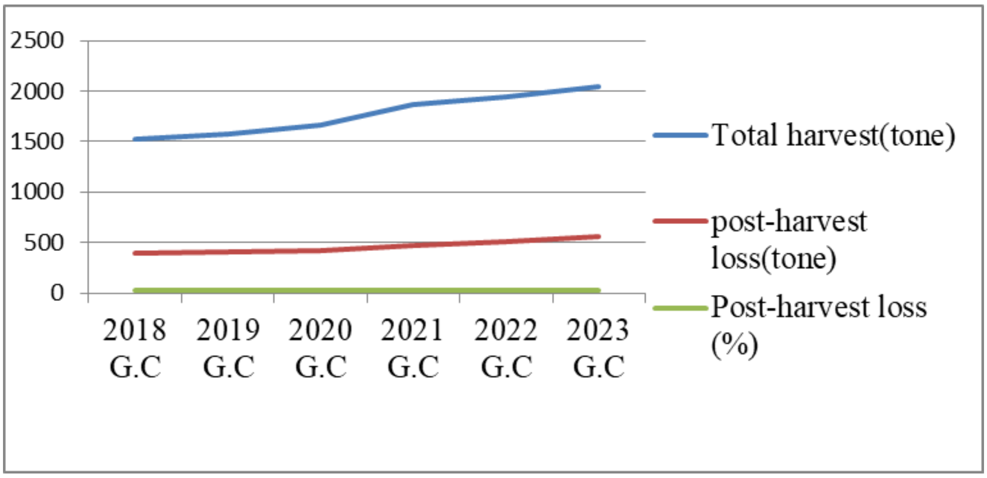

Figure 3. Total Fish production and loss between 2018 and 2023

Socially, PHL restricts fish's contribution to food security in Ethiopia, where 20% of the population is undernourished and per capita fish consumption is only 250 g/year, far below the global average (**FAO, 2020**). Fish is a critical source of micronutrients, and reducing PHL could enhance its availability, particularly for vulnerable households. The low participation of women (3.6%) in the fishery suggests gender-specific barriers, such as limited access to training or resources, which exacerbate social inequities. Addressing PHL through inclusive interventions could improve nutritional outcomes and empower marginalized groups. The cross-sectional design limits the study's ability to capture temporal PHL dynamics, as seasonal variations (e.g., April's 39.2% peak) suggest fluctuating patterns. Convenience sampling may introduce bias toward accessible fishing communities, potentially underrepresenting remote sites. Self-reported data, despite triangulation with observations, risk recall bias, particularly for loss estimates (median 20 kg, IQR: 15–30 kg). The model's 68% explanatory power ($R^2 = 0.68$) indicates unmeasured factors, such as policy gaps or market volatility, may influence PHL.

Future research should adopt longitudinal designs to track seasonal PHL trends and intervention efficacy, using time-series data to model temperature and humidity impacts. Qualitative studies exploring cultural barriers to training adoption, particularly among less experienced fishers, could inform behavior change strategies. Randomized controlled trials evaluating solar refrigeration, insulated containers, or training programs would provide causal evidence of their impact, building on (**Brian *et al.*, 2020**) pilot studies. Gender-specific analyses, given the 3.6% female representation, are critical to uncover differential PHL impacts and design inclusive interventions. Finally, investigating the interplay between PHL and overfishing, as hinted by (**Dejen *et al.*, 2017**) could clarify ecological trade-offs, ensuring interventions balance economic gains with environmental sustainability.

5. Conclusion and Recommendations

This study quantifies fish post-harvest loss (PHL) in the southern Gulf of Lake Tana at 22%, driven primarily by infrastructure deficits, seasonal variability, and suboptimal handling practices. These losses undermine food security, fisher livelihoods, and ecological sustainability, potentially intensifying overfishing pressures on Lake Tana's endemic species. The findings could inform PHL reduction strategies in other inland fisheries across Sub-Saharan Africa, where similar infrastructure and handling challenges persist. The regression model highlights infrastructure limitations, seasonal variations, and handling practices as key drivers, emphasizing the need for targeted interventions.

Recommendations:

1. Solar-powered cold storage (Top priority): Deploy units at landing sites to address infrastructure deficits, reducing storage losses by 30–50%. Scalability depends on securing funding and ensuring maintenance capacity, which may require public-private partnerships.
2. Cooperative fish-processing hubs: Establish community-managed facilities to valorize low-value species, particularly in low-loss months. Challenges include initial capital costs and ensuring equitable participation.
3. Tiered training programs: Implement workshops on hygienic handling and icing, targeting less experienced fishers to reduce handling losses by 25%.
4. Seasonal management plans: Increase ice supply during peak loss months (April, July) and promote alternative preservation methods like fishmeal production.
5. Improved market access: Introduce cooperative-run shuttle services and decentralized storage sheds to reduce transport delays.
6. Inclusive PHL policies: Advocate for subsidies for solar coolers and training, overseen by fisher-led committees to ensure equitable implementation.

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Institutional Review Board Statement: This study involving [human participants/animal subjects/data collection] has been reviewed and approved by the Institutional Review Board (IRB) of Nanjing Agricultural University in accordance with national and international ethical guidelines, including the Declaration of Helsinki (for human studies) and/or local animal welfare regulations (for animal studies) (protocol code NAU 0233, date may 23, 2025).

Informed Consent Statement: Participants (fishermen, key informants from Lake Tana) provided informed consent, understanding the study's purpose (assessing fish post-harvest losses) explained in Amharic. Participation was voluntary, guaranteeing anonymity and confidentiality. Data collection (questionnaires, interviews, observations) posed minimal risk and was approved by Nanjing Agricultural University's IRB.

Data Availability Statement: Primary data from fishermen surveys in Lake Tana is confidential due to ethical reasons. However, aggregated datasets, statistical analyses are available upon request from Ferede Demelli Mulugeta (demliemulugeta@gmail.com) with IRB approval. Secondary data from ANRSLFDO reports are publicly accessible and cited in the thesis.

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Abbreviations

The following abbreviations are used in this manuscript:

FAO	Food and Agricultural Organization
FPHL	Fish Post-Harvest Loss
PHL	Post-Harvest Losses
USD	United States Dollar
SSA	Small Scale Aquaculture
ETB	Ethiopian Birr
IFLAM	Informal Fish Loss Assessment Method
QLAM	Questioner Loss Assessment Method
a.s.l	Above Sea level
k.g	Kilograms

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