

Volume 10, Issue No. 02 (March 2026)

KENYA *Aquatica*



A Scientific Journal of Kenya Marine and
Fisheries Research Institute

KMFRI

©2026

KENYA *Aquatica*

**A Scientific Journal of
Kenya Marine and Fisheries Research Institute**



Editorial

Welcome to Volume 10, Issue 2 of the Kenya Aquatica Journal, a milestone edition that reflects the growing body of scientific knowledge supporting the sustainable management of Kenya's inland water resources. Kenya's marine, coastal, freshwater, and aquaculture systems provide critical ecosystem services, sustain biodiversity, support livelihoods, contribute to national food and nutrition security, and underpin the country's Blue Economy aspirations. As these ecosystems face increasing pressures from climate variability, environmental degradation, pollution, and socio-economic change, the role of science in informing policy and management has never been more important.

The studies presented in this issue address a broad spectrum of ecological, fisheries, socio-economic, and technological challenges affecting Kenya's in-land environments. Several papers document the influence of hydrological change on ecosystem productivity and resilience, including investigations in Lake Baringo, Ferguson's Gulf of Lake Turkana, and Lake Sonachi. Together, these studies demonstrate how changing water regimes can alter habitat quality, species composition, water chemistry and fisheries productivity, highlighting the growing need for climate-responsive management strategies.

Freshwater ecosystem health is another central theme. Research from the Upper Tana River system, River Kathita, and the Njoro and Kamweti rivers applies biological indicators, including fish communities and diatoms, to assess ecological integrity and water quality. These studies provide critical baseline information for monitoring environmental change, guiding restoration efforts and strengthening conservation planning.

The socio-economic dimensions of fisheries receive considerable attention. Two complementary studies on the Omena fishery of Lake Victoria reveal the importance of small indigenous fish species in supporting livelihoods while exposing persistent challenges related to gender inequality, post-harvest losses, governance and market inefficiencies. The findings provide valuable evidence for policies aimed at improving equity, resilience, and sustainability within fisheries value chains.

This issue also demonstrates the practical value of research in responding to emerging environmental challenges. The assessment of the M.T. Rising Phoenix oil-spill incident highlights the social and economic consequences of marine pollution and provides lessons for disaster preparedness and community engagement. Meanwhile, studies on the SolCoolDry preservation technology and the use of water spinach as a locally available aquaculture feed ingredient offer innovative solutions to reduce post-harvest losses, enhance fish production and strengthen food security.

Collectively, the papers in this volume exemplify the vital science-to-policy linkage required for sustainable aquatic resource management. They generate evidence that can inform environmental regulation, fisheries management, climate adaptation, pollution response, biodiversity conservation and community development. Equally important, they contribute to national capacity building by strengthening research expertise, generating baseline datasets, and supporting the next generation of aquatic scientists and resource managers.

We extend our sincere appreciation to all authors, reviewers, editors and partner institutions whose dedication has made this issue possible. We also acknowledge the continued support of the Kenya Marine and Fisheries Research Institute (KMFRI) and collaborating organizations in advancing aquatic science. We trust that the knowledge shared in this volume will contribute meaningfully to informed decision-making and the sustainable stewardship of Kenya's invaluable aquatic resources.

Chief Editor:

Dr. Melckzedek K. Osore, Kenya Marine and Fisheries Research Institute, Mombasa, Kenya

Editors:

Dr. Christopher Aura, KMFRI, Kisumu, Kenya
Ms. Josephine M. Njeru, KMFRI, Mombasa, Kenya

Guest Editors:

Ms. Joan Karanja, KMFRI, Mombasa, Kenya
Faith Nicolyn Achieng' Gwada, KMFRI, Mombasa, Kenya
Dr. Amon Kimeli, KMFRI, Mombasa, Kenya
Dr. Chrisphine Nyamweya, KMFRI, Kisumu, Kenya
Thomas K. Nyamai, KMFRI, Mombasa, Kenya

Copy Editor, Graphics Design and Layout:

Gordon O. Arara, Freelance Graphic Designer, Nairobi, Kenya

About Kenya Aquatica

Kenya Aquatica is the Scientific Journal of the Kenya Marine and Fisheries Research Institute (KMFRI). The aim of the Journal is to provide an avenue for KMFRI researchers and partners to disseminate knowledge generated from research conducted in the aquatic environment of Kenya and resources therein and adjacent to it. This is in line with KMFRI's mandate to undertake research in "marine and freshwater fisheries, aquaculture, environmental and ecological studies, and marine research including chemical and physical oceanography", in order to provide scientific data and information for sustainable development of the Blue Economy.

Disclaimer: Statements in the Kenya Aquatica reflect the views of the authors and not necessarily those of KMFRI or the Editor

KENYA AQUATICA SCIENTIFIC JOURNAL OF THE KENYA MARINE AND FISHERIES RESEARCH INSTITUTE

Volume 10, Issue No. 02 (March 2026)

Subscription Information

The Kenya Aquatica is published semi-annually. It is an open access journal available online at www.kmfri.co.ke

ISSN 2077-432X (print)



ISSN2077-432X-4-1

ISSN 2617-4936 (online)



ISSN2617-4936-4-1

Hard copies may be obtained free of charge from the Kenya Marine and Fisheries Research Institute.

Submitting Articles

Submissions to the Kenya Aquatica Journal are accepted year round for review. Manuscripts may be submitted to the Chief Editor through aquatica@kmfri.go.ke

Featured front cover picture: Diving for knowledge - KMFRI researcher Dr. Juliet Furaha uncovering the rich coral heritage of the Indian Ocean.

Featured back cover picture: Researcher sampling surface plankton in the Kerio River inlet to Lake Turkana. (Photo credit: Mr. John Malala)

Contents

Horizons of opportunity: Seaweed farmer perceptions on adopting deep-water *Cottonii* production in Kenya's South Coast

Faith Kimanga, Edward Waiyaki, Hellen Ngoa, Fridah Munyi, Nicholas Karani, Stephen Makupe, Jacob Ochiewo

6 – 21

Heavy metal contamination in Mombasa's coastal waters and sediments: a systematic review of sources, distribution, ecological risks, and management implications (2015–2024)

Justine Rutto

22 – 32

The Omena (*Rastrineobola argentea*) Value Chain in Lake Victoria: Livelihoods, Gender Dynamics, and Constraints Among Small-Scale Actors

Kevin Victor Onsongo, Jane Fonda Awuor, Patrick Wanguche Otuo, Susan Wandago, Christopher Mulanda Aura, Chrispine Nyamweya, Venny Mziri, Melckzedek Osore, Paul S Orina

33 – 50

Lagrangian modeling of marine plastic debris transport in the western Indian Ocean: effects of currents, wind, and diffusion

Athman Salim Hussein, Charles Mitto

51 – 56

A participatory research approach for marine conservation in Bofa-Kilifi, Kenya

Jelvas Mwaura¹, Siana Philips and Thomas Sagimo

57 – 68

Nile tilapia (*Oreochromis niloticus*) invasion of a saline-alkaline meromictic crater lake in Kenya's Great Rift Valley: implications for management and conservation

Edna Waithaka¹ James Last Keyombe, Alice Mutie, Salima Otieno

69 – 76

Structure and organization of Omena (*Rastrineobola argentea*) fishing enterprises in Lake Victoria, Kenya: labour, income distribution and gender dynamics

Susan Atieno Wandago, Christopher Mulanda Aura, Chrispine S. Nyamweya, Venny Mziri, FondaJane Awuor, Patrick Wanguche Otuo, Victor Kevin Onsongo, Melckzedek Osore, Paul S. Orina

77 – 97

Characterization of the mud crab (*Scylla serrata*) market chain in Kilifi County, Kenya: A reconnaissance survey

Edward Waiyaki, Esther Fondo, Elisha Mrabu, Hellen Ngoa, Faith Kimanga, Stephen Makupe and Nicholas Karani

98 – 109

Optimizing salinity for enhanced reproductive performance of the Kenyan *Artemia franciscana* population

Derick Gitari, Morine Mukami, Sheban Hinzano, David Midumbi, Anthony Nzioka, Mary Opiyo, Cosmas Munga, Miriam Wainaina and Betty Nyonje

110 – 118

Socio-economic determinants and user perceptions of solar cooling and drying (SolCoolDry) technology for fish preservation in Kwale County, Kenya

Josephine Marigu, Morine M. Ngarari, James Mwaluma, Peter Oduor-Odote, Raymond Ruwa, Winnie Jefwa, Derrick Gitari, Immaculate Kinyua, Maureen Kinyua, Rael Achieng', Linus Kosambo, Huxley Makonde

119–137

Horizons of opportunity: Seaweed farmer perceptions on adopting deep-water *Cottonii* production in Kenya's South Coast

Faith Kimanga^{1*}, Edward Waiyaki¹, Hellen Ngoa¹, Fridah Munyi¹, Nicholas Karani¹, Stephen Makupe¹, Jacob Ochiewo¹,

¹Kenya Marine and Fisheries Research Institute, Socioeconomics Directorate, P.O. Box 81651-80100 Mombasa, Kenya

*Corresponding author E-mail: fkimanga@kmfri.go.ke

Abstract

Seaweed farming is a vital livelihood for Kenya's coastal communities, but nearshore cultivation of *Kappaphycus alvarezii* (*Cottonii*) is increasingly constrained by heat stress, disease, and herbivory. Deep-water cultivation offers a potential response to these biophysical challenges. This study examined seaweed farmers' perceptions of adopting deep-water *K. alvarezii* cultivation along Kenya's south coast, focusing on socio-economic factors, perceived benefits, and adoption barriers. Using an exploratory cross-sectional design, 41 predominantly female farmers in Kibuyuni village, Kwale County, were interviewed with a semi-structured questionnaire. Data was analyzed using descriptive statistics and thematic analysis of open-ended responses. Although 95% of respondents were willing to engage in deep-water cultivation, participation depended mainly on adequate training, suitable equipment, and assured market access. Farmers perceived key benefits, including reduced crop losses from herbivorous fish grazing and sedimentation. Major barriers included inadequate boats and equipment, limited technical skills, increased labor demands, and occupational safety risks, particularly drowning. Deep-water *K. alvarezii* farming could improve production resilience and farmer incomes, but adoption requires targeted, participatory support addressing safety, market linkages, technical capacity, infrastructure limitations, and women's equitable participation.

Keywords: Seaweed farming; *Kappaphycus alvarezii*; deep-water cultivation; gender; blue economy; Kenya; technology adoption; occupational safety

Introduction

The global carrageenan market has driven the expansion of eucheumatoid farming from its origins in the Philippines to become the world's largest cultivated marine plant biomass by volume. *Kappaphycus alvarezii*, commonly known as *Cottonii*, represents one of the most commercially significant tropical red seaweeds globally, primarily cultivated for its high kappa-carrageenan content which is a sulphated polysaccharide widely used as a thickening and stabilizing agent in food, pharmaceutical, and

cosmetic industries (Bixler & Porse, 2011). The domestication and commercialization of *Kappaphycus* began in the Philippines during the late 1960s, with the development of the fixed-bottom monoline method that revolutionized tropical seaweed aquaculture. This innovation spread rapidly throughout Southeast Asia, particularly to Indonesia, which has since become the dominant global producer (Valderrama *et al.*, 2015). From Asia, cultivation technology was transferred to other tropical regions, including the Western Indian Ocean, Pacific Islands, Latin America, and the Caribbean.

However, global experience has consistently demonstrated that *Kappaphycus* farming faces significant biophysical constraints. Hayashi *et al* (2010) synthesized decades of research identifying the primary challenges as thermal stress, “ice-ice” disease (a pathogenic condition causing thalli to whiten and disintegrate), epiphyte infestation, and herbivory. Seasonal fluctuations in temperature, water movement, and nutrient availability exacerbate these constraints. Ask and Azanza (2002) documented that optimal growth requires water temperatures between 27 – 30°C, moderate water movement, and high-water transparency conditions increasingly difficult to maintain in nearshore areas subject to anthropogenic and climate-induced stressors. The technological response to these constraints has included the development of deep-water farming techniques. Hurtado and Agbayani (2002) demonstrated the efficacy of the multiple raft, long-line method for deep-sea cultivation in the Philippines, showing that moving farms offshore reduced disease incidence and grazing pressure while improving growth rates. This innovation provided the template for subsequent deep-water trials in other regions, including East Africa.

Seaweed farming was introduced to Africa in the late 1980s, with Tanzania (specifically Zanzibar) serving as the regional entry point for eucheumatoid cultivation (Msuya *et al.*, 2014). From Tanzania, the technology diffused to other Western Indian Ocean countries, including Kenya, Mozambique, and Madagascar, though with variable success.

A distinct gender dimension has characterized the African experience. Across the continent, seaweed farming emerged as a female-dominated livelihood, providing women with independent income in coastal contexts where formal employment opportunities for women are severely limited (Odhiambo *et al.*, 2020; Mireira *et al.*, 2020). In Tanzania, over 80% of seaweed cultivators are women, and the sector has become the country’s second-largest export crop. However, African seaweed farmers have confronted the same biophysical con-

straints documented globally, compounded by region-specific challenges. Bryceson (2002) analyzed coastal aquaculture developments in Tanzania and identified the vulnerability of *Kappaphycus* to temperature fluctuations and disease outbreaks as critical limitations to production stability. Msuya and Porter (2014) documented how rising sea surface temperatures in the Western Indian Ocean have progressively rendered traditional shallow-water farming areas less productive, forcing farmers to consider offshore expansion.

The Western Indian Ocean (WIO) region represents a distinct biogeographic and socioeconomic context for seaweed farming. Msuya *et al* (2014) provided a comprehensive assessment of red seaweed cultivation and utilization across the WIO, documenting production in Tanzania, Kenya, Madagascar, and Mozambique. Their analysis revealed that regional production stood at approximately 15,966 metric tons (dry weight) annually as of 2012, valued at US\$4.2 million, with Tanzania accounting for 95% of this volume. The dominance of Tanzania reflects its earlier adoption of farming technology and more developed market linkages. A critical regional dynamic identified by Msuya *et al* (2014) is the differential performance of *Kappaphycus alvarezii* versus *Eucheuma denticulatum* (Spinosum).

While *Cottonii* commands premium prices for its superior kappa-carrageenan yield, it is more susceptible to thermal stress, herbivory, epiphytic infestation and ice-ice disease throughout the WIO (Msuya, 2013; Valderrama *et al.*, 2015). This has created a production dilemma: farmers face strong economic incentives to cultivate the higher-value species but confront greater crop failure risks. The authors noted that new efforts are being made to curb these problems, including moving seaweed farms to deeper waters.

Comparative research by Kimathi *et al.* (2018) provided critical insights into species and technique performance along Kenya’s coast. Their study compared relative growth rates of *Eucheuma denticulatum* and *Kappaphycus alva-*

rezi under modified off-bottom and floating raft techniques at two sites: Mkwiro and Kibuyuni. Results demonstrated significant seasonal variability, with growth rates ranging from 0.9 – 10.2% per day for *Eucheuma* and 1.7 – 5.7% per day for *Kappaphycus*. Critically, the floating raft technique produced significantly higher growth rates ($4.3 \pm 0.4\%$ per day) than the modified off-bottom method ($3.2 \pm 0.4\%$ per day), providing empirical support for deep-water or floating cultivation approaches.

The study also confirmed the differential vulnerability of the two species: “*Kappaphycus alvarezii* exhibited lower growth rates due to higher herbivory, epiphytes, and susceptibility to ‘ice-ice’ disease”. This finding underscores the technical challenge facing Kenyan farmers who wish to transition from the more resilient but lower-value *Eucheuma* to the premium but sensitive *Kappaphycus*. The authors recommended “further research on the stability of off-bottom methods in deep water and accessibility of floating raft techniques before commercial adoption”.

Yet despite this regional momentum toward deep-water cultivation as a response to biophysical stress, no published study has examined how Kenyan farmers themselves perceive, and are willing to act on, the shift from shallow water to deep-water *Cottonii* production. Seaweed farming in coastal Kenya has historically focused on *Eucheuma denticulatum* (locally known as “*Spinosum*”), which is more tolerant of shallow-water temperature fluctuations but commands lower market prices than *Kappaphycus alvarezii* (“*Cottonii*”).

In response to declining productivity in near-shore farms, the Kenya Marine and Fisheries Research Institute (KMFRI) has promoted experimental deep-water *Cottonii* farming techniques in areas such as Kibuyuni (Kwale County). Deep-water methods aim to mitigate heat stress and herbivory by relocating farms offshore, typically requiring boats, div-

ing capacity, and new skills. While technical trials of deep-water methods have shown promise in Kenya (Kimathi *et al.*, 2018), the social and economic dimensions of adopting this technology, specifically the perceptions, willingness, and constraints of the farmers themselves, remain underexplored. This paper addresses this gap by presenting an analysis of survey data collected from seaweed farmers in Kibuyuni regarding their perceptions of deep-water *K. alvarezii* farming. The objective of this study was to assess the socio-economic factors, perceived benefits, and barriers influencing the adoption of deep-water *K. alvarezii* cultivation among farmers in Kenya’s south coast.

Methodology

Study Area

The survey was conducted in Kibuyuni village, located within the Lunga Lunga Sub-County of Kwale County along Kenya’s south coast. The subset of surveyed respondents was from the adjacent village of Kijiweni. As the site of KMFRI’s deep-water trials, Kibuyuni provided a suitable setting for assessing farmers’ awareness and perceptions of the ongoing intervention (Muthama *et al.*, 2021).

Sampling and data collection.

A purposive sampling strategy was used to select respondents. The sample of 41 farmers represents the core group actively involved in, or adjacent to, KMFRI’s deep-water trials in Kibuyuni, making them key informants on the subject. This selection bias would likely overstate the levels of awareness, trust, and willingness that would be found among the broader, less-exposed seaweed farming population on Kenya’s south coast. The sample size ($n=41$), while modest, constitutes a significant portion of the active shallow-water seaweed farming community engaged with this innovation in the village.

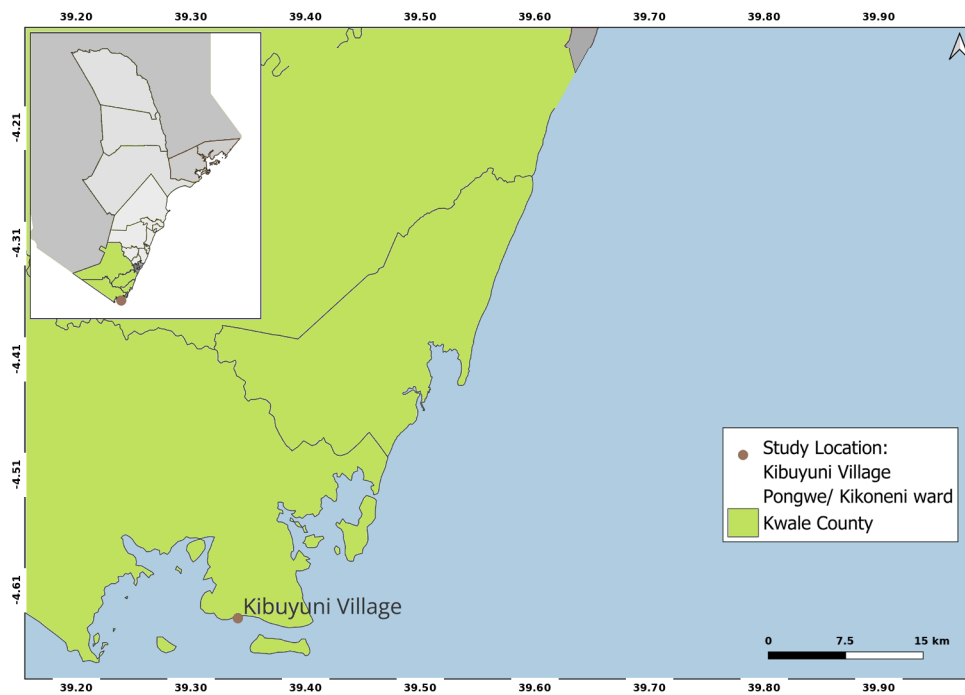


Figure 1: A map showing the study site in Kenya's south coast.

Material

The study used a semi-structured questionnaire with closed-ended questions to collect demographic data and quantifiable perceptions, and open-ended questions to capture detailed qualitative insights on motivations, concerns, and conditions for adoption. The two methods captured: a) demographic characteristics; b) historical farming experience of *Cottonii*; c) awareness and sources of information regarding deep-water *Cottonii* techniques; d) perceived economic, social, gender, health, and environmental implications; and e) willingness to invest, train, and participate in future programs.

Procedure

At the start of the exercise, we introduced ourselves and our employer and then explained the purpose of the survey to each prospective respondent. The interviewer then obtained the farmer's consent before beginning the interview. Respondents were assured that their responses would remain strictly confidential and would be used only for research purposes. They were also informed that providing personal details, such as names and age, was entirely voluntary. Each interview lasted approximately 20–30 minutes.

After completing the survey, respondents were thanked for their cooperation and allowed to leave.

Data Analysis

Data was analyzed in SPSS version 22 using descriptive statistics, including frequencies and proportions. Responses to open-ended questions were analyzed thematically to identify recurring patterns, concerns, and conditions raised by respondents.

Although the sample size was modest, it represented a substantial share of the farmers involved in deep-water farming trials in the village and provided rich, indicative data for programmatic decision-making.

Ethical considerations

Prior to data collection, ethical approval was obtained from the KMFRI's Scientific Steering Committee. Informed consent was obtained verbally from all participants after explaining the purpose of the study, ensuring confidentiality of their responses, and confirming their right to withdraw at any time. No personal identifiers were included in the final dataset to protect respondent anonymity.

Results

Demographic characteristics of seaweed farmers

The survey collected responses from 41 individuals in Kibuyuni and Kijiweni villages, with most respondents (95%) residing in Kibuyuni. The sample was predominantly female, with wom-

en comprising 83% of respondents. The survey conducted in Kibuyuni and Kijiweni villages, which drew responses from 41 individuals, with the vast majority (95%) residing in Kibuyuni, presents a predominantly female demographic profile, with women constituting 83% of the respondents. This gender imbalance indicates that the findings primarily reflect women's perspectives and experiences, likely because women are both key household managers and most seaweed farmers in coastal Kenya. With an average age of 43 years, the respondent group is largely middle-aged, and the majority (70%) are married, pointing towards a stable, traditional family structure. This stability is further reflected in the household composition, where an overwhelming 93% of respondents have children. The household statistics reveal a community characterized by large family units, with an average household size of seven people and an average of five children per household. The dependency burden is particularly pronounced, as households care for an average of three children under the age of eight, placing significant strain on limited resources. Perhaps the most critical finding, however, is the respondents' educational profile, which reveals a stark barrier to socio-economic advancement. Over half of those surveyed (54%) have received no formal education whatsoever, and while 22% have completed primary school, access to secondary and higher education remains minimal. This combination of large family sizes, high dependency ratios, and extremely low educational attainment, particularly among the women who were the primary respondents, paints a picture of a community facing substantial challenges in breaking cycles of poverty and accessing economic opportunities.

Historical farming experience with *Cottonii*

An assessment of the community's historical engagement with seaweed farming reveals that the majority of respondents are not novices to aquaculture, but rather experienced farmers who have grappled with significant production challenges. A substantial 85% of those surveyed had previously attempted to cultivate *Cottonii* in shallow-water settings, indicating that the

concept of seaweed farming is deeply embedded in the local livelihood portfolio. This high rate of prior experimentation suggests that any resistance to the new deep-water technology is unlikely to stem from a fear of the unknown or a reluctance to try aquaculture altogether. Instead, the community's current posture towards seaweed farming is shaped by a collective memory of past failures, which have been both frequent and demoralizing. The reasons cited for crop failure paint a comprehensive picture of a hostile farming environment where multiple stressors converge to undermine production.

Farmers reported a trifecta of challenges that, in combination, made shallow-water farming economically precarious. Biologically, the crops were vulnerable to intensive grazing by local herbivores, particularly rabbitfish from the family Siganidae and sea urchins (*Tripneustes gratilla*), which directly consumed seaweed and caused physical damage to the thalli. Environmentally, the shallows exposed the *Cottonii* to recurrent "heat stress," which manifested as bleaching and rendered the plants susceptible to the debilitating ice-ice disease. This condition, well-documented in seaweed pathology as a response to environmental stress where the algal thallus turns white, softens, and eventually disintegrates (Largo *et al.*, 1995), was a recurring obstacle that farmers observed but could not control. Physically, the seasonal reality of the southeast monsoon winds and rains introduced a period of turbulence that battered the farms, causing physical damage and the outright loss of crops. In many cases, farmers reported that the crop would simply "disappear" or rot, a frustrating outcome that was likely the culmination of these biological, environmental, and physical stressors acting in synergy. This history of accumulated loss is not merely a technical footnote; it is a psychological and economic reality that shapes current attitudes. For these farmers, the proposition of deep-water farming is not evaluated against a blank slate, but against a backdrop of hard-won experience where the sea has proven to be an unpredictable and often unforgiving partner. Their willingness to engage with new methods is therefore contingent on seeing a clear and credible path that avoids repeating the painful lessons of the past.

Awareness of deep-water *Cottonii* farming

An examination of community awareness and institutional exposure reveals that the concept of deep-water *Cottonii* farming has achieved near-universal recognition among the respondents, with approximately 90% of the respondents indicating that they had heard of this specific aquaculture method. This high level of awareness is a direct result of targeted outreach primarily by KMFRI, which respondents consistently

but rather as a tangible, proximate intervention actively being tested within their local marine environment.

However, while awareness is an essential first step, a deeper analysis of the data suggests that it is merely the foundation upon which further understanding must be built. The concept of adoption in agricultural and marine farming contexts is complex, and awareness alone is a necessary but insufficient condition for behavior change.

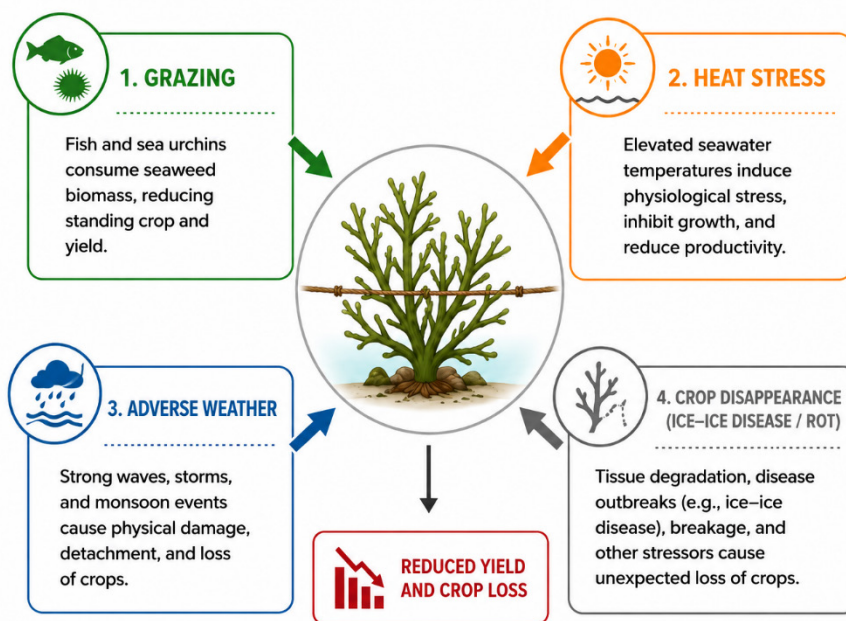


Figure 2: Showing drivers of *Kappaphycus alvarezii* (*Cottonii*) farming failures in shallow waters.

identified as both the primary source of their information and the most trusted source of information. This finding aligns with broader research on agricultural extension in coastal Kenya, which has documented KMFRI's successful community engagement strategies and their role in disseminating marine farming innovations (KMFRI, 2020). The trust vested in KMFRI is a critical asset for any development initiative, as it implies that the messenger is as important as the message itself; communities are more receptive to innovations endorsed by an institution with which they have an established, positive relationship. Furthermore, respondents demonstrated a general awareness of ongoing trials and pilot projects in their vicinity, indicating that deep-water *Cottonii* farming is not perceived as a distant or abstract concept,

The data highlights an important nuance: although the community is aware of the technology and trusts the institution promoting it, farmers' technical understanding of its risks, labor demands, and management requirements remains limited. This gap suggests that enthusiasm may exceed practical readiness. Project implementers should therefore move beyond general awareness-raising toward intensive, participatory training that addresses farmers' practical questions about how deep-water farming can be done safely and profitably. Without this technical support, the 90% awareness rate may translate only into initial

interest rather than sustained adoption. KMFRI's strong community trust provides an effective platform for this next phase, but engagement must now focus on practical implementation within the socio-economic realities of local fishing households.

Economic perceptions: high optimism and willingness to invest

The economic aspirations attached to deep-water *Cottonii* farming reveal a community at the intersection of hope and calculated risk, with a striking 95% of respondents expressing the belief that this innovation will substantively increase both household incomes and local employment opportunities. This optimism is rooted in a subtle

understanding of how technology could address historical production failures. Farmers articulated a multifaceted vision of economic improvement, beginning with the expectation of higher production volumes driven by faster growth rates in the deeper, more optimal marine conditions. They linked this anticipated productivity gain directly to higher production and better prices, recognizing that *Cottonii* commands a premium in regional and international markets compared to other seaweed species. This price advantage, however, was understood to be contingent on quality and consistency, leading respondents to also emphasize improved market access as a key benefit; they articulated a clear logic that a reliable, high-quality supply would attract more buyers to the village, potentially stabilizing prices and reducing the vulnerability associated with dependence on a single, inconsistent buyer. Beyond direct farm income, the community demonstrated a sophisticated appreciation for ripple effects, specifically identifying employment generation for youth and casual laborers as a critical benefit. They envisioned roles in boat operation, farm maintenance, and post-harvest handling, recognizing that the transition to deep-water systems would create a new tier of paid labor that could absorb some of the underemployed young people in the village, thereby addressing both economic and social pressures.

Perhaps the most telling indicator of genuine economic commitment, however, lies in the willingness of these predominantly low-income households to invest their own scarce resources. Despite living

with the precarity that defines coastal poverty, most respondents expressed a readiness to contribute modest personal funds, commonly in the range of KES 3,000 to 5,000 equivalent to USD 23.26 to 38.76, respectively towards the establishment of deep-water farms. This stated willingness to invest represents a critical threshold moving from passive reception to active economic participation and risk-sharing. It signals that the community perceives deep-water farming as a credible opportunity worthy of their scarce resources. However, this commitment places a huge responsibility on implementing agencies: farmers are not just beneficiaries but stakeholders putting their own capital at risk, requiring equally robust technical support, market linkages, and risk mitigation strategies.

Health and safety concerns: acknowledging the new risks of an offshore environment

The transition from familiar, sheltered intertidal zones to the open waters required for deep-water *Cottonii* farming introduces a new dimension of risk that the community has not previously had to negotiate. Critically, the respondents demonstrated a high degree of risk literacy, with a majority explicitly identi-

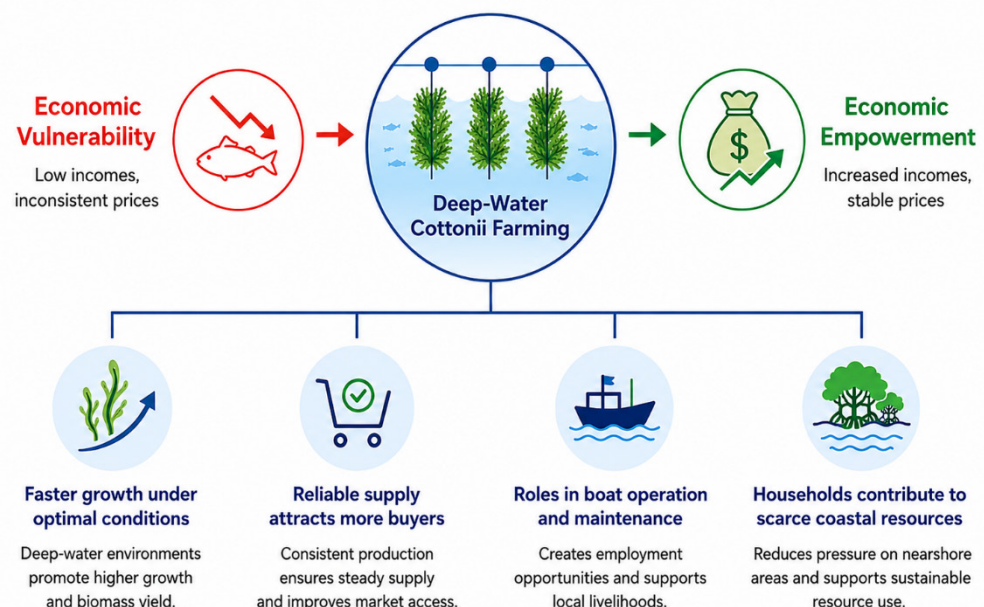


Figure 3: Perceptions of *Cottonii* farming economic outputs.

fying significant health and safety concerns associated with offshore farming. This awareness underscores that the community is not approaching innovation with naive enthusiasm, but rather with a clear assessment of the new hazards they would face. Foremost was the fear of drowning, particularly acute given that many women the primary shallow-water farmers, have limited or no swimming proficiency. The sea, which has been a source of livelihood, is also understood as a potential site of mortality, and the prospect of working regularly in deeper water amplifies this existential anxiety. Beyond the risk of drowning, respondents enumerated other marine hazards, including stings from jellyfish and rays, and bites from venomous fish, risks grounded in lived experience with local waters. These are not abstract fears but are grounded in lived experience; these are waters the community knows intimately, and they are acutely aware of the creatures that inhabit them.

Beyond acute biological hazards, respondents also identified chronic physical risks linked to the labor demands of offshore farming. Prolonged exposure to cold water and wind raised concerns, which can impair judgment and physical performance. Farmers also noted that heavy lifting, especially pulling wa-

terlogged ropes and harvesting from depth, could cause injury and long-term musculoskeletal strain. These responses show that farmers understand occupational hazards as both immediate risks and cumulative physical burdens. However, the most important finding was not simply the presence of fear, but the community's conditional willingness to manage these risks.

Crucially, the perception of these significant health and safety risks did not lead to categorical refusal or a rejection of the entire enterprise. Instead, many respondents engaged in a sophisticated risk-benefit analysis, qualifying their concerns by stating that proper training, the provision of safety equipment such as life jackets and flotation devices, and access to well-maintained, seaworthy boats could effectively mitigate these dangers. This conditional willingness suggests the community is articulating the necessary conditions for a social and physical safety net that would make offshore farming acceptable. The implication for implementing agencies is clear: occupational health and safety are not ancillary add-ons but fundamental prerequisites for ethical and sustainable adoption. The community has signaled that they are willing to venture into deeper waters, but they will only do so if they are equipped and trained to return safely.

Gender implications: the potential for occupational restructuring

The transition from shallow water to deep-water *Cottonii* farming carries profound implications for the gendered division of labor within these coastal communities, potentially restructuring not only who works but also how value, skill, and economic control are distributed within households and the wider community. A dominant and recurring theme emerging from the survey was the near consensus that this technological shift would fun-

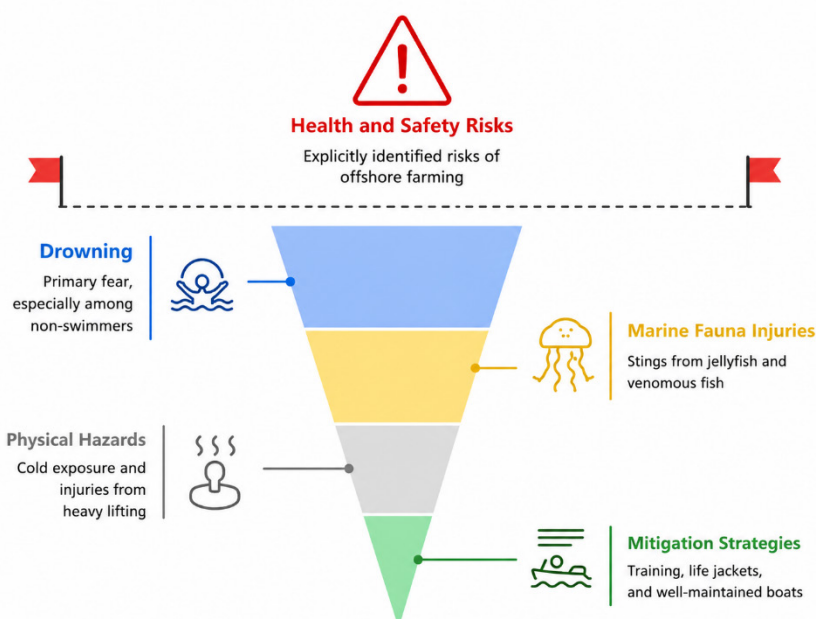


Figure 4: Perceptions on the health and safety risks when deep farming *Cottonii*.

damentally alter the gender composition of the farming workforce, necessitating a greater and more direct involvement of men. Respondents articulated a clear rationale: the physical and technical demands of offshore farming diverge sharply from the traditional female-dominated labor of shallow-water cultivation. Tasks such as diving to secure anchor points, navigating boats to and from farm sites, and managing the heavy initial setup of submerged lines and floating structures were consistently coded as masculine work. This perception is rooted in practical realities; in many coastal communities, swimming and boat-handling skills have historically been transmitted to boys and men, while women, even those who are seaweed farmers, often remain in the intertidal zone. The result is a potential occupational shift where men, who may have been marginally involved or absent from shallow-water farming, become the primary operators and, by extension, the primary earners in the deep-water enterprise.

This anticipated shift prompted a significant and telling response from many women respondents, who indicated they would adapt by hiring male labor or relying on male family members for offshore components while retaining oversight of other aspects. This strategy demonstrates entrepreneurial flexibility but carries inherent risks of economic marginalization, if men become the primary operators and deep-water farming is perceived as the primary source of value, women risk being relegated to secondary, lower-paid post-harvest roles.

However, the narrative was not monolithic, and a minority of respondents, often younger women, offered a countervailing perspective. These individuals acknowledged that

with targeted training and support, women could and should participate directly in all aspects of deep-water farming. This viewpoint challenges the assumption that the offshore environment is inherently masculine and asserts a claim for women's right to access the full range of opportunities and skills associated with the innovation. These younger women recognized that the barriers are not biological inevitabilities but socially constructed skill deficits that could be addressed through intentional programming. Their perspective highlights a critical choice point for implementing agencies. The transition to deep-water farming is not a gender-neutral technical adjustment; it is a moment of occupational restructuring that will either entrench existing gender inequalities or create pathways for more equitable participation. If projects default to training only men in swimming, boat handling, and diving, they will inadvertently engineer a male-dominated deep-water sector. Conversely, if they actively recruit and support young women to acquire these same skills, they can challenge entrenched norms and ensure that women are not left behind as the industry evolves. The gender implications of this transition are therefore not predetermined; they will be shaped by the deliberate choices made in project design, training curricula, and resource allocation (Figure 5). The voices of those younger women serve as a reminder that the future of work in this community is still being written, and there is an opportunity to write a more inclusive chapter.



Figure 5: Perceptions on gender implications of deep Cotonii farming.

Environmental perceptions: an awareness of ecosystem interactions

The community's engagement with the prospect of deep-water *Cottonii* farming extends beyond economic calculations and safety concerns to encompass a sophisticated and nuanced understanding of the potential environmental implications of this technological transition. Farmers demonstrated that their knowledge is not confined to practical cultivation techniques but includes a keen awareness of how their proposed farming activities would interact with the broader marine ecosystem. This ecological literacy is a critical asset, as it positions the community as informed stakeholders capable of participating in discussions about sustainable resource management rather than passive recipients of externally designed interventions. The perceived environmental benefits articulated by respondents reveal a hopeful vision of coexistence between aquaculture and the surrounding ecosystem. A prominent expectation was that the offshore farm structures would function as Fish Aggregating Devices (FADs), attracting a diversity of fish species to the vicinity of the farms. This expectation is not merely wishful thinking but is grounded in documented ecological observations; research has confirmed that floating structures in the ocean do indeed create artificial habitats that concentrate fish populations (Bergman *et al.*, 2001). For the community, this potential benefit represents a dual-use opportunity, where seaweed farming could simultaneously support fisheries by enhancing fish stocks in accessible offshore areas, potentially benefiting both farmers and artisanal fishers. Furthermore, respondents demonstrated a clear understanding that relocating farms offshore would alleviate the physical pressure on the fragile intertidal zone, reducing trampling and anchoring damage to seagrass beds and reef flats, aligning with scientific literature on ecological impacts of intertidal aquaculture (Eklöf *et al.*, 2006). and it reflects a community ethic that values the health of the near-shore environment upon which so many other livelihood activities depend.

However, this environmental awareness was balanced by an equally clear-eyed assessment of the potential ecological and spatial risks associated with offshore farming. A recurring concern among respondents was the issue of marine litter, specifically the prospect of abandoned, degraded, or broken polypropylene ropes and lines contributing to the already pervasive problem of plastic pollution in the ocean. Farmers, who witness daily the impact of marine debris on their shores and fishing grounds, were acutely sensitive to the irony of introducing a "clean" economic activity that could itself become a source of pollution if not managed responsibly. This concern signals a willingness to engage in discussions about sustainable materials and end-of-life infrastructure planning. In addition to pollution, respondents identified the potential for user conflicts with artisanal fishers who have traditionally navigated and fished in the deeper channels and offshore areas now being considered for farm placement. This recognition of spatial competition demonstrates an understanding that the ocean is not a space but a contested common, already parceled by customary use patterns and livelihood practices. The prospect of excluding fishers from productive grounds or creating navigational hazards was acknowledged as a genuine risk requiring consultation and negotiation. Finally, farmers expressed a keen awareness of the increased weather vulnerability associated with offshore farming. Having witnessed the destructive power of the south-east monsoon from the safety of the shore, they understood that moving farms into exposed waters would render them more susceptible to storm damage, crop loss, and infrastructure destruction during rough weather. This perception is not a barrier to adoption but a call for robust farm design, strategic site selection, and perhaps insurance or risk-sharing mechanisms. Collectively, these perceptions reveal a community thinking holistically about the transition, weighing ecological benefits against potential costs, and implicitly demanding that implementation be conducted with care for the marine environment. Their awareness transforms them from potential adopters into potential stewards, provided their knowledge is respected through participatory planning and adaptive management.

Willingness to train and participate

The overwhelming willingness to engage with the proposed deep-water farming intervention constitutes one of the most encouraging yet conditionally complex findings of the entire survey, with a approximately 95% of respondents expressing a clear desire to receive training and to participate actively if the intervention were formally introduced. This near-universal enthusiasm transcends passive acceptance and signals a genuine appetite for change within a community that has grown weary of watching production failures. It reflects a population that is not trapped in fatalistic resignation but is instead poised and ready to invest their time, energy, and hopes in a new venture that promises to address the chronic production failures they have endured for years. However, to interpret this 95% figure simply as unqualified eagerness would be to miss the critical nuance embedded within the responses. Farmers made it abundantly clear that their willingness was decidedly conditional, articulating a set of preconditions distilled from hard-worn experience.

Foremost among these preconditions was access to boats, a critical capital constraint that represents the single most significant barrier to entry for individual households. Unlike shallow-water farming, which requires little more than a pair of legs and some string, deep-water farming demands seaworthy vessels capable of transporting farmers, equipment, and harvested crops safely to and from offshore sites. For households living on the economic margin, the cost of a reliable boat is prohibitive, and farmers made it clear that without some mechanism for accessing this essential capital asset, their participation would remain impossible, regardless of their willingness. Closely linked to this was the demand for a reliable seed supply, a precondition that speaks to the fundamental bottleneck in seaweed farming systems globally. Farmers know from bitter experience that the quality and availability of seedlings at planting time determine the entire production cycle; poor-quality seed leads to disease susceptibility, slow growth, and ultimately crop failure (Hurtado *et al.*, 2013). They are asking for assurance that this

foundational input will be consistent, healthy, and accessible when needed, rather than leaving them to scramble for substandard planting material as the planting season arrives. Beyond inputs, farmers demanded market assurance, a condition born of the vulnerability inherent in producing a perishable commodity for volatile markets. They have experienced the power imbalance of facing buyers alone, accepting whatever price is offered because the alternative is watching their harvest rot on the beach. Their demand for guarantees of a buyer and a stable, fair price is not a request for charity but a call for market infrastructure that can absorb their production reliably and reward their labor predictably. Finally, and perhaps most tellingly, respondents insisted on transparent management structures for any cooperative or group-based enterprise that might emerge. This precondition reflects a deep-seated wariness born of past experiences with mismanaged community projects, where unclear governance, opaque finances, and unequal power dynamics have undermined collective efforts and eroded trust. Farmers are effectively stating that they will not invest their limited time and meager resources into an organization whose rules, leadership, and financial flows are hidden from view. They demand clarity, accountability, and a voice in the decisions that will affect their livelihoods. Collectively, these conditions transform the 95% willingness from a simple statistic into a complex social contract. The community is signaling readiness to invest their labor, but requires the enabling conditions of boats, seeds, markets, and transparent governance, for their hard work to translate into sustainable success.

Discussion

The findings from Kibuyuni village paint a compelling portrait of a farming community standing at a critical crossroads, poised between the familiar hardships of shallow-water farming and the uncertain promise of an offshore future. These respondents are not passive recipients of an external intervention but are rather informed actors who possess high awareness of deep-water Cottonii technology, grounded economic optimism about its potential, and

a strong conditional willingness to engage with the innovation. Their historical experience with recurrent crop failure driven by biological stressors like rabbitfish grazing, environmental pressures such as heat stress and ice-ice disease, and physical losses during monsoon seasons provides a powerful motive for change (Largo *et al.*, 1995). They have endured the frustration of watching their crops “disappear” or rot, and they understand that the shallow-water model has reached its productive limits. Moreover, their nuanced perceptions of the new risks associated with offshore farming, their sophisticated understanding of gendered labor implications, and their awareness of potential environmental interactions all indicate a capacity for sophisticated decision-making that should be respected and harnessed by implementing agencies. This is a community that has learned hard lessons from the past and is applying that wisdom to evaluate a proposed future. Their near-universal willingness to participate, contingent on specific enabling conditions, represents not naivety but a reasoned calculation: they will invest their labor and limited capital if, and only if, the structural barriers that have defeated previous efforts are systematically addressed. However, translating this potential into sustainable success requires confronting three critical structural tensions that emerge from the data, each of which must be intentionally addressed through program design rather than left to resolve itself through market forces or community adaptation.

Gendered Access to Offshore Space

The first and perhaps most fundamental tension concerns gendered access to offshore space. The historical pattern of seaweed farming in this region, as documented in recent research from the very same communities, reveals that women have dominated the activity at farming and processing levels while men have largely controlled marketing (Fröcklin *et al.*, 2012; Williams, 2018). The transition to deep-water farming threatens to disrupt this gendered division of labor in ways that could systematically disadvantage women. If, as respondents anticipated, men become the primary operators of boats, divers for anchor placement, and man-

agers of offshore lines, women risk being transformed from direct producers with economic agency into “farm owners” who hire male labor or depend on male relatives. This shift could erode the economic autonomy that seaweed farming has historically provided to women in coastal communities (UNCTAD, 2023). The risk is not merely hypothetical; research from Tanzania indicates that despite women comprising 67% of seaweed producers, structural barriers, including limited access to extension services and climate-resilient technologies, continue to reinforce existing inequalities (UNCTAD, 2023). Interventions must therefore be explicitly designed to build women’s technical capacity in swimming, diving, and boat handling, perhaps through women-only training cohorts and the provision of appropriate, safe technologies that accommodate different skill levels and comfort zones (Fröcklin *et al.*, 2012; Williams, 2018). This requires moving beyond rhetorical commitments to gender equality and allocating real resources to skills development, recognizing that without deliberate intervention, the offshore transition could inadvertently concentrate new wealth and power in male hands while women are relegated to lower-paid post-harvest roles. The younger women in the community who expressed willingness to participate directly in all aspects of deep-water farming signal that gender norms are not immutable; they are waiting for an invitation and the enabling conditions to claim their place in the offshore future.

Occupational health as a systematic issue

The second structural tension revolves around occupational health as a systemic issue rather than a collection of individual risks. The respondents’ explicit identification of drowning, marine fauna injuries, cold exposure, and physical strain as significant concerns demonstrates a clear-eyed assessment of the hazards inherent in offshore work. However, the tendency in development projects is often to treat such risks as personal responsibility matters of individual caution or skill, rather than as systemic failures of an occupational safety framework. The research literature from neighboring Tanzanian seaweed farming contexts reveals the scale of

this challenge: studies have documented that a 87% of workers report musculoskeletal symptoms affecting the wrist, 84% report back pain, 80% experience skin problems, and 51% suffer from heat-related and asthma-like symptoms (Muthama *et al.*, 2021). Walk-through hazard evaluations in these contexts have identified pervasive ergonomic, biological, and chemical hazards, yet interventions remain generally lacking across all regions (Muthama *et al.*, 2021). This pattern must not be replicated in Kibuyuni. The community's conditional enthusiasm for adoption, their stated willingness to participate, provided safety concerns are addressed, places a clear obligation on implementing agencies. Project budgets must include dedicated funds for personal flotation devices, first-aid kits equipped for marine emergencies, comprehensive safety training that includes swimming instruction and hazard recognition, and well-maintained boats with appropriate safety equipment. Drawing on best practices from offshore aquaculture operations, personnel safety must be addressed through systematic attention to emergency escape arrangements, life-saving appliances, and equipment reliability, treating these not as optional extras but as core components of the technology transfer. The international maritime code Safety of Life at Sea (SOLAS) provides a benchmark for acceptable safety standards, and while small-scale seaweed farming cannot be expected to meet industrial shipping requirements, the principle of treating worker safety as a design parameter rather than an afterthought is directly transferable. When farmers report that their participation depends on safety provisions, they are not making unreasonable demands; they are articulating the minimum conditions under which it is rational to accept the inherent risks of offshore labor.

Market dependency and value chain integration

The third structural tension concerns market dependency and value chain integration, arguably the most critical determinant of long-term sustainability. The farmers' conditional willingness rightly highlights market assurance as a

non-negotiable precondition for their participation, and this demand reflects a sophisticated understanding of where value chain interventions have historically failed. The history of aquaculture development is replete with examples of production increases leading to price collapses due to lack of market coordination, and the seaweed sector is particularly vulnerable to this dynamic (Valderrama *et al.*, 2015). Recent research from Tanzania reveals alarming structural weaknesses: 87.8% of seaweed farmers depend on middlemen for market access, and only 3.1% engage in any form of value addition (UNCTAD, 2023). This dependence on intermediaries, combined with the absence of collective bargaining mechanisms, creates conditions where price spreads can exceed 73% and marketing efficiencies drop as low as 0.04, indicating that primary producers capture a minuscule fraction of the final value (UNCTAD, 2023). The pattern is consistent across multiple contexts; studies from Indonesia confirm that seaweed value chains often operate as low-maturity traditional systems with limited vertical coordination and asymmetrical information flow that systematically disadvantages farmers (Valderrama *et al.*, 2015). A successful deep-water program in Kibuyuni must therefore do more than boost production; it must simultaneously strengthen the entire value chain architecture. This could involve facilitating direct contracts with processors or exporters, thereby bypassing exploitative intermediary layers. It could mean supporting the formation and capacitation of farmer cooperatives with transparent governance structures, enabling collective bargaining power that individual farmers cannot exercise alone (Valderrama *et al.*, 2015). It might also include exploring certification schemes for sustainable or fair-trade seaweed, building on models trialed in Zanzibar that differentiate products in international markets and command premium prices (Msuya *et al.*, 2022). The farmers' demand for market assurance is not a request for charity or price guarantees; it is a demand for market infrastructure that can absorb their production reliably, reward their labor predictably, and insulate them from the volatility that has historically characterized the

sector. Without such infrastructure, increased production will simply flood local markets, depress prices, and replicate the cycles of poverty that the technology was meant to break.

This near-universal willingness to venture into deep-water farming (95%) should not be read as evidence that the structural tensions discussed above are minor or peripheral; rather, the two findings are two sides of the same data. Respondents' conditionality was explicit and specific. Training, equipment, and market access were named as preconditions, not preferences, which means the 95% figure already encodes an implicit forecast of where adoption would fail if those conditions went unmet. The three tensions identified here are therefore not the authors' speculative overlay on an otherwise straightforwardly positive result; they are an elaboration of the same preconditions farmers themselves named, read alongside regional evidence on how comparable conditions have historically gone unmet elsewhere in the Western Indian Ocean. Willingness this high (95%), in other words, is not unconditional optimism but a conditional bet, and the structural tensions describe exactly what determines whether that bet pays off."

Alignment with national policy frameworks

Deep-water *Cottonii* (*Kappaphycus alvarezii*) farming can support Kenya's development goals by diversifying coastal livelihoods, expanding income opportunities especially for women and

youth—and strengthening the country's Blue Economy growth agenda (GOK, 2016). In Kenya's south coast, seaweed farming has been associated with supplementary household income, reduced pressure on capture fisheries, and enhanced livelihood resilience in the context of climate variability (Msuya & Hurtado, 2017). The relatively low capital requirements and short production cycles make deep-water *Cottonii* an accessible entry point into mariculture for small-scale producers, thereby strengthening inclusive local value chains. Beyond biomass production, seaweed supports downstream value addition in carrageenan processing, animal feeds, cosmetics, and organic fertilizers, aligning with Kenya's industrialization and agro-processing priorities. At the policy level, the Fisheries Management and Development Act provide the statutory framework for sustainable aquaculture and mariculture expansion (GOK, 2016). Similarly, the Kenya Fisheries Policy 2022–2032 identifies aquaculture intensification and value chain development as strategic pillars for sectoral transformation (SDBEF, 2022). These frameworks are embedded within Kenya Vision 2030's broader agenda of employment creation, poverty reduction, and economic diversification. Deep-water *Cottonii* farming, therefore, intersects directly with national commitments to inclusive growth under the Blue Economy Strategy. However, implementation challenges including limited extension support, processing infrastructure gaps, and market coordination constraints continue to shape farmer perceptions and adoption decisions. Within this enabling yet evolving governance landscape, deep-water *Cottonii* production represents both a development opportunity and a policy-aligned pathway for socio-economic upgrading in Kenya's coastal counties.

Conclusion

In conclusion, the community of Kibuyuni stands at a genuine inflection point, holding in their collective hands the possibility of transforming their relationship with the sea that sustains them. They possess the awareness, the motivation, and the conditional willingness to embark on this transition. But awareness and willingness, how-

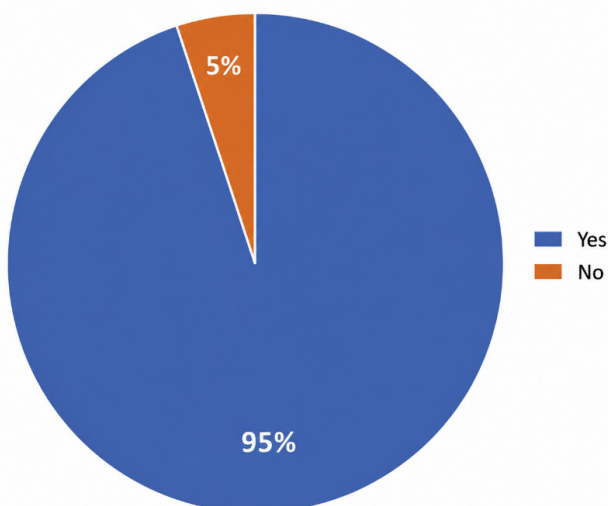


Figure 6: Farmers' willingness to engage in deep-water seaweed farming.

ever widespread, are not sufficient to guarantee success. The three structural tensions identified here, gendered access to offshore space, occupational health as a systemic challenge, and market dependency requiring value chain integration, represent the fault lines along which the project will either succeed or fail. Each tension is addressable through intentional, adequately resourced, and participatory program design. Gender equity requires targeted training and technologies that enable women's full participation (Fröcklin *et al.*, 2012; Williams, 2018). Occupational safety requires treating protective equipment and training as core budget items, not ancillary considerations (Muthama *et al.*, 2021). Market sustainability requires building the institutional infrastructure for collective bargaining and value addition before production scales up (Valderrama *et al.*, 2015; Msuya *et al.*, 2022). The farmers have done their part: they have spoken clearly about what they need, what they fear, and what they hope for. The responsibility now rests with implementing agencies, researchers, and policymakers to demonstrate that they have listened, and to match the community's conditional willingness with an equally conditional commitment to creating the enabling environment that turns potential into lasting prosperity.

Acknowledgement

We would like to acknowledge the Government of Kenya's support through Kenya Marine and Fisheries Research Institute (KMFRI) under the GoK SEED Fund in supporting the field activity and the preparation of this manuscript. Much appreciation is given to the Scientific and Technical teams at KMFRI involved in the data collection and analysis, without whom this exercise would not have been a success.

Funding

This research received no external funding. The study was conducted as part of the institutional research programme of the Kenya Marine and Fisheries Research Institute (KMFRI).

References

- Ask EI, Azanza RV (2002) Advances in cultivation technology of commercial eucheumatoid species: A review with suggestions for future research. *Aquaculture*, 206(3–4): 257–277
- Bergman KC, Svensson S, Öhman MC (2001) Influence of algal farming on fish assemblages. *Marine Pollution Bulletin*, 42(12): 1379–1389
- Bixler HJ, Porse H (2011) A decade of change in the seaweed hydrocolloids industry. *Journal of Applied Phycology*, 23(3): 321–335
- Bryceson I (2002) Coastal aquaculture developments in Tanzania: Sustainable and non-sustainable experiences. *Western Indian Ocean Journal of Marine Science*, 1: 1–19
- Eklöf JS, Henriksson R, Kautsky N (2006) Effects of tropical open-water seaweed farming on seagrass ecosystem structure and function. *Marine Ecology Progress Series*, 325: 73–84
- Fröcklin S, de la Torre-Castro M, Lindström L, Jiddawi NS (2012) Seaweed mariculture as a development project in Zanzibar, East Africa: A price too high to pay? *AMBIO*, 41(7): 726–739
- Government of Kenya (2016) Fisheries Management and Development Act, 2016 (No. 35 of 2016). Kenya Law [<https://new.kenyalaw.org/akn/ke/act/2016/35/eng@2022-12-31>]
- Hayashi L, Hurtado AQ, Msuya FE, Bleicher-Lhonneur G, Critchley AT (2010) A review of Kappaphycus farming: Prospects and constraints. In *Seaweeds and their role in globally changing environments* (pp. 251–283)
- Hurtado AQ, Agbayani RF (2002) Deep-sea farming of Kappaphycus using the multiple raft, long-line method. *Botanica Marina*, 45: 438–444
- Hurtado AQ, Gerung GS, Yasir S, Critchley AT (2013) Cultivation of tropical red seaweeds in the BIMP-EAGA region. *Journal of Applied Phycology*, 25(6): 1765–1776

- Kenya Marine and Fisheries Research Institute (2020) Annual report on marine aquaculture extension services in coastal Kenya. KMFRI Press
- Kimathi AG, Wakibia JG, Gichua MK (2018) Growth rates of *Eucheuma denticulatum* and *Kappaphycus alvarezii* (Rhodophyta; Gigartinales) cultured using modified off-bottom and floating raft techniques on the Kenyan coast. *Western Indian Ocean Journal of Marine Sciences*, 17(2): 11–24
- Largo DB, Fukami K, Nishijima T (1995) Occasional pathogenic bacteria promoting ice-ice disease in the carrageenan-producing red algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Solieriaceae, Gigartinales, Rhodophyta). *Journal of Applied Phycology*, 7(6): 545–554
- Mirera DO, Kimathi A, Ngarari MM, Magundu EW, Wainaina M, Ototo A (2020) Societal and environmental impacts of seaweed farming in relation to rural development: The case of Kibuyuni village, south coast, Kenya. *Ocean & Coastal Management*, 194: 105253
- Msuya FE (2013) Social and economic dimensions of carrageenan seaweed farming in the United Republic of Tanzania. In *Social and economic dimensions of carrageenan seaweed farming* (pp. 115–146)
- Msuya FE, Buriyo A, Omar I, Pascal B, Narrain K, Ravina JJ, Mrabu E, Wakibia JG (2014) Cultivation and utilisation of red seaweeds in the Western Indian Ocean (WIO) region. *Journal of Applied Phycology*, 26(2): 699–705
- Msuya FE, Hurtado AQ (2017) The role of women in seaweed aquaculture in the Western Indian Ocean and South-East Asia. *European Journal of Phycology*, 52(4): 482–494 [<https://doi.org/10.1080/09670262.2017.1357084>]
- Msuya FE, Jiddawi NS, Kyewalyanga M (2022) Fair-trade seaweed certification in Zanzibar: Opportunities and challenges for smallholder farmers. *Aquaculture International*, 30(3): 1245–1262
- Muthama DM, Muthumbi A, Okuku E (2021) Occupational health and safety risks in small-scale fisheries and aquaculture in Kenya. *Western Indian Ocean Journal of Marine Science*, 20(2): 45–58
- Odhiambo JO, Wakibia J, Sakwa MM (2020) Effects of monitoring and evaluation planning on the implementation of poverty alleviation mariculture projects in the coast of Kenya. *Marine Policy*, 119: 104050
- State Department for the Blue Economy and Fisheries (2022) National Aquaculture Policy 2025 (Draft). Ministry of Mining, Blue Economy and Maritime Affairs
- United Nations Conference on Trade and Development (2023) An ocean of opportunities: The potential of seaweed to advance food, environmental and gender dimensions of the SDGs. UNCTAD
- Valderrama D, Cai J, Hishamunda N, Ridler N, Neish IC, Hurtado AQ, Msuya FE, Krishnan M, Narayanakumar R, Kronen M, Robledo D, Gasca-Leyva E, Fraga J (2015) The economics of *Kappaphycus* seaweed cultivation in developing countries: A comparative analysis of farming systems. *Aquaculture Economics & Management*, 19(2): 251–277 [<https://doi.org/10.1080/13657305.2015.1024348>]
- Williams S (2018) Gender and marine aquaculture in East Africa: Women's access to and control over productive resources (FAO Fisheries and Aquaculture Technical Paper No. 623). Food and Agriculture Organization of the United Nations

Heavy metal contamination in Mombasa's coastal waters and sediments: a systematic review of sources, distribution, ecological risks, and management implications (2015–2024)

Justine Rutto

Kenya Marine and Fisheries Research Institute (KMFRI), P.O. Box 81651-80100, Mombasa, Kenya

*Corresponding author E-mail: justinerutto@gmail.com

Abstract

Heavy metal contamination is an increasing environmental concern in coastal ecosystems, particularly in rapidly urbanizing and industrializing regions where anthropogenic activities intensify pollutant inputs. This review synthesizes studies published between 2015 and 2024 on heavy metal contamination in the coastal waters and sediments of Mombasa, a major economic and maritime hub along the Western Indian Ocean. The review evaluates the occurrence, spatial distribution, sources, and ecological risks associated with key trace metals, including lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), and zinc (Zn). Elevated concentrations of these metals were consistently reported in areas influenced by port operations, industrial discharges, sewage effluents, and urban runoff, with Tudor Creek, Port Reitz, Makupa, and Kilindini Harbour identified as pollution hotspots. Coastal sediments function as both repositories and potential secondary sources of contaminants, thereby prolonging environmental exposure. Evidence of bioaccumulation in fish and mollusks underscores potential risks to marine biodiversity, ecosystem functioning, and human health through seafood consumption. Despite growing research efforts, significant gaps remain in long-term environmental monitoring, standardized ecological risk assessment, and integrated contaminant management. The review highlights the need for coordinated pollution control strategies, strengthened regulatory enforcement, and enhanced stakeholder and community participation to safeguard the ecological integrity and sustainable management of Mombasa's coastal and marine ecosystems.

Keywords: Heavy metal pollution, Mombasa, coastal sediments, bioaccumulation, ecological risk

Introduction

Heavy metal pollution in marine environments is a significant global concern, particularly in coastal regions where urbanization, industrialization, maritime activities, and agricultural runoff intersect. Unlike organic pollutants, heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), zinc (Zn), and copper (Cu) are non-biodegradable and can persist in the environment for decades. These elements accumulate in marine sediments, water columns, and living organisms, ultimately entering

food chains and posing threats to both ecological and human health (Eggleton and Thomas, 2004; Ali *et al.*, 2019).

Globally, several coastal systems—such as the Pearl River Delta in China (Cai *et al.*, 2021), Chesapeake Bay in the USA (Buchman, 2008), and the Gulf of Mexico (Younis *et al.*, 2020) — have reported significant accumulation of heavy metals in sediments and biota. The primary sources of this pollution include industrial discharges, untreated sewage, urban storm water runoff, shipping activities, and atmospheric

deposition (Chatterjee *et al.*, 2007; Islam *et al.*, 2015). Climate change exacerbates these issues by altering ocean chemistry and hydrology, potentially remobilizing metals from sediments back into the water column (Zhao *et al.*, 2022).

Heavy metals accumulate in sediments, which serve as the ultimate sink in aquatic systems. However, they can become secondary sources of pollution under varying environmental conditions, such as changes in pH, salinity, and redox potential (Eggleton and Thomas, 2004; Förstner and Wittmann, 2012). The bioaccumulation of heavy metals in marine organisms—including mollusks, polychaetes, crustaceans, and fish—poses significant risks to ecosystem functioning and to human populations that rely on seafood (Rainbow, 2002; Otieno *et al.*, 2016; Swaleh *et al.*, 2016). For example, studies conducted in Asia, Europe, and Africa have demonstrated that benthic organisms accumulate high concentrations of Cd, Pb, and Hg, which can negatively affect their reproductive and developmental processes (Islam and Tanaka, 2004; UNEP, 2016).

In Africa, coastal cities such as Lagos (Nigeria), Accra (Ghana), and Mombasa (Kenya) are experiencing increased marine pollution, linked to rapid population growth and inadequate waste management infrastructure (Biney *et al.*, 1994; Kithiia *et al.*, 2015). In Mombasa, heavy metal contamination has become particularly pronounced in recent years due to expanded port operations, industrial activities, and informal settlements discharging waste directly into marine waters (Kamau *et al.*, 2015; Okuku *et al.*, 2019). Areas such as Tudor Creek, Port Reitz, Kilindini Harbour, and Makupa Creek are among the most affected (Mwangi *et al.*, 2020; Mwatsahu *et al.*, 2020).

The situation in Mombasa exemplifies broader regional and global challenges in managing coastal pollution. Multiple studies from 2015 to 2024 document heavy metal enrichment in sediments and water, with some concentrations surpassing the World Health Organization (WHO) and Food and Agriculture Organization (FAO) limits for ecological safety and human consumption (Njiru *et al.*, 2016; Wanjeri *et al.*, 2024).

Furthermore, limited monitoring, weak enforcement of environmental regulations, and a lack of public awareness have hindered mitigation efforts (Obura *et al.*, 2018; Mutia *et al.*, 2019).

Given the critical socio-economic and ecological importance of coastal waters, which support fisheries, tourism, and biodiversity, there is an urgent need to evaluate the trends and risks associated with heavy metal contamination. This review aims to address that need by systematically synthesizing published research from 2015 to 2024 on heavy metal pollution in Mombasa's coastal waters and sediments. The key objectives are to synthesize current knowledge on the occurrence, sources, distribution, bioavailability, ecological and human health risks of heavy metals in Mombasa's coastal environment, and identify priority interventions and research needs for effective pollution management and sustainable coastal ecosystem protection. This review contributes to the ongoing discussion on sustainable coastal governance and environmental stewardship in rapidly urbanizing tropical regions by contextualizing heavy metal pollution in Mombasa within the broader global issue of marine contamination.

Materials and methods

This review employed a systematic literature review approach to synthesize published evidence on heavy metal contamination in Mombasa's coastal waters and sediments between 2015 and 2024. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility in study identification, screening, and selection. Electronic databases including Web of Science, Scopus, ScienceDirect, Google Scholar, SpringerLink, and PubMed were systematically searched using combinations of keywords such as heavy metals, trace metals, marine pollution, coastal sediments, Mombasa, Kenya coast, lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), zinc (Zn), arsenic (As), bioaccumulation, and ecological risk. Additional publications were identified through reference lists of relevant articles and reports published by governmental and in-

ternational organizations. Only peer-reviewed studies published in English between January 2015 and December 2024 that reported original data on heavy metal concentrations in coastal waters, sediments, or marine organisms within the Mombasa coastal ecosystem were included, while studies outside the study area, conference abstracts, theses without peer review, duplicate publications, and articles lacking quantitative information were excluded. Studies were screened independently based on titles, abstracts, and full texts following predefined inclusion and exclusion criteria.

Relevant information was extracted from each eligible study using a standardized data extraction template. Variables collected included publication year, sampling location, environmental matrix (water, sediment, or biota), heavy metals investigated, analytical techniques employed (e.g., Atomic Absorption Spectrophotometry [AAS] and Inductively Coupled Plasma Mass Spectrometry [ICP-MS]), reported metal concentrations, pollution sources, ecological and human health risk indices, and key management recommendations. The quality of included studies was evaluated based on sampling design, analytical methodology, quality assurance and quality control procedures, and reporting completeness. Extracted data were synthesized using qualitative narrative analysis complemented by comparative tabulation of heavy metal occurrence, spatial distribution, contamination hotspots, sources, bioaccumulation patterns, and reported ecological and health risks. Where available, reported concentrations were compared with international sediment and water quality guideline values, including those of the World Health Organization (WHO), Food and Agriculture Organization (FAO), and other internationally recognized environmental quality standards, to facilitate interpretation of contamination status and identify priority knowledge gaps for future monitoring and pollution management.

Results and discussion

Concentrations and distribution patterns of heavy metals

Studies conducted between 2015 and 2024 consistently reveal elevated concentrations of key heavy metals, including lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), chromium (Cr), and mercury (Hg) across various coastal zones in Mombasa. Hotspots of pollution, such as Tudor Creek, Port Reitz, Makupa Creek, and Kilindini Harbour, are primarily affected due to their proximity to industrial areas, port activities, and informal settlements (Kamau *et al.*, 2015; Mwangi *et al.*, 2020; Mwatsahu *et al.*, 2020). For instance, Pb levels in sediments from Tudor Creek have been recorded at values exceeding 100 mg/kg, which surpass the threshold effect concentrations (TEC) and indicate potential ecological risk (Kairu *et al.*, 2018) (Table 1). Similarly, Cd and Cu levels in Port Reitz and Kilindini Harbour have been found to exceed sediment quality guidelines (Mutia *et al.*, 2019), with accumulation influenced by localized sources such as ship maintenance, antifouling paints, and untreated sewage discharge (Fig. 1).

Spatial distribution patterns show a clear gradient, with metal concentrations generally increasing in enclosed and slow-flushing areas, such as mangrove-lined creeks and estuaries (Muthumbi *et al.*, 2018). These zones act as sinks where fine-grained sediments, organic matter, and heavy metals co-deposit due to limited water circulation. Seasonal variations have also been observed, with higher concentrations often recorded during the dry season, attributed to reduced dilution and stronger sediment binding under low flow conditions (Okuku *et al.*, 2019). Temporal comparisons further indicate a gradual increase in metal loads over the past decade, reflecting rising anthropogenic pressures from urban expansion, industrial effluents, and increased port throughput (Njiru *et al.*, 2016; Wanjeri *et al.*, 2024).

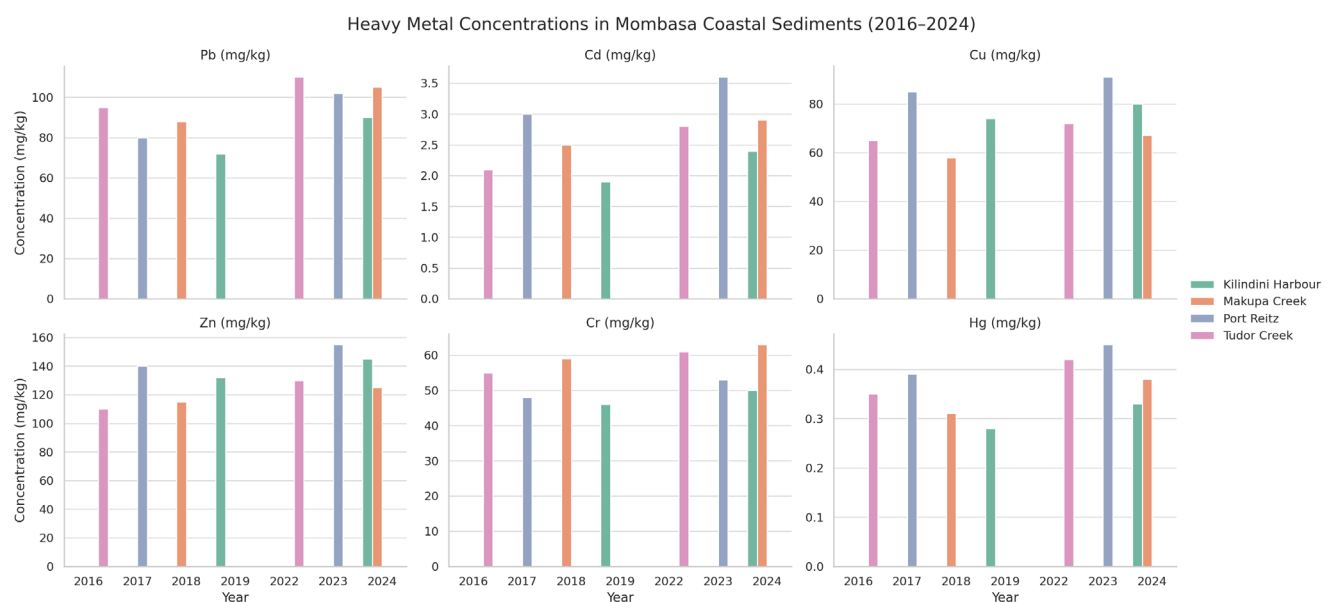
Table 1. Summary table of heavy metal concentrations in sediments from key sites in Mombasa's coastal environment (2016–2024).

Location	Year	Pb (mg/kg)	Cd (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Cr (mg/kg)	Hg (mg/kg)
Kilindini Harbour	2019	72	1.90	74	132	46	0.28
Kilindini Harbour	2024	90	2.40	80	145	50	0.33
Makupa Creek	2018	88	2.50	58	115	59	0.31
Makupa Creek	2024	105	2.90	67	125	63	0.38
Port Reitz	2017	80	3.00	85	140	48	0.39
Port Reitz	2023	102	3.60	91	155	53	0.45
Tudor Creek	2016	95	2.10	65	110	55	0.35
Tudor Creek	2022	110	2.80	72	130	61	0.42

The distribution of heavy metals is also specific to each metal: Zn and Cu are generally more uniformly distributed due to widespread urban runoff and domestic waste, while Pb and Cr hotspots are strongly linked to industrial effluents and road runoff (Fig. 1). Studies show that metal partitioning between sediment and water differs, with higher concentrations typically found in sediments due to their strong adsorption onto organic and clay particles (Förstner and Wittmann, 2012). These findings underscore the need for site-specific monitoring and management interventions tailored to pollution hotspots and the types of metals present.

Anthropogenic sources and transport pathways of heavy metals

The elevated concentrations of heavy metals in Mombasa's coastal waters and sediments can largely be traced to various land-based human activities concentrated around the city's industrial, residential, and maritime zones. Key sources include industrial discharges, domestic sewage, storm water runoff, port-related activities, and solid waste dumping (Okuku *et al.*, 2011; Kamau *et al.*, 2015; Muthumbi *et al.*, 2018) (Fig. 2). Industrial facilities near Port Reitz and Makupa Creek release untreated or partially treated effluents containing metals such as lead

**Figure 1. A graphical Representation of Heavy Metal Concentrations in Mombasa Coastal Sediments (2016– 2024).**

(Pb), cadmium (Cd), copper (Cu), and zinc (Zn). These metals typically originate from processes like metal fabrication, electroplating, paint production, and petroleum refining (Mutia *et al.*, 2019; Mwatsahu *et al.*, 2020).

Urban and peri-urban settlements that lack adequate sanitation infrastructure also contribute to heavy metal contamination through the direct discharge of greywater and sewage into creeks and estuarine waters. Informal dumpsites in coastal areas, particularly near Tudor and Makupa creeks, leach metals into the aquatic system, especially during the rainy season when stormwater runoff occurs (Kairu *et al.*, 2018; Okuku *et al.*, 2019). Moreover, increased vehicular traffic in the rapidly expanding urban transport network contributes lead (Pb), zinc (Zn), and chromium (Cr) through tire wear, brake linings, and residues from fuel combustion that are washed into the marine environment by runoff (Wanjeri *et al.*, 2024).

Port activities at Kilindini Harbour represent another significant source of heavy metals. These activities involve ship maintenance, cargo handling, ballast water discharge, and the use of antifouling paints that contain copper (Cu)

and organotin compounds (UNEP, 2016; Njiru *et al.*, 2016). Additionally, marine traffic introduces atmospheric deposition of metal particles, particularly from fuel combustion and maintenance operations.

The transport of these contaminants occurs through surface runoff and hydrological connectivity, especially via the creeks and estuarine systems that drain urban and industrial areas into the coastal ocean. Tidal action, sediment resuspension, and bioturbation further facilitate the horizontal and vertical redistribution of heavy metals within coastal sediments (Förstner and Wittmann, 2012). Fine sediments with high organic content, commonly found in mangrove areas of Mombasa, serve as long-term sinks for these pollutants (Munga *et al.*, 2021). During heavy rainfall or dredging activities, historically deposited contaminants can be remobilized, reintroducing metals into the water column and increasing their bioavailability and ecological risk. These human-induced inputs and transport mechanisms highlight the complex interplay between urban development, waste management practices, and coastal hydrodynamics in shaping the fate of heavy metals in Mombasa's marine environment.

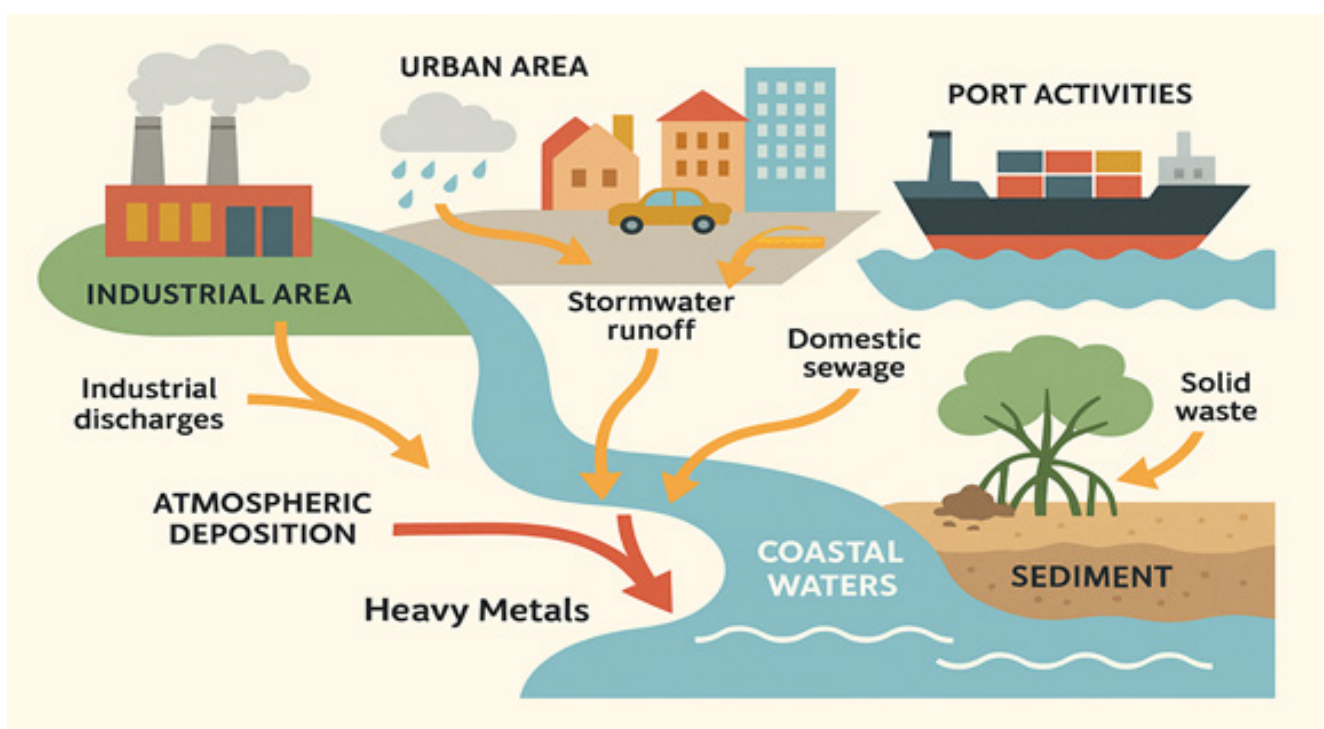


Figure 2. Anthropogenic Sources and Transport Pathways of Heavy Metals in Mombasa's Coastal Environment.

Bioavailability and accumulation of heavy metals in marine biota

The bioavailability of heavy metals and their subsequent accumulation in marine organisms are crucial factors that determine the ecological and human health risks in contaminated coastal ecosystems. In the coastal waters of Mombasa, several studies have reported significant bioaccumulation of metals in marine organisms, particularly in filter feeders, benthic organisms, and top predators. For instance, research on gastropods and bivalves from Tudor Creek and Kilindini Harbour has revealed elevated levels of cadmium (Cd), lead (Pb), and mercury (Hg), with concentrations surpassing the permissible limits for seafood (Swaleh *et al.*, 2016; Otieno *et al.*, 2016) (Table 2). The patterns of bioaccumulation are influenced by factors such as the feeding habits of the organisms, their trophic position, and the type of sediment in their environment.

Bioavailability—referring to the fraction of a metal that is accessible to organisms—fluctuates based on various environmental conditions. Sediment characteristics, including organic content, pH, and redox potential, play a significant role in determining metal availability to benthic organisms. Metals that are bound to fine particles and organic matter are more readily bioavailable to filter-feeding organisms, such as oysters and clams, which accumulate these metals in their tissues through passive absorption from both water and sediment pore water (Rainbow, 2002; Förstner and Wittmann, 2012). In contrast, metals in highly mobile, dissolved forms are more bioavailable to planktonic organisms and smaller fish species (Ali *et al.*, 2019). Studies by Otieno *et al.* (2016) and Mutia

et al. (2019) indicate that the highest concentrations of metals in organisms are found in the digestive glands and gills, which are the organs that interact directly with contaminated water and sediment (Fig. 3).

The accumulation of heavy metals in marine biota poses significant ecological threats, as these metals can disrupt biological processes, including reproduction, growth, and metabolism. For example, in Mombasa, high levels of mercury in fish species such as *Lethrinus harak* and *Scomberomorus commerson* have been linked to altered growth patterns and decreased reproductive success (Mwangi *et al.*, 2021). Aside from the direct impact on marine life, the bioaccumulation of metals has serious implications for human health. Coastal communities that rely on fish and shellfish as their primary protein source are at risk of consuming seafood contaminated with metals, leading to chronic toxicity and bioaccumulation in human tissues (Kamau *et al.*, 2015; Swaleh *et al.*, 2016) (Table 3). Mercury and cadmium are particularly concerning due to their long-term toxic effects, which include kidney damage and neurological disorders in humans (Rainbow, 2002).

Metal bioavailability in Mombasa's coastal environment is affected by various environmental and biological factors. The bioaccumulation of these metals in marine organisms presents both ecological and public health risks. Further research is needed to monitor long-term trends in bioaccumulation and to explore mitigation strategies, such as sustainable fisheries management and pollution control, aimed at protecting both marine ecosystems and human populations.

Table 2. Heavy Metal Concentrations in Marine Biota from Mombasa's Coastal Areas. Values are based on studies conducted between 2015 and 2024 of Swaleh *et al.* (2016) and Mwatsahu *et al.* (2020).

Organism	Site	Heavy Metals (mg/kg)	Highest Metal Concentration	Trophic Level
Oyster (<i>Crassostrea gasar</i>)	Tudor Creek	Pb: 12.5, Cd: 1.4, Hg: 0.05	Pb (12.5 mg/kg)	Filter feeder
Mussel (<i>Perna perna</i>)	Kilindini Harbour	Zn: 20.3, Cu: 6.1, Pb: 3.2	Zn (20.3 mg/kg)	Filter feeder
Fish (<i>Lethrinus harak</i>)	Port Reitz	Hg: 0.2, Cd: 1.1, Pb: 3.4	Pb (3.4 mg/kg)	Carnivorous
Gastropod (<i>Turbo sp.</i>)	Makupa Creek	Cu: 5.8, Zn: 7.5, Hg: 0.02	Zn (7.5 mg/kg)	Herbivorous
Crustacean (<i>Carcinus sp.</i>)	Port Reitz	Cd: 2.2, Pb: 1.7, Cu: 4.3	Cu (4.3 mg/kg)	Omnivorous

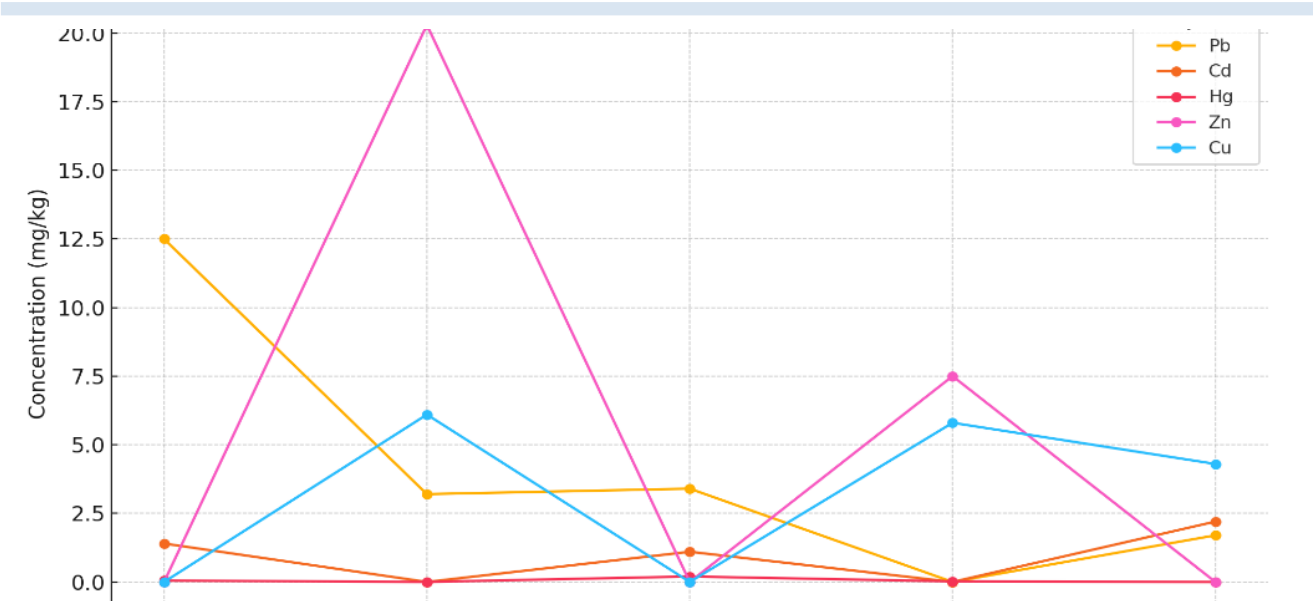


Figure 3. A graphical representation of heavy metal concentrations in marine biota from Mombasa (2015– 2024).

Table 3. Effects of Heavy Metal Bioaccumulation on Marine Biota. Note: Based on findings from Otieno *et al.* (2016) and Mwangi *et al.* (2021).

Species	Heavy Metals Accumulated	Effect on Organism	Ecological Impact
Gastropod (<i>Turbo</i> sp.)	Cu, Zn	Growth inhibition, reduced reproductive success	Altered species composition, reduced biodiversity
Mussel (<i>Perna perna</i>)	Pb, Cd	Reduced filtration rate, weakened immune system	Decreased water quality, disrupted food webs
Fish (<i>Lethrinus harak</i>)	Hg, Pb	Liver damage, impaired behavior, and stunted growth	Disruption of predator-prey dynamics
Crustacean (<i>Carcinus</i> sp.)	Cd, Pb	Shell deformities, reduced molting success	Reduced abundance of important invertebrates

Ecological and health risks associated with heavy metal pollution

The presence of elevated heavy metal concentrations in the coastal waters and sediments of Mombasa poses significant ecological and public health risks. Heavy metals such as cadmium (Cd), lead (Pb), copper (Cu), and mercury (Hg) are known to bioaccumulate in marine organisms, including mollusks, crustaceans, and fish. This bioaccumulation disrupts biological processes such as enzyme function, reproduction, and growth (Rainbow, 2002; Islam and Tanaka, 2004). Studies conducted in Kilindini Harbour, Tudor Creek, and Port Reitz indicate that sediment concentrations of Pb, Cd, and Cu often exceed the NOAA’s Effects Range-Low (ERL) and Effects Range-Median (ERM) guidelines, suggesting a high likelihood of adverse effects on benthic fauna (Kamau *et al.*, 2015; Mutia *et al.*, 2019) (Table 4). For example, Muthumbi *et al.* (2018) found altered community

structures and reduced diversity of polychaetes and bivalves in heavily contaminated mangrove areas, which highlights the sub-lethal and chronic toxic impacts on benthic ecosystems.

From a human health perspective, the risks are especially pronounced for coastal communities that rely on seafood as a primary source of protein. Bioaccumulation studies conducted between 2015 and 2024 reveal that commonly consumed fish and shellfish species contain metal concentrations that exceed the permissible limits set by the FAO/WHO (Otieno *et al.*, 2016; Swaleh *et al.*, 2016; Wanjeri *et al.*, 2024). For instance, lead levels in fish tissues sampled near Makupa Creek and Port Reitz are above 2.0 mg/kg—the maximum recommended level—raising concerns over neurotoxicity, developmental risks in children, and kidney dysfunction in adults (UNEP, 2016) (Fig. 4). Additionally, mercury exposure through fish consumption has been linked to neurological and cardiovascular dam-

age, with pregnant women and young children being particularly vulnerable (Ali *et al.*, 2019).

Various risk assessment indices, such as the Geoaccumulation Index (Igeo), Contamination Factor (CF), and Potential Ecological Risk Index (PERI), have been employed in multiple studies to quantify the severity of contamination in Mom-

basa. The results typically indicate moderate to high ecological risk levels, particularly in areas near industrial outfalls and informal settlements (Njiru *et al.*, 2016; Mwangi *et al.*, 2020). These findings underscore the urgent need for regulatory intervention, ongoing biomonitoring, and public awareness campaigns aimed at minimizing exposure and preserving ecosystem integrity.

Table 4. Comparison of heavy metal concentrations in marine biota vs FAO/WHO Permissible Limits. Concentrations are reported as dry weight (mg/kg). FAO/WHO limits vary slightly depending on the country and regulatory interpretation; these represent global averages. "Risk Level" is based on comparison with limits, considering bioaccumulation and consumption patterns.

Heavy Metal	Species Sampled	Sampling Location	Mean Concentration (mg/kg)	FAO/WHO Limit (mg/kg)	Reference	Risk Level
Lead (Pb)	<i>Lutjanus fulviflamma</i> (snapper)	Port Reitz	2.4	2.0	Swaleh <i>et al.</i> , 2016	Exceeds limit
Cadmium (Cd)	<i>Perna viridis</i> (green mussel)	Tudor Creek	1.1	0.5	Otieno <i>et al.</i> , 2016	High concern
Copper (Cu)	<i>Siganus sutor</i> (rabbitfish)	Kilindini Harbour	3.6	10.0	Mwangi <i>et al.</i> , 2020	Within limit
Zinc (Zn)	<i>Crassostrea cucullata</i> (oyster)	Makupa Creek	60.2	100.0	Wanjeri <i>et al.</i> , 2024	Within limit
Mercury (Hg)	Mixed demersal fish species	Port Reitz & Tudor Creek	0.7	0.5	UNEP, 2016; Ali <i>et al.</i> , 2019	Slightly elevated
Chromium (Cr)	<i>Perna perna</i> (brown mussel)	Tudor & Makupa Creeks	1.8	1.0	Njiru <i>et al.</i> , 2016	Exceeds limit

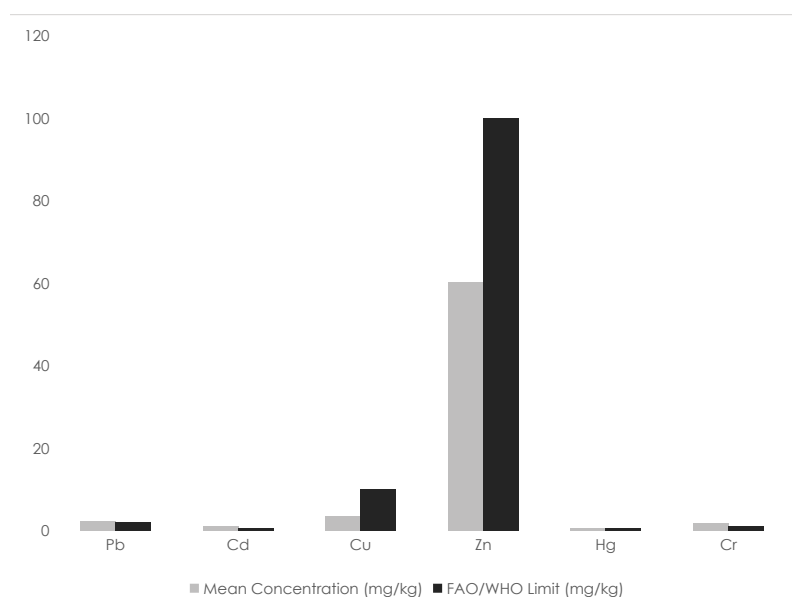


Figure 4. A comparison of heavy metal concentration in biota vs FAO/WHO limits in Mombasa coastal waters.

Strategic interventions and research priorities for pollution mitigation

Effective mitigation of heavy metal pollution in Mombasa's coastal waters requires a comprehensive strategy that integrates policy, infrastructure, community engagement, and science-based decision-making. First, it is essential to upgrade wastewater treatment infrastructure. Many discharges into creeks and harbors originate from informal settlements and industries that have little or no treatment (Okuku *et al.*, 2019). Establishing Decentralized Wastewater Treatment Systems (DEWATS) in coastal urban areas could significantly reduce direct pollutant loads. Secondly, enforcing existing environmental regulations, such as the Environmental Management and Coordination Act (EMCA), through regular industrial audits and coastal water quality monitoring, will help curb illegal discharges and improve compliance (NEMA, 2015). Additionally, the implementation of **Best Management Practices** (BMPs) in industries should be incentivized; these practices may include heavy metal filtration technologies, zero-effluent discharge systems, and cleaner production techniques.

Urban storm-water management must also be prioritized. Constructed wetlands, bioswales, and retention basins can help reduce metal-laden runoff from roads and industrial areas before it reaches marine ecosystems. In high-risk zones such as Tudor Creek and Port Reitz, sediment remediation measures—including dredging, capping, or phytoremediation—should be considered based on ecological risk assessments (Förstner and Wittmann, 2012; Mutia *et al.*, 2019).

On a governance level, developing a coastal pollution action plan led by the County Government of Mombasa, in collaboration with the Kenya Marine and Fisheries Research Institute (KMFRI), NEMA, and local stakeholders, would ensure better coordination of interventions. From a research perspective, future priorities should include: (1) establishing long-term heavy metal monitoring programs that integrate both water and sediment assessments; (2) mapping metal fluxes using spatial modeling and remote

sensing; (3) investigating metal bioavailability and trophic transfer within local food webs; and (4) assessing cumulative health risks to coastal communities that rely on seafood. Community-based research approaches, where local fishers and residents participate in monitoring and awareness campaigns, can enhance data collection and foster stewardship. Moreover, interdisciplinary collaborations among marine scientists, public health experts, and urban planners will be essential in developing adaptive, science-based solutions for sustainable coastal pollution control.

Conclusion and recommendations

This review demonstrates that heavy metal contamination remains a persistent environmental challenge in Mombasa's coastal waters and sediments, with elevated concentrations of lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), and zinc (Zn) consistently reported in pollution hotspots, including Tudor Creek, Port Reitz, Kilindini Harbour, and Makupa Creek. The predominant sources of contamination are anthropogenic, notably untreated municipal wastewater, industrial effluents, urban runoff, and port and maritime activities associated with rapid urbanization and industrial expansion. Coastal sediments function as both long-term sinks and potential secondary sources of heavy metals, facilitating their remobilization under changing environmental conditions and increasing their availability to aquatic organisms. Consequently, bioaccumulation in fish, mollusks, and crustaceans poses significant ecological risks and raises concerns regarding seafood safety and human health, while continued contamination threatens marine biodiversity and ecosystem resilience.

Although considerable progress has been made in documenting the spatial distribution of heavy metals in Mombasa's marine environment, important knowledge gaps remain regarding long-term monitoring, contaminant bioavailability, cumulative ecological effects, and standardized ecological and human health risk assessments. Future efforts should prioritize the establishment of comprehensive

monitoring programmes, adoption of harmonized analytical and risk assessment protocols, strengthened enforcement of environmental regulations, improved wastewater treatment and storm-water management infrastructure, and pollution prevention measures targeting industrial and maritime sources. Furthermore, enhanced interdisciplinary research, public awareness, stakeholder participation, and ecosystem-based coastal management are essential to support evidence-based decision-making. Integrating scientific research with effective governance and community engagement will be critical for mitigating heavy metal pollution, protecting coastal ecosystems, safeguarding public health, and advancing the sustainable development of Kenya's Blue Economy.

References

- Ali H, Khan E, Ilahi I (2019) Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, 1–14 [https://doi.org/10.1155/2019/6730305]
- Biney C, Amuzu AT, Calamari D, Kaba N, Mbome IL, Naeve H, Saad MAH (1994) Review of heavy metals in the African aquatic environment. *Ecotoxicology and Environmental Safety*, 28(2): 134–159 [https://doi.org/10.1006/eesa.1994.1041]
- Buchman MF (2008) NOAA Screening Quick Reference Tables. NOAA OR&R, Office of Response and Restoration Division, National Oceanic and Atmospheric Administration, Seattle, WA
- Cai P, Cai G, Chen X, Li S, Zhao L (2021) The concentration distribution and biohazard assessment of heavy metal elements in surface sediments from the continental shelf of Hainan Island. *Marine Pollution Bulletin*, 166: 112254 [https://doi.org/10.1016/j.marpolbul.2021.112254]
- Chatterjee M, Silva Filho EV, Sarkar SK, Sella SM, Bhattacharya A, Satpathy KK, Prasad MVR, Chakraborty S (2007) Heavy metals in the surface sediments of the northern portion of the South China Sea shelf: Distribution, contamination, and sources. *Environmental Geology*, 51(3): 375–386 [https://doi.org/10.1007/s00254-006-0325-7]
- Eggleton J, Thomas KV (2004) A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. *Environment International*, 30(7): 973–980 [https://doi.org/10.1016/j.envint.2004.03.001]
- Förstner U, Wittmann GTW (2012) Metal pollution in the aquatic environment. *Springer Science & Business Media*
- Islam MS, Tanaka M (2004) Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries, and approach for management: A review and synthesis. *Marine Pollution Bulletin*, 48(7–8): 624–649 [https://doi.org/10.1016/j.marpolbul.2003.12.004]
- Islam MS, Ahmed MK, Raknuzzaman M, Habibullah-Al-Mamun M, Islam MK (2015) Heavy metal pollution in surface water and sediment: A preliminary assessment of an urban river in a developing country. *Ecological Indicators*, 48: 282–291 [https://doi.org/10.1016/j.ecolind.2014.08.016]
- Kamau JN, Mohamed AI, Ndirangu M (2015) Heavy metal contamination and distribution in selected marine sediments in Mombasa, Kenya. *Western Indian Ocean Journal of Marine Science*, 14(1): 13–26
- Kairu JK, Mohamed AI, Ndirangu M (2018) Levels and ecological risks of heavy metals in coastal sediments of Makupa Creek, Mombasa, Kenya. *Journal of Environmental Science and Engineering*, B7: 155–166
- Kithiia J, Muasya RM, Owako D (2015) Impacts of urbanization on the coastal environment: A case study of Mombasa City. *African Journal of Environmental Science and Technology*, 9(6): 518–525
- Munga D, Mohamed MOS, Ong'anda H, Ndiran-

- gu M (2021) Organic matter and heavy metal concentrations in mangrove sediments of the Kenyan coast. *Regional Studies in Marine Science*, 45: 101825
- Mutia TM, Okuku EO, Ndirangu M (2019) Heavy metal distribution and ecological risk in estuarine sediments of Port Reitz, Mombasa, Kenya. *Marine Pollution Bulletin*, 149: 110643
- Muthumbi AW, Mwaluma JM, Kimani EN (2018) Heavy metal effects on macrobenthic community structure along a pollution gradient in Tudor Creek, Kenya. *Journal of Coastal Research*, 85(sp1): 167–175
- Mwangi JG, Muthumbi AW, Ong'anda H (2020) Sediment quality assessment of Kilindini Harbour using pollution indices. *Western Indian Ocean Journal of Marine Science*, 19(1): 1–12
- Mwangi JG, Otieno DO, Ong'anda H (2021) Heavy metal accumulation and health risk in fish species from Kilindini Harbour and Tudor Creek, Kenya. *Marine Pollution Bulletin*, 172: 112897
- Mwatsahu M, Mohamed AI, Munga D (2020) Assessment of heavy metals in surface sediments of Tudor and Makupa creeks, Mombasa, Kenya. *Western Indian Ocean Journal of Marine Science*, 19(2): 55–64
- National Environment Management Authority (NEMA) (2015) State of the Coast Report II: Enhancing Integrated Management of Coastal and Marine Resources in Kenya. National Environment Management Authority, Nairobi, Kenya
- Njiru JM, Okuku EO, Otieno DO (2016) Pollution monitoring and assessment of heavy metals in sediments of selected sites in Mombasa, Kenya. *Western Indian Ocean Journal of Marine Science*, 15(1): 41–53
- Obura D, Church J, Gabri   C (2018) Assessing management effectiveness of marine protected areas: A guide for the Western Indian Ocean. IUCN, Nairobi
- Okuku EO, Owino JO, Munga D (2011) Heavy metal pollution and sediment quality in the Mombasa marine environment. Kenya Marine and Fisheries Research Institute Technical Report 9(2): 1–14
- Okuku EO, Mohamed AI, Munga D (2019) Levels, distribution, and potential ecological risk of heavy metals in surface sediments of Makupa and Tudor Creeks, Mombasa, Kenya. *Marine Pollution Bulletin*, 149: 110511
- Otieno DO, Njiru JM, Okuku EO (2016) Heavy metal concentrations in edible marine organisms in Mombasa, Kenya, and potential risks to human health. *Journal of Environment and Earth Science*, 6(6): 81–89
- Rainbow PS (2002) Trace metal concentrations in aquatic invertebrates: Why and so what? *Environmental Pollution*, 120(3): 497–507 [[https://doi.org/10.1016/S0269-7491\(02\)00238-5](https://doi.org/10.1016/S0269-7491(02)00238-5)]
- Swaleh AM, Otieno DO, Okuku EO (2016) Heavy metal accumulation in fish species and public health risks in Tudor Creek, Kenya. *Western Indian Ocean Journal of Marine Science*, 15(2): 35–46
- United Nations Environment Programme (UNEP) (2016) UNEP/GPA Regional Seas Reports and Studies No. 185: Regional State of the Coast Report: Western Indian Ocean. United Nations Environment Programme, Nairobi
- Wanjeri VO, Mwangi JG, Otieno DO (2024) Heavy metal concentrations and ecological risk assessment in coastal sediments and marine organisms in Mombasa, Kenya. *Marine Pollution Bulletin*, 195: 115013
- Younis NS, Ali MB, Tawfik A (2020) Pollution assessment of heavy metals in the Gulf of Mexico sediments: Sources and ecological risk. *Marine Pollution Bulletin*, 158: 111399
- Zhao Z, Pan X, Li X, Guo L, Zhang J (2022) Climate change impact on remobilization of heavy metals from sediments: A critical review. *Science of the Total Environment*, 807: 150715

The Omena (*Rastrineobola argentea*) Value Chain in Lake Victoria: Livelihoods, Gender Dynamics, and Constraints Among Small-Scale Actors

Kevin Victor Onsongo^{1*}, Jane Fonda Awuor¹, Patrick Wanguche Otuo¹, Susan Wandago¹, Christopher Mulanda Aura¹, Chrispine Nyamweya¹, Venny Mziri¹, Melckzedek Osore², Paul S Orina²

¹Kenya Marine and Fisheries Research Institute, P.O. Box 1881, Kisumu, Kenya.

²Kenya Marine and Fisheries Research Institute P.O. Box 81651–80100, Mombasa, Kenya

*Corresponding author E-mail: kevinonsongo33@gmail.com

Abstract

Small indigenous fish species play critical roles in livelihoods across Sub-Saharan Africa, yet their value chains remain poorly understood, particularly regarding gender dynamics and economic constraints. This study examined income levels, livelihood diversification, value chain constraints, and gender-differentiated roles in the Omena (*Rastrineobola argentea*) value chain along Kenya's Lake Victoria shores. Primary data were collected from 115 respondents (31 producers, 29 processors, 55 traders) across five riparian counties. Results revealed significant seasonal income variation, with boat owners earning mean monthly incomes of KES 72,441 (low season) to KES 126,000 (high season; 73.9% increase, $p < 0.001$), while crew earned KES 9,548 to KES 24,651 (158.2% increase, $p = 0.010$). Producers demonstrated long-term commitment (mean 15.7 years' experience), with 51.6% engaging in vertical integration across multiple value chain segments. Post-harvest losses affected 80.6% of producers and 54.5% of traders, representing critical systemic inefficiency. The value chain exhibited extreme gender segmentation: production was 71% male-dominated while processing (93% female) and trading (80% female) showed overwhelming female concentration. Among boat owners, male monthly earnings (KES 151,469) exceeded female earnings (KES 58,083) by 2.6-fold. Processing revealed net-drying dominance (96.6%), with 82.1% targeting human consumption versus animal feed. Multiple intersecting barriers constrain women's advancement: limited asset control, cultural restrictions on night fishing, time poverty from domestic responsibilities, and mobility constraints. These findings demonstrate Omena fishing as a sustained livelihood strategy generating substantial income alongside persistent gender inequities, post-harvest inefficiencies, and seasonal vulnerabilities. Transformative value chain development requires integrated interventions addressing post-harvest infrastructure, gender-equitable access to productive assets, financial inclusion mechanisms, and climate-resilient processing technologies while centering women's voices in policy formulation.

Keywords: Omena, value chain, livelihoods, gender, constraints, income, small-scale, post-harvest loss

Introduction

Small indigenous fish species (SIFS), typically defined as species measuring 6–10 cm when mature, have emerged as critical yet undervalued components of global food systems, contributing significantly to nutrition security, livelihoods, and sustainable development (FAO, 2014; Thilsted *et al.*, 2016). Globally, small-scale fisheries, which predominantly harvest these species, account for approximately 40% of total fish catch and 44% of the economic value generated by fisheries worldwide, while directly supporting nearly 500 million people's livelihoods, with women comprising nearly half of this workforce (Basurto *et al.*, 2025; FAO, 2022). In 2022, approximately 26 million tonnes of small pelagic species were landed globally from wild-capture fisheries, with 76% used for direct human consumption and 24% processed into fishmeal and fish oil, primarily for aquaculture feed (FAO, 2024; IFFO, 2024).

In Sub-Saharan Africa (SSA), where approximately one-third of the global population suffering from chronic hunger resides, small indigenous fish species have assumed paramount importance for food and nutrition security among the poor and marginalized communities (Aura *et al.*, 2022; Muringai *et al.*, 2021). African waters are endowed with micronutrient-rich SIFS including the Silver cyprinid (*Rastrineobola argentea*) found in Lake Victoria, Usipa (*Engraulicypris sardella*) of Lake Malawi, Kapenta (*Limnothrissa miodon*) in Lakes Cahora Bassa, Kariba, Kivu, and Tanganyika, and Guinean sprat (*Pellonula leonensis*) in Lakes Kainji and Volta (Muringai *et al.*, 2021; Hasselberg *et al.*, 2020). These species, typically sun-dried and consumed whole, serve as vital sources of animal-source foods for resource-poor households who cannot afford larger, more expensive fish species (AU-IBAR, 2018). Small-scale fisheries in Africa contribute disproportionately to global catch and nutrition, making them indispensable for achieving Sustainable Development Goal 2 on ending hunger and achieving food security (Basurto *et al.*, 2025). However, the sector faces critical challenges including overfishing, deterioration of natural habitats, climate change impacts, and inadequate policy frameworks that fail to recog-

nize the nutritional and economic significance of SIFS (Aura *et al.*, 2022; Kolding *et al.*, 2019). The tension between using these species for direct human consumption versus industrial applications, particularly as fishmeal and fish oil for aquaculture feed, poses significant food security implications for vulnerable populations (Pounds *et al.*, 2025; WorldFish, 2018).

In East Africa, the Lake Victoria Basin stands as a critical epicenter for small fish fisheries, supporting over 33 million people residing in the basin area across Kenya, Tanzania, and Uganda (Hasselberg *et al.*, 2020; Kolding *et al.*, 2019). The region's fisheries employ over two million people and generate substantial economic value through both domestic consumption and regional trade (The EastAfrican, 2020). *Rastrineobola argentea*—locally known as dagaa in Tanzania, omena in Kenya, and mukene in Uganda—has emerged as the dominant fishery in Lake Victoria, accounting for 72% of the lake's total landings by volume (The EastAfrican, 2020; AU-IBAR, 2018). This small zooplanktivorous cyprinid, rarely exceeding 8 cm in length, has an estimated biological production of approximately 5.5 million tonnes per year in Lake Victoria, with a potential sustainable yield exceeding 2 million tonnes annually—four times the current harvest levels (Kolding *et al.*, 2019; Hasselberg *et al.*, 2020). Regional trade in omena has expanded significantly, with production rising from 418,590 tonnes in 2010 to 674,616 tonnes in 2015, reflecting both stock abundance and increased fishing effort (WorldFish, 2018). Uganda and Tanzania emerged as net exporters, with major destinations including the Democratic Republic of Congo (15,015 tonnes annually), Kenya (4,374 tonnes), South Sudan (4,069 tonnes), and Rwanda (WorldFish, 2018). The species serves dual purposes: approximately 30% is consumed as human food, while over 70% enters industrial feed mills as raw material for poultry, fish, and livestock feeds, highlighting the ongoing tension between nutritional and commercial applications (WorldFish, 2018; Pounds *et al.*, 2025).

In Kenya, fisheries constitute a vital economic sector, with total fish production reaching 168,424 tonnes valued at KES 39.6 billion (ap-

proximately USD 297 million) in 2024, representing a 4.4% increase from the previous year (Kenya Fisheries Service, 2024). The country's aquatic resources include Lake Victoria (4,128 km²), Lake Turkana (6,405 km²), and numerous smaller water bodies, with an additional 600 km of coastal shoreline providing marine fishing opportunities (Greenlife, 2025). Inland capture fisheries dominate production, contributing 52% of total output (86,527 tonnes), with Lake Victoria alone accounting for 67,575 tonnes valued at KES 10.8 billion in 2024 (KeFS, 2024). Despite Kenya controlling only 6% of Lake Victoria's total surface area (4,100 km²), the lake contributes approximately 60% of the country's total fish production and supports critical livelihoods for lakeside communities across five counties: Homa Bay, Siaya, Kisumu, Busia, and Migori (Aura *et al.*, 2023; KeFS, 2024). The Kenyan portion of Lake Victoria produced three commercially significant species in 2024: *Rastrineobola argentea* (Omena) at 30,483 tonnes, *Oreochromis niloticus* (Nile tilapia) at 11,200 tonnes, and *Lates niloticus* (Nile perch) at 7,136 tonnes, with Haplochromines contributing an additional 15,433 tonnes (Eastleigh Voice, 2025). Notably, Omena has emerged as the dominant species by volume, representing over 45% of Lake Victoria's total catch in the Kenyan sector and surpassing 50% in recent assessments—a dramatic shift from historical patterns where Nile perch dominated (Aura *et al.*, 2023; KeFS, 2024).

Lake Victoria's dominance in Kenya's Omena production is unequivocal, with the lake serving as the exclusive natural source of this species within the country's borders. Comparative analysis of Kenya's major water bodies reveals that while Lake Turkana produced 15,618 tonnes of total fish in 2024 (predominantly Nile perch and tilapia), and other lakes including Baringo (456 tonnes), Naivasha (declining production), and Jipe (319 tonnes) contribute to national fisheries, none support commercial Omena fisheries (KeFS, 2024). The estimated value of Omena at landing sites ranges from KES 350–420 per kilogram for dried product, with significant sea-

sonal and quality-based price variations (eCAS, 2022–2025). The fishery employs distinct value chain actors including night fishers using light attraction methods, predominantly female processors who sun-dry the catch, and traders who distribute product to urban centers and regional markets (The EastAfrican, 2020; AU-IBAR, 2018). However, the sector faces critical constraints: post-harvest losses exceed 40% due to inadequate drying infrastructure, suboptimal handling practices, and weather-related spoilage during rainy seasons (AU-IBAR, 2018; WorldFish, 2018). Quality degradation from sand, grass, and microbial contamination renders approximately 80% of dried product suitable only for animal feed rather than human consumption markets (The EastAfrican, 2020). Environmental pressures including pollution, eutrophication, water hyacinth proliferation, and climate change threaten long-term sustainability, with KMFRI projecting potential 36–45% reductions in fishing effort needed to maintain ecological balance (Aura *et al.*, 2023).

This study therefore seeks to address these knowledge gaps through comprehensive analysis of the Omena value chain in Kenya's Lake Victoria region, with specific focus on small-scale producers, processors, and traders operating within the Migori, Homa Bay, Siaya, Kisumu, and Busia counties. The research is guided by four specific objectives: The study aims to assess how Omena moves from water to market, examining fishing methods, processing and drying techniques, storage, packaging, transport, and pricing; to explore income levels, sources of income, reliance on fishing versus other work, and business scale among value chain actors; to analyze gender dynamics including men's and women's roles, income control, barriers women face, and differences in decision-making power and resource access. By addressing these, this research provides empirical foundation for evidence-based interventions to strengthen the Omena value chain while balancing competing demands for this critical small fish resource.

Materials and Methods

Study Area

This study was conducted along the Kenyan shores of Lake Victoria, where primary data were collected across five riparian counties—Migori, Homa Bay, Busia, Siaya, and Kisumu. The data captured fishing, processing, and trading activities during the transition period between seasons (Njiru *et al.*, 2008). The study focused on major Omena landing sites including Sori, Litare, Uhanya, Sindo, Ngore, Dunga, Kibro, Marenga, and Asat. The sites function as critical nodes for catch landing, processing, and wholesale trading across the study counties (Aura *et al.*, 2022; Kamau & Ngigi, 2013).

Study Design

This study employed a mixed-methods research design combining primary cross-sectional survey data with secondary longitudinal data analysis to comprehensively examine the Omena value chain. The primary survey component utilized structured questionnaires administered to purposively sampled value chain actors. This design enabled quantification of income levels and livelihood diversification, identification of production-processing-trade constraints, and examination of gender-differentiated roles and barriers across the value chain (Creswell & Creswell, 2018).

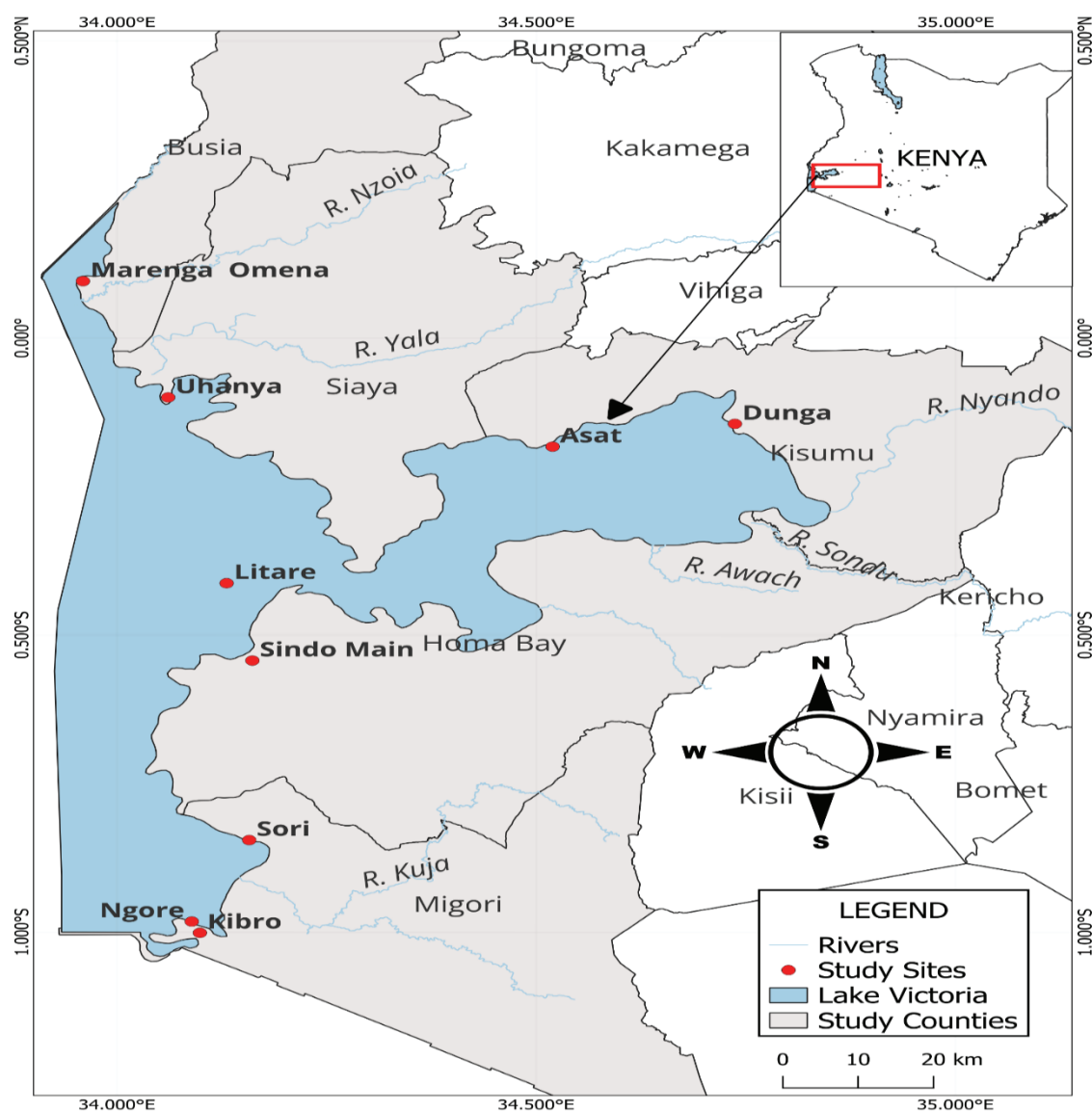


Figure 1: Sites where the study was conducted along the 5 riparian counties that border the Lake Victoria, Kenya (Migori, Homabay, Kisumu, Siaya, Busia).

Data collection

Primary data was collected through structured face-to-face interviews using three different questionnaires developed for producers, processors, and traders. The producer questionnaire captured fishing methods and effort, boat and gear assets, catch volumes and prices, crew sharing systems, seasonal variations, operating costs, post-harvest losses, employment patterns, climate perceptions, and gender roles in fishing households. The processor questionnaire focused on drying methods and surfaces, storage facilities, processing losses and quality issues, labor employment, value addition practices, and market linkages. The trader questionnaire documented volumes traded, buying and selling prices by quality grade, transport modes and costs, storage capacity, market destinations, trading agreements, and seasonal trading patterns. All questionnaire included gender-sensitive modules examining household decision-making, income control, asset access, time allocation, and gender-specific constraints. Questionnaires were piloted and administered in Kiswahili and English by trained enumerators. Informed consent was obtained following ethical protocols (Israel & Hay, 2006).

Data analysis

Data were analyzed using descriptive and inferential statistics in Jamovi and Excel. Descriptive statistics (frequencies, means, medians, standard deviations) characterized demographic profiles, income levels, catch volumes, prices, and participation patterns. Comparative analyses using t-tests and ANOVA examined differences in income and constraints across value chain segments, seasons, and gender. Chi-square tests assessed associations between categorical variables (gender, value chain role, decision-making, resource access). Regression analysis identified income determinants and post-harvest loss factors. Value chain mapping visualized Omena flows and margin distribution. Gender analysis utilized the Harvard Analytical Framework examining resource access/control, labor division, benefits, and constraints (March *et al.*, 1999).

Results and discussion

Sociodemographic

The sociodemographic of Omena value chain actors reveals significant patterns in gender distribution and age composition across different segments. Gender distribution exhibited statistically significant variation across value chain segments ($\chi^2 p < 0.001$), with pronounced occupational segregation reflecting deeply entrenched cultural and economic divisions of labor. Production remained male-dominated at 71.0% ($n = 22$), consistent with broader patterns in African small-scale fisheries where men control access to boats, fishing gear, and night fishing operations that characterize Omena harvesting (Fröcklin *et al.*, 2013; Kleiber *et al.*, 2017). In stark contrast, processing demonstrated extreme female concentration at 93.1% ($n = 27$ of 28), with only one male processor recorded, mirroring trends across sub-Saharan Africa where women constitute up to 90% of post-harvest workforce engaged in labor-intensive fish drying and preservation activities (WorldFish, 2024; Nabayunga *et al.*, 2021). Trading exhibited female majority at 80.0% ($n = 44$ of 55), positioning women as dominant actors in market distribution despite systematic disadvantages in pricing power, market access, and mobility constraints documented throughout East African fisheries contexts (Ameyaw *et al.*, 2020; Torell *et al.*, 2021). Overall, women comprised 70.2% of total value chain actors ($n = 80$ of 114), yet their numerical dominance masks economic marginalization, as they are concentrated overwhelmingly in post-harvest segments that generate narrower profit margins compared to male-dominated high-value production activities, perpetuating gender-based income disparities and limiting wealth accumulation opportunities (Béné & Merten, 2008; Rice *et al.*, 2024). Age distribution across value chain segments revealed statistically significant differences ($F = 5.23$, $p = 0.006$), with processors averaging younger (37.9 ± 7.8 years, range 23–57) compared to producers (44.3 ± 10.1 years, range 23–63) and traders (44.4 ± 10.1 years, range 29–73) as shown in Table 2. The overall mean age of 42.8 ± 9.9 years indicates that Omena value chain participants are predominantly middle-aged adults in their economically productive years, challenging narratives of fishing as employment of last resort for

youth or elderly populations and instead revealing it as sustained livelihood strategy for experienced workers (Béné, 2006; Allison & Ellis, 2001). The younger average age among processors likely reflects the physically demanding nature of fish handling, spreading, and turning during sun-drying processes, which may favor younger workers with greater physical stamina, while the broader age range among traders (29–73 years) suggests trading activities accommodate diverse age groups and may represent livelihood transitions as individuals age out of more physically intensive roles (Harper *et al.*, 2020). The relatively narrow standard deviations across all segments indicate age homogeneity within each value chain node, suggesting that actors tend to cluster around similar life stages, potentially reflecting cohort effects in entry to the fishery or age-specific role specialization driven by household responsibilities, physical capacity, and accumulated capital that varies across the life course (Cinner & Bodin, 2010).

Income levels and livelihood diversification

Income analysis revealed significant seasonal variations across producer categories, patterns consistent with small pelagic fisheries globally where resource abundance drives concentrated income generation during specific periods (Kolding *et al.*, 2019; Béné & Friend, 2011). As shown in Figure 2, boat owners earned substantially higher

incomes than crew members, with mean monthly earnings of KES 72,441 during low season increasing to KES 126,000 during high season (73.9% increase, $p < 0.001$), while crew earned considerably less with mean monthly incomes of KES 9,548 (low season) increasing to KES 24,651 (high season), representing a proportionally larger 158.2% increase ($p = 0.010$). This differential seasonal response suggests crew earnings are more tightly linked to catch volumes whereas boat owners’ incomes may be partially buffered by asset ownership and ability to adjust fishing effort strategically (Fröcklin *et al.*, 2013; Béné *et al.*, 2010). The median values (boat owners: KES 19,000 to 75,000; crew: KES 4,300 to 15,000) were consistently lower than means, indicating right-skewed income distributions with a small number of high earners pulling up averages, while standard deviations exceeding means in most categories revealed substantial within-group inequality, likely reflecting heterogeneous fishing operations with differential access to productive assets (boat capacity, gear quality), prime fishing grounds, and high-value market networks (Béné *et al.*, 2010; Geheb *et al.*, 2008). Comparing crew median incomes (KES 4,300–15,000 month⁻¹) to Kenya’s official poverty line (KES 3,252 month⁻¹; KNBS, 2018) and minimum wage (KES 13,572 month⁻¹ for general workers), crew earnings fall in the lower-middle income range, confirming Omena fishing’s role as critical

employment for vulnerable populations while highlighting income inadequacy for many participants (Geheb *et al.*, 2008; Fiorella *et al.*, 2014). The statistically significant seasonal differences ($t = 5.75$ for boat owners, $t = 2.81$ for crew) underscore not only the critical importance of high season to annual income generation but also point to the need for seasonal credit facilities and income smoothing mechanisms to support consumption during low season periods when fishing intensity and earnings decline sharply (Allison & Ellis, 2001; Béné & Friend, 2011).

Table 1: Gender distribution for the respondents across all the counties where the study took place.

Value Chain Segment	Male	Female	Total	Chi-square
Producers (n = 31)	22 (71.0%)	9 (29.0%)	31	P < 0.001
Processors (n = 28)	1 (3.4%)	27 (93.1%)	28	
Traders (n = 55)	11 (20.0%)	44 (80.0%)	55	
Total (n = 114)	34 (29.8%)	80 (70.2%)	114	

Table 2: Age distribution for the respondents across all the counties where the study took place.

Segment	n	Mean (SD)	Range	F-statistic
Producers	31	44.3 (± 10.1)	23–63	F = 5.23 p = 0.006
Processors	28	37.9 (± 7.8)	23–57	
Traders	55	44.4 (± 10.1)	29–73	
Overall	114	42.8 (± 9.9)	23–73	

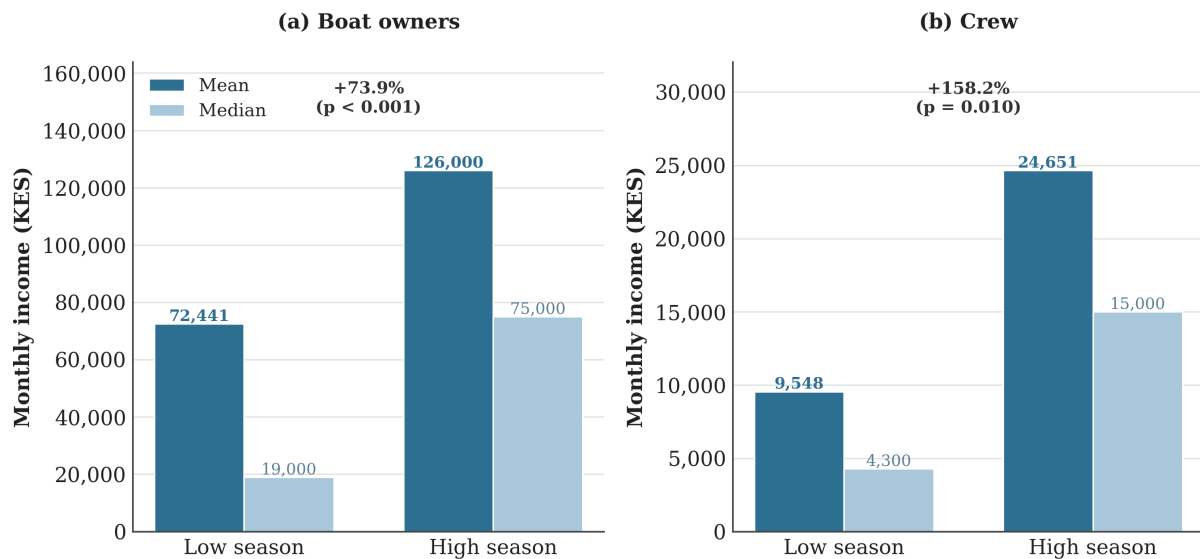


Figure 2: The average monthly income for the producer both the low and high season for a, the boat owners and b, the crew who engage in the Omena daily catch in Lake Victoria Kenya.

Livelihood Experience and Diversification

Producers demonstrated substantial livelihood commitment to Omena fishing, with mean experience of 15.7 years as demonstrated in figure. This contradicts narratives of fishing as temporary or last-resort employment and instead revealing omena fishing as a sustained, long-term livelihood strategy (Béné, 2006; Allison & Ellis, 2001). This extended experience base, with 58.1% having over 10 years in the fishery, indicates development of specialized skills, accumulated local ecological knowledge on fishing grounds and seasonal patterns, and embedded social capital within the sector—assets that become increasingly valuable over time and may create barriers to exit even when incomes are modest (Cinner & Bodin, 2010). Importantly, this experiential knowledge represents critical human capital that should be systematically integrated into co-management frameworks and fisheries policy formulation through participatory processes rather than relying solely on top-down scientific management (Jentoft, 2000; Berkes, 2009). Regarding livelihood diversification strategies, 51.6% ($n = 16$) of producers engaged in vertical integration, participating in multiple value chain segments beyond fishing such as sun-drying their catch during periods of low beach prices or buying from other fishers to trade in urban markets, reflecting strategic

risk management and income enhancement whereby actors capture value at multiple nodes, smooth income across fishing and non-fishing periods, gain market intelligence, and exercise greater control over product quality and pricing (Ellis, 2000; Thorpe *et al.*, 2005; Ferrol-Schulte *et al.*, 2013). This finding aligns with livelihood diversification theory emphasizing portfolios of income sources as vulnerability reduction strategies in seasonally variable and unpredictable environments, though diversification success depends critically on available capital, skills, market access, and time—potentially limiting participation by the poorest fishers and thereby reinforcing existing inequalities (Béné *et al.*, 2016). The 48.4% ($n = 15$) who specialized exclusively in production may reflect either insufficient capital to invest in downstream activities, time constraints from intensive fishing operations, or strategic choices to maximize fishing productivity through focused effort. Business association membership was remarkably high at 77.4% ($n = 24$), primarily through Beach Management Units (BMUs), indicating strong social capital and collective organization that provides platforms for collective action on resource management, access to government support and extension services, collective marketing arrangements, conflict resolution mechanisms, and representation in policy processes (Njaya *et al.*, 2012; Nunan, 2014). However, while BMU membership is wide-

spread, effectiveness varies considerably across landing sites, with many facing persistent challenges including elite capture of benefits and decision-making, weak internal governance structures, inadequate financial and technical resources, and limited capacity for enforcement of fishing regulations or collective marketing initiatives (Nunan, 2014; Ratner *et al.*, 2014). These findings collectively demonstrate that Omena fishing represents neither purely specialized dependence nor completely diversified portfolios, but rather a continuum of livelihood strategies wherein producers balance deep sectoral commitment and experiential investment with strategic diversification to manage seasonal and market risks, leveraging both individual adaptive capacity and collective organizational structures to navigate an inherently uncertain and variable livelihood environment.

Constraints affecting production, processing, and trade

Post-harvest losses constituted a major constraint across the value chain. Among producers, 80.6% ($n = 25$ of 31) reported experiencing post-harvest losses, while 54.5% of traders ($n = 30$ of 55) encountered similar challenges. Primary causes of losses among producers in-

cluded spoilage, pest infestation, theft, poor drying conditions, contamination, and delayed landing all reported by substantial proportions of respondents. These losses directly reduce income, threaten food security, and undermine value chain efficiency. The high prevalence of post-harvest losses points to critical infrastructure deficits (drying facilities, storage), technical capacity gaps (proper handling, processing techniques), and coordination failures (timely market linkages) requiring urgent attention in interventions. These findings align with patterns observed across Lake Victoria fisheries, where inadequate infrastructure and poor handling practices drive physical, quality, and market-related losses at multiple value chain nodes (Marigu *et al.*, 2023). The multiple causes identified spoilage, pest infestation, theft, poor drying conditions, contamination, and delayed landing mirror those documented in recent assessments of East African fisheries, where delays in net hauling, absence of proper storage facilities, and reliance on traditional sun-drying methods expose fish to environmental contamination and accelerated deterioration (Asmare *et al.*, 2024; Owaga *et al.*, 2017). In Kenya's Lake Victoria region, over 97% of sun-drying operations occur directly on bare ground or old fishing nets, exposing Omena

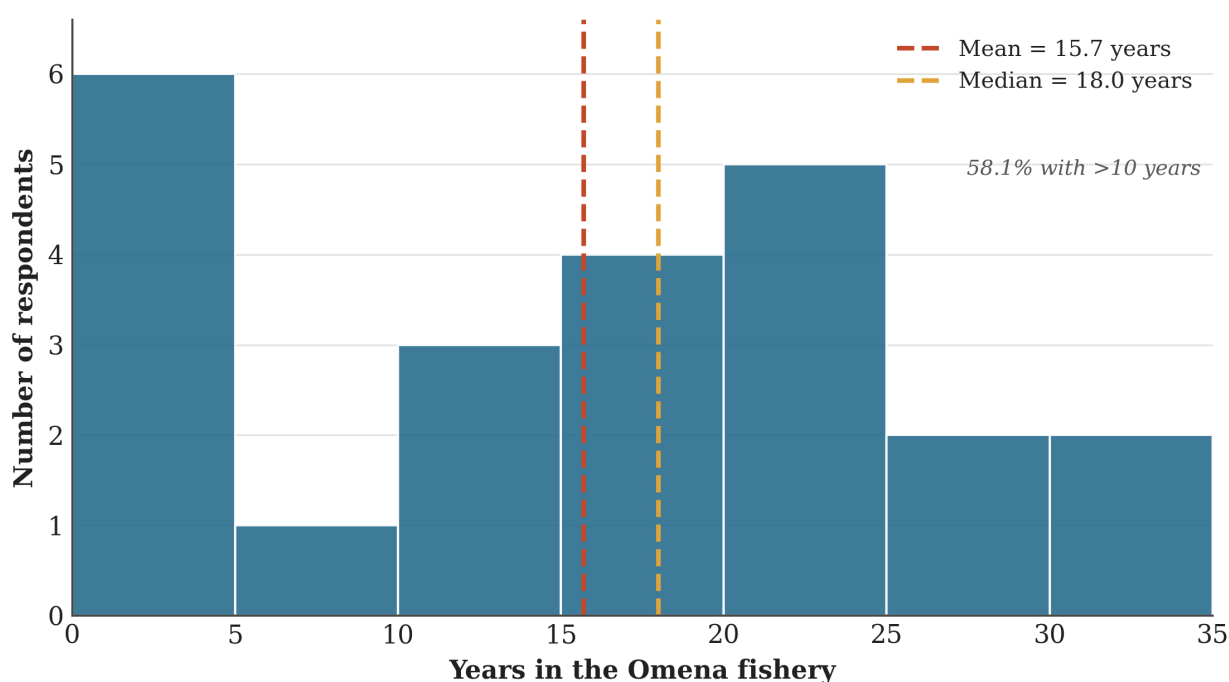


Figure 3: The average number of years fishermen have been involved in fishing of Omena in Lake Victoria, Kenya.

to dust, animal scavenging, and weather fluctuations that compromise quality and reduce shelf life (Onyango *et al.*, 2017). The infrastructure deficits identified here particularly the absence of cold storage, ice-making facilities, and proper drying structures have been repeatedly cited as critical barriers to loss reduction across African fisheries, with recent governmental initiatives investing billions of shillings in landing site infrastructure to address these gaps (Kenya News Agency, 2024). Technical capacity limitations exacerbate infrastructure shortcomings, as many value chain actors lack training in proper fish handling, hygienic processing techniques, and time-temperature control necessary to prevent microbial growth and biochemical degradation that drive spoilage (Lokuruka, 2016; Ward & Signa, 2017). Coordination failures between producers and markets result in delayed sales and forced acceptance of lower prices, particularly affecting women traders who face systematic disadvantages in market access and often absorb losses when fish spoils before reaching buyers (Tesfay & Teferi, 2017). The economic consequences of these losses are severe, with recent studies from Lake Tana estimating annual financial losses ex-

ceeding 5,000 Ethiopian Birr per fisher losses that translate directly into reduced household income, diminished food security, and perpetuation of poverty among fishing communities (Asmare *et al.*, 2024). The persistence of post-harvest losses despite widespread recognition of their impact suggests that technological solutions alone are insufficient; effective interventions require integrated approaches combining infrastructure development, skills training, market linkages, and supportive policies that address the multiple intersecting causes simultaneously (Affognon *et al.*, 2015; Entee, 2015).

Gender Roles, Income Control, And Barriers

Production (fishing) remained male-dominated with 71.0% male ($n = 22$), 29.0% female ($n = 9$) participation. In contrast, processing exhibited extreme female concentration at 93.1% ($n = 27$ of 29), with only one male processor recorded. Under Trading, it showed female majority at 80.0% ($n = 44$ of 55) as reflected on figure 5. Overall, women comprised 70.2% of total value chain actors ($n = 80$ of 114), concentrated overwhelmingly in post-harvest segments (processing, small-scale trading)

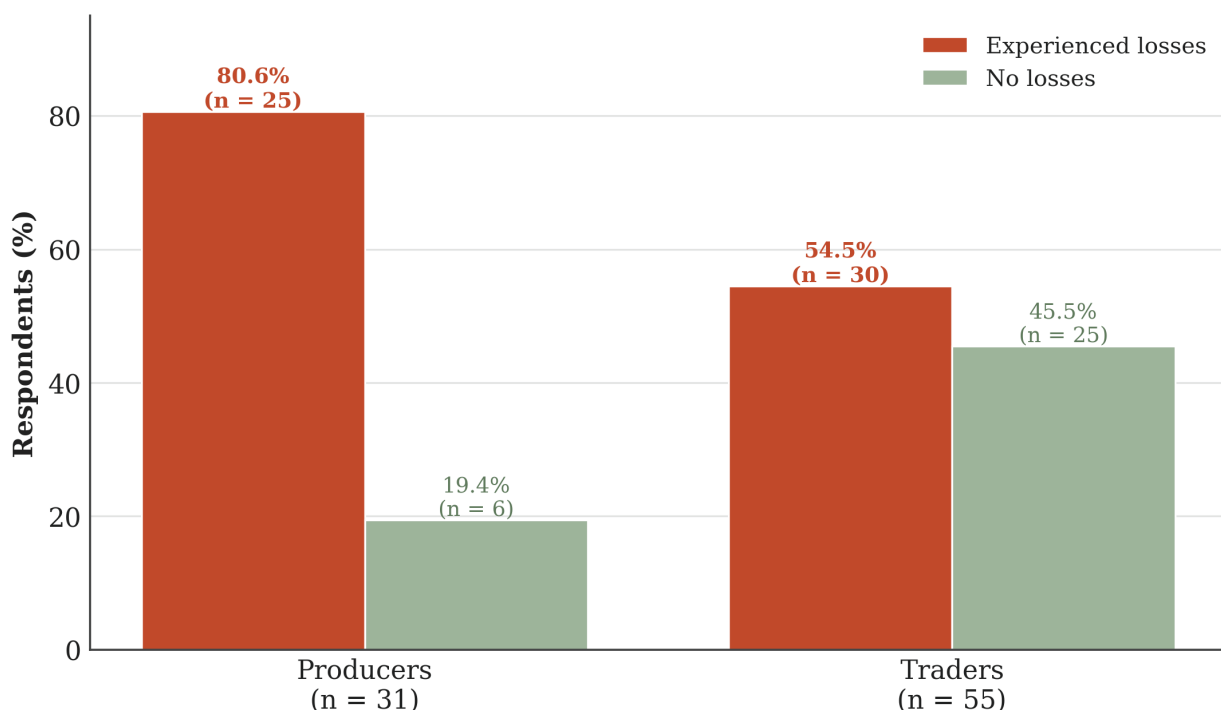


Figure 4: The level of post-harvest loss experienced by both the producers and the traders across the Omena value chain actors in Lake Victoria, Kenya.

while men dominated high-value production activities. These findings align with widespread gender segmentation patterns documented across African small-scale fisheries, where women comprise most post-harvest workers while men dominate extractive activities (Nabuyunga *et al.*, 2021). The extreme concentration of women in processing (93.1%) mirrors trends observed throughout sub-Saharan Africa, where women account for up to 90% of those engaged in post-harvest activities such as processing and trading (WorldFish, 2024). This occupational segregation reflects deeply embedded cultural norms and institutional barriers that systematically channel women into labor-intensive, lower-margin segments of the value chain while restricting their access to productive technologies and high-value fishing activities (Torell *et al.*, 2015; Weeratunge *et al.*, 2018). The male dominance in production activities documented here is consistent with findings from Lake Victoria and other East African fisheries, where men control access to boats, fishing gear, and night fishing operations that yield higher returns (Fröcklin *et al.*, 2013; Rice & Gondwe, 2024). Women's marginal participation in fishing (29.0%) often stems from socio-cultural restrictions including be-

liefs that women aboard fishing vessels bring bad luck, prohibitions on night fishing, and limited access to credit for purchasing productive assets (Kaminski *et al.*, 2017; Kleiber *et al.*, 2017). The concentration of women in trading (80.0%) reflects patterns across West and East African fisheries where women traders face systematic disadvantages including being offered fish at higher prices than male traders, having restricted access to high-value species, and lacking formal market infrastructure (Fröcklin *et al.*, 2013; Ameyaw *et al.*, 2020). Recent research emphasizes that this gendered division of labor perpetuates economic inequality, as post-harvest activities typically generate narrower profit margins compared to direct fish capture, thereby reinforcing women's economic vulnerability despite their numerical dominance in the value chain (Béné & Merten, 2008; Rice *et al.*, 2024). Furthermore, women's substantial yet invisible contributions to fisheries through unpaid reproductive labor—including net mending, baiting, fish cleaning, and household provisioning remain unrecognized in formal fisheries statistics and governance structures, further marginalizing their participation in decision-making processes (Harper *et al.*, 2020; Galappaththi *et al.*, 2022).

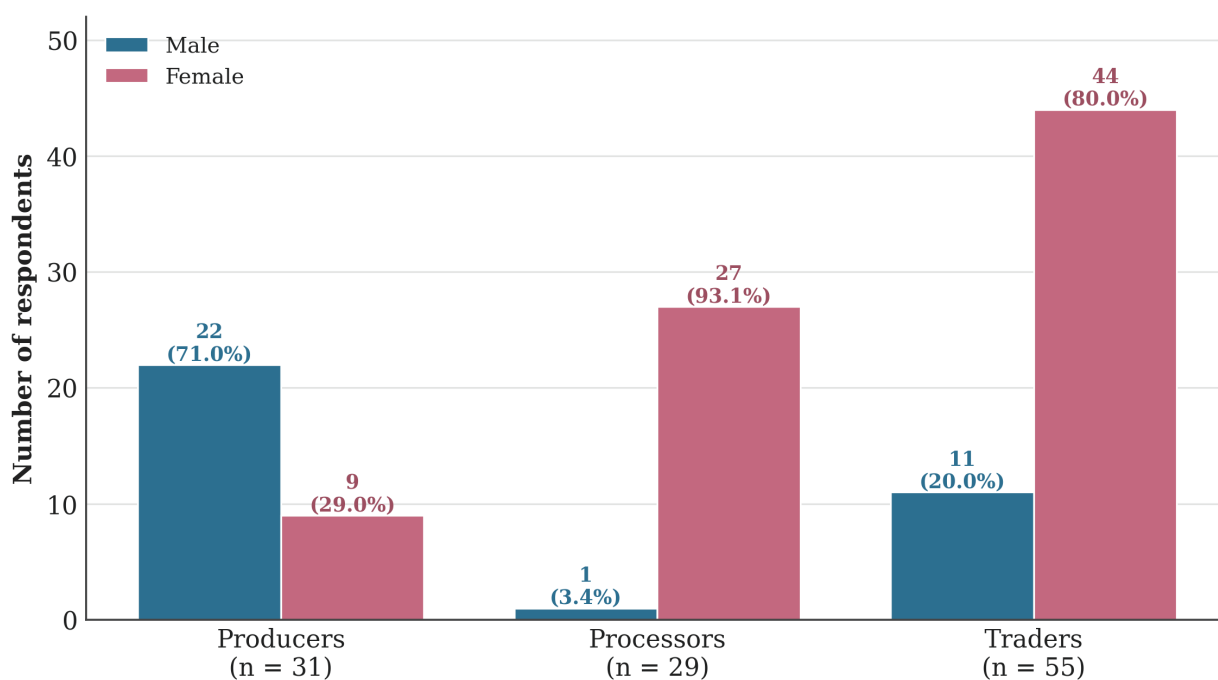


Figure 5: The gender distribution among the producers, traders and processors who are main key players across the Omena value chain.

Gender Income Disparities for the boat owners on the Omena value chain

Among boat owners, substantial gender income gaps emerged. Income disparity is at 2.6:1 indicating that male earnings monthly exceed that of the female by nearly 2.6 times (160%). Male boat owners ($n = 16$) earned mean monthly incomes of KES 151,469 (median KES 93,000) during high season, while female boat owners ($n = 6$) earned KES 58,083 (median KES 48,000). While this difference was not statistically significant at $p < 0.05$ level ($t = 0.86$, $p = 0.399$), likely due to small female sample size and high within-group variability. This finding resonates with broader patterns documented across African fisheries, where women who successfully acquire capital assets continue to face systematic constraints that limit their earning potential. The magnitude of this gap with male boat owners earning nearly 160% more than their female counterparts likely stems from multiple intersecting disadvantages that compound to restrict women's profitability even after they have overcome formidable entry barriers to asset ownership. Research from Kenya's Lake Victoria region indicates that women

boat owners typically operate with smaller vessels, fewer crew members, and less advanced fishing gear compared to men, directly constraining their production capacity and market competitiveness (Adam *et al.*, 2024; FAO *et al.*, 2023). Women's limited access to formal credit institutions, which systematically view them as higher-risk borrowers and require collateral that women rarely control, prevents them from investing in gear upgrades or vessel expansion that could enhance productivity (Nabayunga *et al.*, 2021; Mutia *et al.*, 2020). Beyond capital constraints, women boat owners face temporal disadvantages rooted in gendered household responsibilities, as their continued involvement in unpaid domestic work and childcare limits the fishing effort they can sustain, restricting their ability to maximize high-season earnings when fish abundance peaks (Weeratunge *et al.*, 2018; Harper *et al.*, 2020). Market access disparities further exacerbate income gaps, with evidence from coastal Kenya and Lake Victoria showing that women fish sellers receive lower prices than men for comparable catches due to discriminatory pricing by buyers and limited bargaining power in male-dominated market spaces (To-

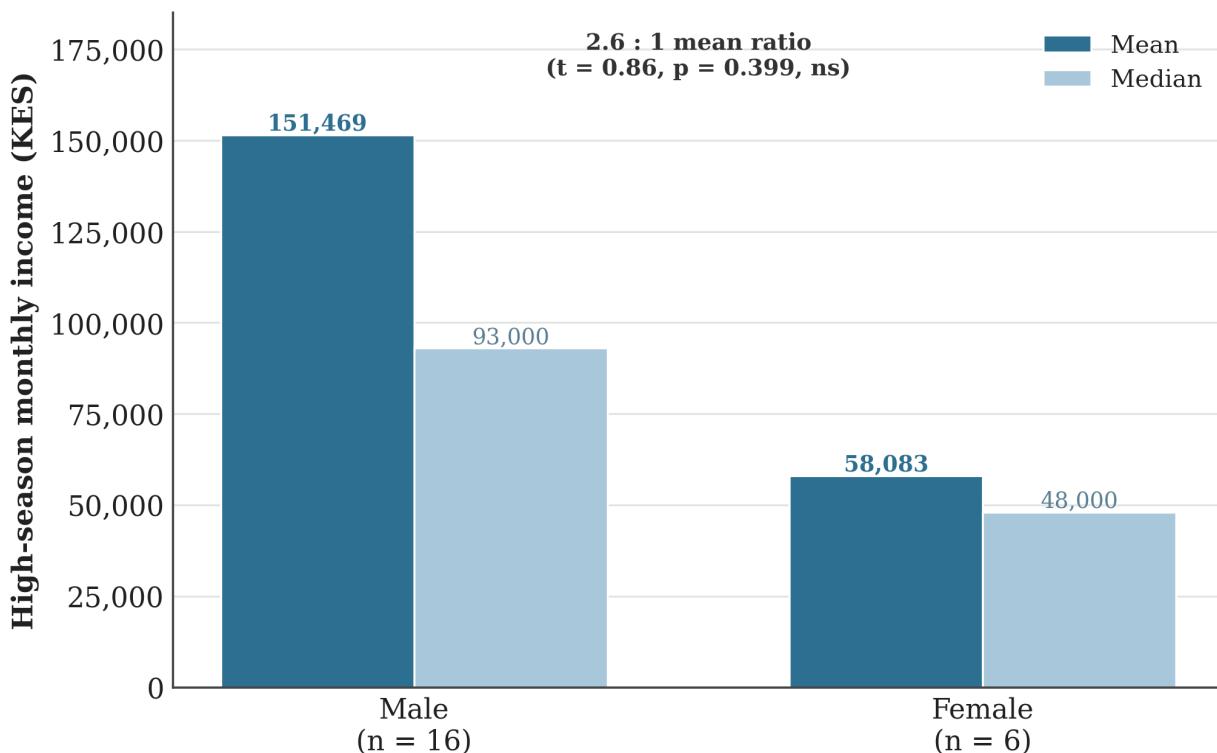


Figure 6: Gender income disparities for male and female producers on the Omena value chain along Lake Victoria, Kenya.

rell *et al.*, 2021; Fröcklin *et al.*, 2013). The lack of statistical significance in this study, attributable to small sample size and high variability, should not diminish the economic and policy relevance of the observed gap, as similar income disparities have been documented consistently across East African fisheries contexts where women's structural disadvantages in accessing technology, labor, and markets systematically depress their returns relative to men's (Kleiber *et al.*, 2017; Ameyaw *et al.*, 2020). This income gap underscores a critical reality: asset ownership alone is insufficient to achieve gender equity in fisheries; transformative interventions must address the multiple layers of discrimination that constrain women's ability to leverage their assets effectively, including targeted credit programs, gender-responsive market infrastructure, household-level negotiations around labor distribution, and policy measures that challenge discriminatory pricing practices (McDougall *et al.*, 2015; Cole *et al.*, 2018).

Barriers to Women's Advancement

The observed patterns point to intersecting systemic barriers that constrain women's economic advancement in the Omena value chain despite their numerical dominance. Women's limited control over productive assets boats, nets, and capital emerges as a foundational constraint that restricts their income potential and channels them into lower-margin activities. Research across African fisheries demonstrates that women boat owners typically operate smaller vessels with fewer crew members and less advanced gear compared to men, directly limiting their production capacity and competitiveness as shown in figure 6 (Murphy *et al.*, 2020; Kaminski *et al.*, 2017). This asset gap reflects deeper structural inequalities in property rights and inheritance systems that systematically disadvantage women, with land ownership and capital assets predominantly controlled by men even in female-headed households (Byamugisha & Ansu, 2017). Cultural norms and social taboos further compound these disadvantages by restricting women's access to high-value fishing activities, with widespread beliefs that women aboard fishing vessels bring

bad luck, prohibitions on night fishing operations that yield the highest catches, and restrictions on boat operation that effectively exclude women from direct extraction activities (Oloko *et al.*, 2024; Kleiber *et al.*, 2017). Time poverty constitutes another critical barrier, as women's disproportionate responsibility for unpaid reproductive labor including childcare, cooking, household provisioning, and care for sick family members limits the hours they can dedicate to fishing or trading activities and prevents them from maximizing earnings during peak seasons (Gustavsson *et al.*, 2021; Harper *et al.*, 2020). Evidence from Kenya and other African contexts shows that women traders face significant mobility restrictions and safety concerns that limit their access to distant high-value markets, with socio-cultural norms discouraging women from traveling alone for business purposes and exposing them to gender-based violence and exploitation including the pervasive "sex for fish" practice where women exchange sexual favors for access to fish supplies (Mugambi, 2025; Torell *et al.*, 2021). Access to formal credit represents a particularly severe constraint, as financial institutions systematically view women as higher-risk borrowers, require collateral such as land titles that women rarely possess, and fail to recognize informal business activities documented through mobile money transactions as legitimate proof of business operations (Njeri, 2025; Githukia *et al.*, 2021). Women in African fisheries also lack the financial literacy and record-keeping skills necessary to become investor-ready, further limiting their ability to secure formal loans for business expansion or gear upgrades (Njeri, 2025). These barriers operate cumulatively and intersectionally, creating a self-reinforcing cycle where limited asset ownership restricts earning potential, low incomes prevent capital accumulation, time poverty limits participation in high-value activities, mobility restrictions reduce market access, and credit exclusion prevents investment in productivity-enhancing technologies (FAO, 2018; Rice *et al.*, 2024). The persistence of these constraints despite women's substantial numerical presence in the value chain demonstrates that increasing women's participation alone is insuf-

ficient; transformative change requires dismantling the structural barriers through targeted interventions including gender-responsive credit programs with flexible collateral requirements, infrastructure investments that reduce time burdens, legal reforms strengthening women's property rights, capacity-building programs on financial literacy and business management, and policy measures that challenge discriminatory social norms and address gender-based violence in fisheries spaces (FAO, 2017; Galapaththi *et al.*, 2022)

Conclusion and recommendations

This study reveals the critical importance of Omena (*Rastrineobola argentea*) for livelihoods in Kenya's Lake Victoria region while exposing profound structural inequalities limiting the value chain's potential. Producers demonstrated long-term commitment with 15.7 years average experience and strategic diversification, earning KES 126,000 (boat owners) to KES 24,651 (crew) during high season, with substantial seasonal variations highlighting vulnerability and need for income-smoothing mechanisms. The most significant finding concerns severe gender segmentation. While women comprise 70.2% of value chain actors, they are concentrated in lower-margin post-harvest segments (93.1% of processors, 80.0% of traders) while men dominate high-value production (71.0%). The 2.6:1 income disparity between male and female boat owners reflects systematic constraints including limited asset ownership, restricted credit access, time poverty, mobility restrictions, and discriminatory pricing that trap women in economically marginal positions despite their numerical dominance. Post-harvest losses affecting 80.6% of producers and 54.5% of traders, driven by infrastructure deficits and coordination failures, further undermine value chain efficiency and food security. Strengthening the Omena value chain requires moving beyond increasing women's participation to dismantling structural barriers through integrated interventions: gender-responsive credit programs, infrastructure development, legal reforms strengthening property rights, capacity-building on financial literacy, safe market infrastructure, and poli-

cies challenging discriminatory norms. By simultaneously addressing gender inequalities, post-harvest losses, and seasonal income volatility, stakeholders can enhance both efficiency and equity of this critical fishery supporting millions across the Lake Victoria basin. Based on the aforementioned, following recommendations maybe implemented to support the Omena (*rastrineobola argentea*) value chain in Lake Victoria: livelihoods, gender dynamics, and constraints among small scale actors.

Gender-Responsive Financial Inclusion

Financial institutions and government agencies should develop targeted credit programs specifically designed for women in the Omena value chain, featuring flexible collateral requirements that recognize alternative assets such as mobile money transaction histories, group guarantees, and movable property. Microfinance institutions should establish women-focused loan products with lower interest rates and longer repayment periods aligned with seasonal fishing patterns, enabling women to invest in larger vessels, advanced fishing gear, and improved processing equipment. Additionally, financial literacy training programs should be implemented to enhance women's capacity in business management, record-keeping, and investment planning, making them more investor-ready and capable of accessing formal financial services.

Infrastructure Development for Post-Harvest Loss Reduction

Government and development partners must invest in critical infrastructure at major landing sites, including covered drying platforms with raised surfaces to prevent ground contamination, cold storage facilities for preserving fresh catch during peak seasons, ice-making plants to maintain product quality during transport, and weatherproof storage warehouses to protect dried Omena from rain and pests. These investments should prioritize sites with highest production volumes and incorporate community participation in design and management to ensure sustainability. Technical training should accompany infrastructure development, equip-

ping processors with hygienic handling practices, optimal drying techniques, proper storage methods, and quality grading systems that can command premium prices in urban markets.

Market Access and Value Addition Support

Establish market linkages connecting producers and processors directly to high-value urban markets, institutional buyers, and export opportunities, reducing dependence on exploitative middlemen who offer discriminatory prices. Support women traders through provision of safe market infrastructure including designated trading spaces with security, toilet facilities, and childcare centers that reduce time poverty constraints. Promote value addition activities such as packaging in consumer-friendly sizes, branding for quality differentiation, and product diversification into ready-to-eat snacks and fortified blended foods that capture higher margins. Government should enforce standardized quality grading systems and fair pricing mechanisms that prevent discriminatory practices against women sellers.

Legal and Policy Reforms

Strengthen legal frameworks governing women's property rights and asset ownership, particularly regarding inheritance of fishing vessels and gear, and ensure effective enforcement of existing laws. Review and reform fisheries policies to explicitly recognize women's contributions across the entire value chain, not just in post-harvest activities, and mandate their participation in Beach Management Units and fisheries governance structures. Develop social protection programs including seasonal safety nets, weather-indexed insurance schemes, and pension provisions for aging fishers who have dedicated decades to the sector.

Capacity Building and Organizational Strengthening

Invest in technical training for all value chain actors on improved fishing techniques, sustainable harvesting practices, hygienic processing methods, and business management skills. Strengthen Beach Management Units through provision of adequate resources, governance training, and

enforcement capacity to ensure they serve as effective platforms for collective action rather than elite-captured structures. Facilitate formation of women-led cooperatives that can achieve economies of scale in purchasing inputs, accessing credit, and marketing products collectively. These integrated recommendations require coordinated action across government agencies, development partners, financial institutions, and community-based organizations to transform the Omena value chain into an equitable, efficient, and sustainable source of livelihoods and nutrition security for Lake Victoria communities.

References

- Abelti A, Teka T (2024) Post-harvest fish losses and loss reduction strategies in small-scale fisheries of Ethiopia. *Fisheries Research*, 270: 106875
- Adam MS, Oduor FO, Njiru JM (2024) Gender dynamics in Lake Victoria fisheries: Implications for sustainable management. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, 29(1): e12456
- Affognon H, Mutungi C, Sanginga P, Borgemeister C (2015) Unpacking postharvest losses in sub-Saharan Africa: A meta-analysis. *World Development*, 66: 49–68
- Akintola SL, Fakoya KA (2017) Small-scale fisheries in the coastal area of Ondo State, Nigeria: Status, challenges and prospects. *African Journal of Food, Agriculture, Nutrition and Development*, 17(4): 12618–12632
- Allison EH, Ellis F (2001) The livelihoods approach and management of small-scale fisheries. *Marine Policy*, 25(5): 377–388
- Ameyaw GA, Chaigneau T, Owusu AB, Brown DR (2020) Women's participation in the fishing value chain in coastal Ghana. *Marine Policy*, 120: 104114
- Asmare E, Getahun A, Lemma B (2024) Post-harvest fish loss and its determinants in Lake Tana, Ethiopia. *Cogent Food & Agriculture*, 10(1): 2298765

- African Union Inter-African Bureau for Animal Resources (2018) The fisheries of Lake Victoria: Status, challenges and opportunities
- Aura CM, Kimani E, Musa S, Kundu R, Njiru JM, Oketch R, Waweru V, Ongore C, Okechi J, Obegi B, Wakibia J (2022) Consequences of calamities and their management: The case of COVID-19 pandemic and flooding on inland capture fisheries in Kenya. *Journal of Great Lakes Research*, 48(6): 1424–1435
- Aura CM, Nyamweya CS, Odoli CO, Owiti H, Njiru JM, Otuo PW, Waithaka E, Malala J (2023) Consequences of climate-induced environmental changes on the fish stocks, fisher communities, management and policy of Lake Victoria fisheries. *Fisheries Management and Ecology*, 30(4): 356–372
- Basurto X, Bennett A, Lindkvist E, Schlüter M (2025) Governing the commons in an interconnected world: A social-ecological systems perspective. *Environmental Research Letters*, 20(1): 013001
- Béné C (2006) Small-scale fisheries: Assessing their contribution to rural livelihoods in developing countries (FAO Fisheries Circular No. 1008). Food and Agriculture Organization of the United Nations
- Béné C, Friend RM (2011) Poverty in small-scale fisheries: Old issue, new analysis. *Progress in Development Studies*, 11(2): 119–144
- Béné C, Macfadyen G, Allison EH (2010) Increasing the contribution of small-scale fisheries to poverty alleviation and food security (FAO Fisheries and Aquaculture Technical Paper No. 481). Food and Agriculture Organization of the United Nations
- Béné C, Merten S (2008) Women and fish-for-sex: Transactional sex, HIV/AIDS and gender in African fisheries. *World Development*, 36(5): 875–899
- Béné C, Barange M, Subasinghe R, Pinstrup-Andersen P, Merino G, Hemre GI, Williams M (2016) Feeding 9 billion by 2050: Putting fish back on the menu. *Food Security*, 7(2): 261–274
- Berkes F (2009) Evolution of co-management: Role of knowledge generation, bridging organizations and social learning. *Journal of Environmental Management*, 90(5): 1692–1702
- Byamugisha FFR, Ansu Y (2017) Women's land rights in Africa. World Bank Policy Brief. World Bank
- Cinner JE, Bodin Ö (2010) Livelihood diversification in tropical coastal communities: A network-based approach to analyzing 'livelihood landscapes'. *PLoS ONE*, 5(8): e11999
- Cole SM, McDougall C, Kaminski AM, Kefi AS, Chilala A, Chisule G (2018) Postharvest fish losses and unequal gender relations: Drivers of the social-ecological trap in the Barotse Floodplain fishery, Zambia. *Ecology and Society*, 23(2): 18
- Creswell JW, Creswell JD (2018) Research design: Qualitative, quantitative, and mixed methods approach (5th ed.). Sage Publications
- Eastleigh Voice (2025) Lake Victoria fish production statistics for Kenya 2024. [<https://www.eastleighvoice.com>]
- Ellis F (2000) Rural livelihoods and diversity in developing countries. Oxford University Press
- Entee C (2015) Fisheries of the lower Mekong Basin: Status and perspectives (Mekong River Commission Technical Paper No. 47). Mekong River Commission
- Food and Agriculture Organization of the United Nations (2014) The State of World Fisheries and Aquaculture 2014. Food and Agriculture Organization of the United Nations

- Food and Agriculture Organization of the United Nations (2017) Towards gender-equitable small-scale fisheries governance and development. Food and Agriculture Organization of the United Nations
- Food and Agriculture Organization of the United Nations (2018) The State of World Fisheries and Aquaculture 2018: Meeting the Sustainable Development Goals. Food and Agriculture Organization of the United Nations
- Food and Agriculture Organization of the United Nations (2022) The State of World Fisheries and Aquaculture 2022: Towards blue transformation. Food and Agriculture Organization of the United Nations
- Food and Agriculture Organization of the United Nations (2024) The State of World Fisheries and Aquaculture 2024. Food and Agriculture Organization of the United Nations
- Food and Agriculture Organization of the United Nations, Duke University, WorldFish (2023) Illuminating hidden harvests: The contributions of small-scale fisheries to sustainable development. Food and Agriculture Organization of the United Nations, Duke University, & WorldFish
- Ferrol-Schulte D, Wolff M, Ferse S, Glaser M (2013) Sustainable livelihoods approach in tropical coastal and marine social-ecological systems: A review. *Marine Policy*, 42: 253–258
- Fiorella KJ, Milner EM, Bukusi E, Fernald LC (2014) Quantity and species of fish consumed shape breast-milk fatty acid concentrations around Lake Victoria, Kenya. *Public Health Nutrition*, 17(7): 1557–1566
- Fröcklin S, de la Torre-Castro M, Lindström L, Jiddawi NS, Bandeira SO (2013) Fish traders as key actors in fisheries: Gender and adaptive management. *AMBIO*, 42(8): 951–962
- Galappaththi EK, Ichien ST, Hyman AA, Aubrac CJ, Ford JD (2022) Climate change adaptation in fisheries. *Fish and Fisheries*, 23(1): 4–21
- Geheb K, Kalloch S, Medard M, Nyapendi AT, Lwenya C, Kyangwa M (2008) Nile perch and the hungry of Lake Victoria: Gender, status and food in an East African fishery. *Food Policy*, 33(1): 85–98
- Githukia M, Obiero K, Meulenbroek P, Nzau B, Githukia CM, Manyala JO, Wakibia J (2021) Economic performance and determinants of fish farming in Kenya: The case of Kirinyaga and Vihiga Counties. *Aquaculture Economics & Management*, 25(4): 471–492
- Greenlife (2025) Kenya's aquatic resources and fisheries production overview. [<https://www.greenlife.co.ke>]
- Gustavsson M, Lindberg M, Andersson E, Oscarsson E (2021) Gendered time poverty: Time use among women and men in rural and urban settings in Kenya. *Sustainability*, 13(21): 12207
- Harper S, Zeller D, Hauzer M, Pauly D, Sumaila UR (2020) Women and fisheries: Contribution to food security and local economies. *Marine Policy*, 39: 56–63
- Hasselberg AE, Alanära A, Hossain MAR (2020) Fish as food and the case for increased aquaculture production. *Nutrition and Health*, 26(4): 307–319
- IFFO (2024) The Marine Ingredients Organisation annual report 2024. IFFO
- Israel M, Hay I (2006) Research ethics for social scientists. Sage Publications
- Jentoft S (2000) Legitimacy and disappointment in fisheries management. *Marine Policy*, 24(2): 141–148
- Kamau P, Ngigi M (2013) Determinants of small-scale fish traders' choice of marketing channel and the corresponding economic returns: Case of Omena fish trade in the Lake Victoria region, Kenya. *International Journal of Economics and Management Sciences*, 2(11): 52–62
- Kaminski AM, Cole SM, Kefi AS, Chilala A, Chisule G, Teoh SJ, Marinda P, Charo-Karisa H (2017) Fisheries livelihoods and gender in the Barotse Floodplain. WorldFish

- Kenya Fisheries Service (2024) Annual fisheries statistics report 2024. Ministry of Blue Economy and Fisheries
- Kenya Fisheries Service (2024) Kenya fisheries production performance 2024. Kenya Fisheries Service
- Kenya News Agency (2024) Government invests in landing site infrastructure to reduce post-harvest losses. [<https://www.kenyanews.go.ke>]
- Kleiber D, Harris LM, Vincent ACJ (2017) Gender and marine protected areas: A case study of Danajon Bank, Philippines. *Maritime Studies*, 14(1): 12
- Kenya Marine and Fisheries Research Institute (2020) Electronic Catch Assessment Survey (eCAS) implementation manual. Kenya Marine and Fisheries Research Institute
- Kenya National Bureau of Statistics (2018) Basic report on well-being in Kenya: Based on the 2015/16 Kenya Integrated Household Budget Survey. Kenya National Bureau of Statistics
- Kolding J, van Zwieten P, Mkumbo O, Silsbe G, Hecky R (2019) Are the Lake Victoria fisheries threatened by exploitation or eutrophication? Towards an ecosystem-based approach to management. *Inland Fisheries Evolution and Management: Case Studies from Four Continents*, 62: 62–89
- Lokuruka MNI (2016) Food and nutrient intake by children, adolescent girls and women in East Africa: A review. *East African Medical Journal*, 93(9): 359–369
- Lake Victoria Fisheries Organization (2020) Regional status report on Lake Victoria biennial frame surveys between 2000 and 2018. Lake Victoria Fisheries Organization
- March C, Smyth I, Mukhopadhyay M (1999) A guide to gender-analysis frameworks. Oxfam
- Marigu WN, Wambua M, Ongore C (2023) Post-harvest losses in Lake Victoria fisheries and implications for food security. *Journal of Agriculture and Food Research*, 12: 100568
- McDougall C, Lentisco A, Luomba J, Muyaule C (2015) Putting women at the center of community-level governance for improved food security. *WorldFish Conference Proceedings*, 72: 1–12
- Mugambi M (2025) Sex-for-fish practices persist in Lake Victoria communities. The Standard. [<https://www.standardmedia.co.ke>]
- Muringai RT, Mafongoya PL, Lottering R (2021) A review of African indigenous knowledge systems and their contribution to sustainable development. *Sustainability*, 13(5): 2985
- Murphy L, Ferse SCA, Adhuri DS, Adhiguna A, Prayitno T (2020) Why do we have to follow the sea? Costs and benefits of fishing in a Bajau fishing community in Indonesia. *Marine Policy*, 122: 104213
- Mutia TM, Virani MZ, Moturi WN, Muyela B, Mavuti KM, Lalah JO (2020) Copper, lead and cadmium concentrations in surface water, sediment and fish, *C. carpio*, samples from Lake Naivasha: Effect of recent anthropogenic activities. *Environmental Earth Sciences*, 79(1): 24
- Nabayunga S, Oduol J, Ferris RSB (2021) Gender roles, income control, and fish value chain participation in Uganda. *Gender, Technology and Development*, 25(2): 212–234
- Njaya F, Donda S, Béné C (2012) Analysis of power in fisheries co-management: Experiences from Malawi. WorldFish Center Policy Brief
- Njeri M (2025) Why women entrepreneurs in Kenya still struggle to access credit. Business Daily Africa. <https://www.businessdailyafrica.com>
- Njiru M, Kazungu J, Ngugi CC, Gichuki J, Muhoozi L (2008) An overview of the current status of Lake Victoria fishery: Oppor-

- tunities, challenges and management strategies. *Lakes & Reservoirs: Research and Management*, 13(1): 1–12
- Nunan F (2014) Wealth and welfare? Can fisheries management succeed in achieving multiple objectives? A case study of Lake Victoria, East Africa. *Fish and Fisheries*, 15(1): 134–150
- Oloko M, Awuor JF, Aura CM (2024) Cultural beliefs and women’s participation in Lake Victoria fisheries. *African Journal of Marine Science*, 46(2): 145–158
- Onyango DM, Wandili S, Kakai R, M’Erimba C (2017) Post-harvest handling practices and losses for Lake Victoria Nile perch in Kenya. *African Journal of Food Science*, 11(1): 1–9
- Owaga EE, Onyango DM, Njiru M (2017) Recent trends in temperature, turbidity and dissolved oxygen in northern Lake Victoria, Kenya. *Lakes & Reservoirs: Research and Management*, 22(4): 339–348
- Pounds L, Budy P, Conner MM, Rohatgi G (2025) Fish meal and oil in aquaculture feeds: Trends and implications for wild fisheries. *Reviews in Aquaculture*, 17(1): 234–251
- Ratner BD, Asgard B, Allison EH (2014) Fishing for justice: Human rights, development, and fisheries sector reform. *Global Environmental Change*, 27: 120–130
- Rice J, Gondwe MJ (2024) Gender and small-scale fisheries in Africa: A systematic review. *Maritime Studies*, 23(1): 89–112
- Rice J, Sow FN, Attwood S (2024) Reducing gender inequality in African fisheries value chains. *Marine Policy*, 159: 105898
- Tesfay S, Teferi M (2017) Assessment of post-harvest fish losses and determining causes and magnitude of losses in Hawassa and Ziway Ethiopian fish markets. *Agriculture and Food Security*, 6(1): 4
- The EastAfrican (2020) Lake Victoria’s dagaa catch hits record high. The EastAfrican Newspaper. [<https://www.theeastafrican.co.ke>]
- Thilsted SH, Thorne-Lyman A, Webb P, Bogard JR, Subasinghe R, Phillips MJ, Allison EH (2016) Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy*, 61: 126–131
- Thorpe A, Reid C, van Anrooy R, Brugere C (2005) When fisheries influence national policy-making: An analysis of the national development strategies of major fish-producing nations in the developing world. *Marine Policy*, 29(3): 211–222
- Torell E, Mmochi A, Mtui B, Mahenge J (2015) Assessing the economic impacts of mangrove and reef destruction on the livelihoods of coastal communities in Tanzania. *Coastal Management*, 43(5): 500–516
- Torell E, Bilecki D, Owusu A, Crawford B, Beran K, Kent K, Yussuf Y, Gruby RL (2021) Assessing the impacts of COVID-19 on small-scale fisheries and aquaculture producers. *Marine Policy*, 131: 104618
- Ward A, Signa A (2017) Fish quality and safety in African small-scale fisheries. *Journal of Food Protection*, 80(4): 561–570
- Weeratunge N, Béné C, Siriwardane R, Charles A, Johnson D, Allison EH, Nayak PK, Badjeck MC (2018) Small-scale fisheries through the wellbeing lens. *Fish and Fisheries*, 15(2): 255–279
- WorldFish (2018) Small fish, big impact: A review of the role of small indigenous fish species in food and nutrition security. WorldFish
- WorldFish Center (2024) Gender transformative approaches in small-scale fisheries. WorldFish Center

Lagrangian modeling of marine plastic debris transport in the western Indian Ocean: effects of currents, wind, and diffusion

Athman Salim Hussein¹, Charles Mitto¹

¹Kenya Marine and Fisheries Research Institute (KMFRI), P.O. Box 81651–80100, Mombasa, Kenya

*Corresponding author Email: asalim@kmfri.go.ke

Abstract

Marine plastic pollution poses a severe ecological and economic threat to the Western Indian Ocean, a region of globally significant biodiversity and coastal livelihoods. This study presents a high-resolution Lagrangian particle-tracking simulation of plastic debris transport along the northern Kenyan coast, forced by Hybrid Coordinate Ocean Model (HyCOM) ocean current fields and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis wind data. Thirteen particles from two source clusters were tracked over 193 hourly time steps under controlled advection, wind age (2%), and stochastic diffusion. A 5-metre beaching criterion was applied. Results reveal a rapid initial onshore transport phase in which 61.5% of particles beached within the first half of the simulation, followed by a dynamic equilibrium in which the remaining 38.5% persisted offshore. This bifurcation of particle fate, a coastal impact group and a long-term offshore hazard group, is driven primarily by HyCOM-resolved current fields. These findings provide a physically plausible, regionally specific assessment of plastic beaching dynamics, with direct implications for coastal waste management prioritization and future climate-scenario modelling in the Western Indian Ocean.

Keywords: Lagrangian model; marine plastic debris; Western Indian Ocean; particle tracking; HyCOM; coastal transport

Introduction

The persistent and accelerating threat of marine plastic pollution is increasingly worsened by climate-change-driven alterations to global and regional ocean circulation (Costa, 2025). The Western Indian Ocean, encompassing the Kenyan coast and surrounding waters, represents a region of high ecological sensitivity and economic dependence on fisheries, tourism, and blue-economy industries, all of which are vulnerable to plastic debris accumulation. Despite its importance, the transport dynamics of buoyant plastic in this domain remain poorly understood at high spatial resolution.

Understanding the synergistic relationship between physical oceanographic processes, ocean currents, wind stress, and turbulent diffusion, and pollutant dispersal is critical for evidence-based

risk assessment and coastal management. Lagrangian particle-tracking models offer a well-established framework for simulating the fate of floating debris by resolving individual particle trajectories under prescribed hydrodynamic forcing (Lattanzi *et al.*, 2022; Irfan *et al.*, 2024).

This study employs a Lagrangian particle-tracking model integrating HyCOM surface currents and ECMWF wind reanalysis data to simulate the fate of buoyant plastic debris in the Western Indian Ocean coastal environment, on the Northern side of Kenya. The objectives are to (i) characterize the temporal evolution of particle beaching, (ii) identify the dominant physical drivers of onshore transport, and (iii) assess the implications of model parameterization choices for regional plastic pollution risk assessment.

Materials and methods

Study area and model framework and forcing data

The current model was developed using the coastal of Kenya as a case study of plastic pollution site (Fig. 1). The model was built on a Lagrangian framework in which particles are advected as massless tracers by the resolved hydrodynamic velocity field (Lattanzi *et al.*, 2022). Two external forcing datasets were used: horizontal velocity fields (u_o , v_o) sourced from the HyCOM global ocean model at hourly temporal resolution; and surface wind vectors (eastward_wind, northward_wind) sourced from the ECMWF ERA5 reanalysis dataset (wind_data). High-resolution coastline geometry was used to construct a unified land polygon for beaching detection, ensuring precise near-shore boundary handling (Zhou *et al.*, 2023).

Particle initialization

Thirteen (13) particles were initialized from insitu with specified coordinates, forming two distinct clusters representing separate source regions. One source was from the northern side, and the other from the southern side of the study site. The northern cluster comprised particles located entirely in the open ocean at $t = 0$, while the southern cluster was partially within the beaching zone at $t = 0$, reflecting a near-shore source scenario.

cs and parameters

The particle velocity at each time step was calculated as the vector sum of current-driven advection, wind-driven transport, and stochastic diffusion:

$$dx/dt = U_current + Windage \times U_wind + U_diffusion$$

The following parameters were calibrated to control particle movement and fate: time step (dt) of 3,600 seconds (1 hour); current scaling

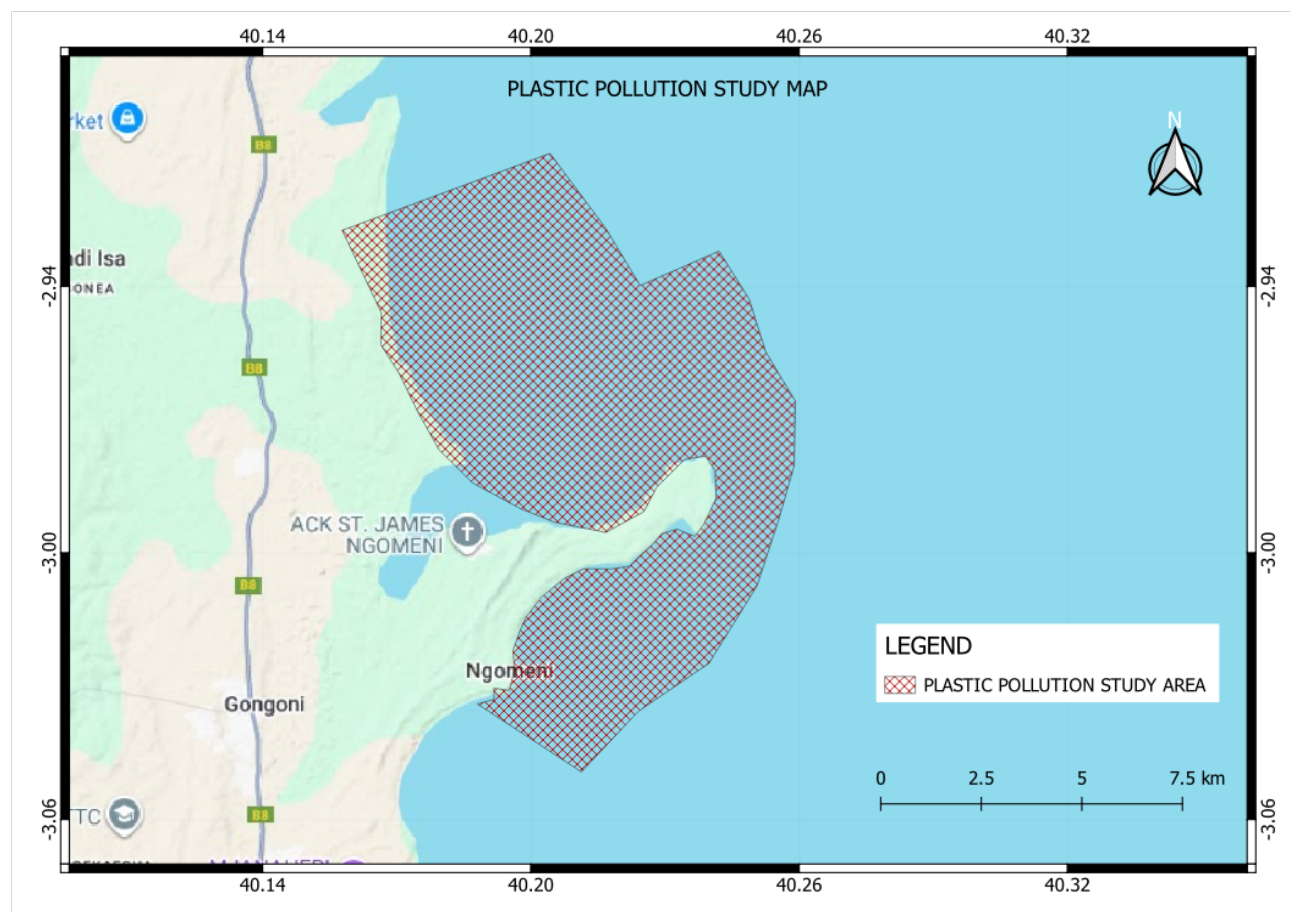


Figure 1. Map showing the plastic pollution study area on the northern Kenyan coast in the Western Indian Ocean.

factor of 1.0 (full HyCOM current strength)(Van-Swieten *et al.*, 2014); windage coefficient of 0.02 (2% of wind speed transferred to particle velocity)(Tong *et al.*, 2021); wind scaling factor of 0.5 to prevent wind-field dominance; diffusion coefficient (D) of $0.01 \text{ m}^2 \text{ s}^{-1}$ scaled by diffusion scaling = 0.005; and a velocity limit of 0.05 m s^{-1} to prevent unrealistic particle speeds. A particle was considered beached if it crossed the land polygon boundary or came within 0.000045° ($\sim 5.0 \text{ m}$) of the coastline(Chubarenko *et al.*, 2018). Resuspension probability was set at 0.005, making beaching an effectively terminal state.

Results

Temporal evolution of particle fate

The simulation revealed a non-linear, two-phase progression in particle beaching. All beaching events were concentrated in the first half of the model run, after which the system reached a stable equilibrium with no further state changes (Table 1 and 2). By the midpoint (time step 96/193), 61.5% of particles had beached, a value that remained unchanged through the final time step (192/193).

Table 1. Temporal summary of particle fate across the simulation. Beaching stabilizes at the midpoint, indicating rapid early-phase onshore transport followed by dynamic equilibrium.

Model State	Time Step	Moving Particles	Beached Particles	Beached (%)
Initial	1/193	10	3	23.1%
Midpoint	96/193	5	8	61.5%
Final	192/193	5	8	61.5%

Table 2. Simulation metadata and parameters.

Parameter	Value
Model Type	Lagrangian Particle-Tracking (Custom Python)
Total Particles	13
Current Forcing	HYCOM Global Ocean Model (1.0× scaling)
Wind Forcing	ECMWF Reanalysis (0.5× windage)
Windage Coefficient	0.02 (2% of wind speed)

Parameter	Value
Diffusion Coefficient (D)	$0.01 \text{ m}^2 \text{ s}^{-1}$ (diffusion_scaling = 0.005)
Time Step	3,600 s (1 hour) × 193 steps
Beaching Distance	5.0 m (0.000045°)
Velocity Limit	0.05 m s^{-1}
Resuspension Probability	0.005
Final – Moving	5 particles (38.5%)
Final – Beached	8 particles (61.5%)
Computational Domain	$38.97^\circ\text{E} - 41.44^\circ\text{E}$, $4.22^\circ\text{N} - 1.74^\circ\text{S}$

Spatial dynamics and final distribution

At the initial state ($t = 0$), three particles in the southern cluster were immediately beached while the northern cluster was entirely offshore. By the midpoint ($t = 50\%$), a significant onshore transport event occurred, driven by resolved HYCOM currents and moderated wind forcing, with five additional particles beaching predominantly from the northern cluster. At the final state ($t = 100\%$), particle distribution stabilized at the midpoint configuration: 8 beached and 5 persistently offshore in dynamic equilibrium (Figures 2–5).

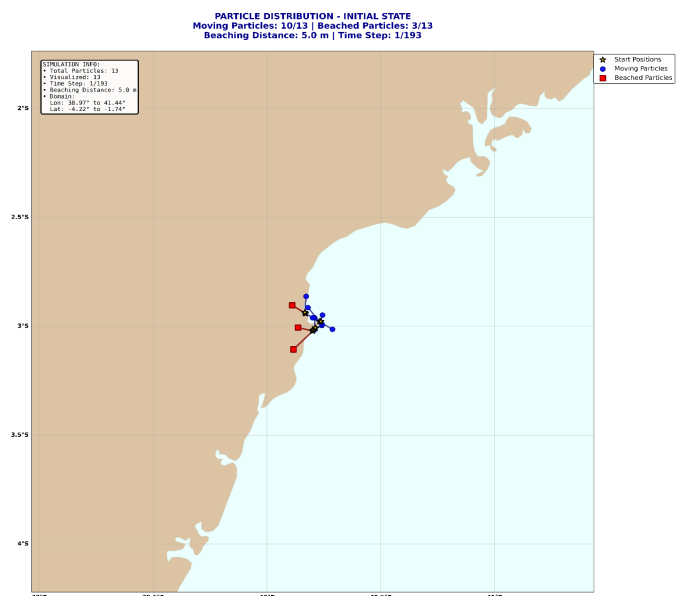


Figure 2. Particle trajectories at initial state ($t = 0$). Northern cluster entirely offshore; three southern particles already beached.

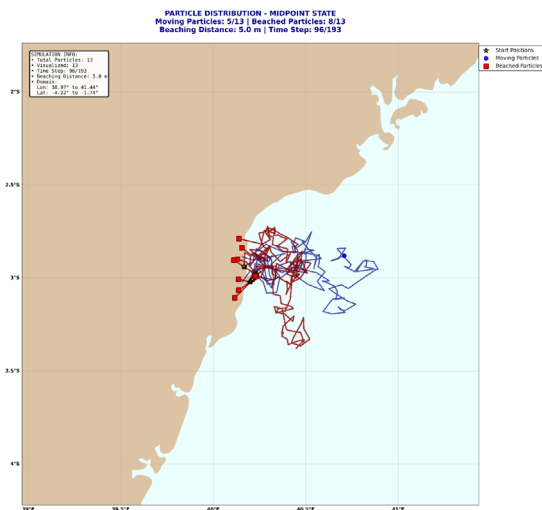


Figure 3. Particle trajectories at midpoint ($t = 50\%$). Five additional particles beached under HYCOM-resolved onshore current forcing.

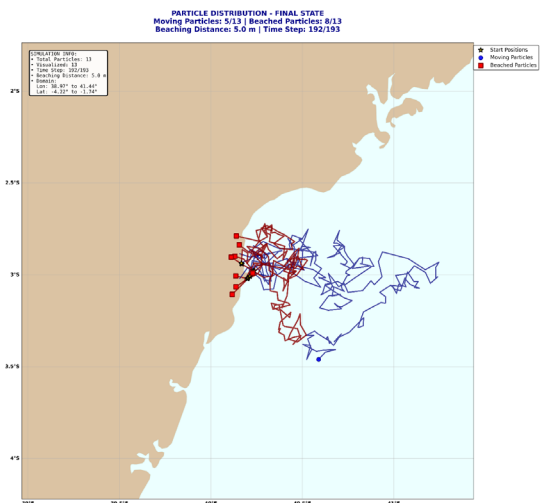


Figure 4. Particle trajectories at final state ($t = 100\%$). Stable bifurcation: 8 beached (61.5%), 5 persistently offshore (38.5%).

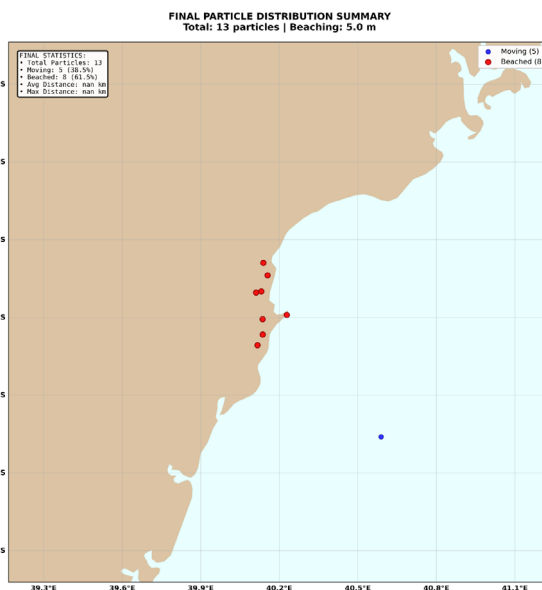


Figure 5. Cumulative beaching timeline showing the rapid early-phase beaching event and subsequent dynamic equilibrium.

Discussion

Dominance of model-resolved onshore transport

The rapid beaching of five particles between the initial and midpoint states is a direct consequence of HyCOM-resolved current fields interacting with the nearshore coastal geometry. The current scaling factor of 1.0 confirms that the model's inherent onshore flow was the primary transport driver, consistent with known upwelling and monsoon-driven circulation patterns in the Western Indian Ocean (Vinayachandran *et al.*, 2021). The wind scaling factor (0.5) and velocity limit successfully constrained unrealistic particle dispersion, yielding a physically plausible simulation (Castelli *et al.*, 2018).

Dynamic equilibrium and the persistent offshore fraction

The stabilization of beached particle counts after the midpoint represents a scientifically significant finding. The five persistently offshore particles were entrained in current systems where net shoreward advection was balanced by offshore flow components and diffusion. The low resuspension probability (0.005) ensured that beaching was effectively terminal for impacted particles, consistent with field observations of plastic accumulation on beaches in the Western Indian Ocean (Irfan *et al.*, 2024). The persistent offshore fraction represents a long-term pollution reservoir with ongoing hazard potential for marine ecosystems and fisheries.

Implications of model parameterization

The 5-metre beaching criterion required high-resolution coastline data and precise geodetic distance calculations, making the model sensitive to final-stage stranding processes that coarser models would miss. The use of scaling factors and velocity limits demonstrates the critical importance of tuning general circulation model (GCM) outputs for regional particle-tracking applications to prevent over-dispersion and maintain physical realism. The use of 13 particles represents a proof-of-concept simulation; future operational applications should use larger ensemble sizes ($n \geq 100-500$) to generate statistically robust beaching probability fields.

Climate change implications

Climate change is projected to alter the intensity and pathways of major Indian Ocean circulation features, including the South Equatorial Current and the East African Coastal Current (Costa, 2025). Strengthening of monsoon-driven circulation could raise the beaching percentage and shorten the timeframe to coastal impact, increasing the urgency of coastal waste interception infrastructure. Projected changes in monsoon intensity and seasonality could modify the windage contribution to plastic transport, potentially redistributing the offshore accumulation group (Lermusiaux *et al.*, 2019; Ko *et al.*, 2020). Increased frequency of cyclonic activity in the Western Indian Ocean may generate episodic, high-magnitude transport events not captured in climatological forcing.

Conclusion and recommendations

This high-resolution Lagrangian modelling study, forced by realistic HYCOM current and ECMWF wind data, successfully characterizes the transport and beaching dynamics of plastic debris along the northern Kenyan coast. The principal finding is a clear divergence of particle fate into a coastal impact group (61.5% beached) and an offshore hazard group (38.5% persistently mobile), with beaching events concentrated in a rapid early-phase onshore transport episode before the system stabilized. These results provide a physically grounded, regionally specific baseline for understanding plastic pollution risk in the Western Indian Ocean, with direct relevance to coastal management, fisheries protection, and climate adaptation planning. The study further recommends the incorporation of wave-induced Stokes drift and time-variable wind age coefficients in future model iterations; scaling of particle numbers to $n \geq 500$ per source location to generate probabilistic beaching maps; running of transient climate scenarios using CMIP6-forced HyCOM and ECMWF projections; initiation of field sampling campaigns in high-impact coastal zones to ground-truth model results and constrain resuspension probability; and using risk maps to prioritize coastal waste management infrastructure and community engagement programmes in identified high-impact zones.

Acknowledgements

Special thanks are extended to Kenya Marine and Fisheries Research Institute (KMFRI) divers Mr. Masoud Zamu and Mr. Muhamed Tashwish for their invaluable assistance during the collection of plastic particles.

Funding

The authors gratefully acknowledge the KMFRI for providing financial support to undertake the field activities for this study.

References

- Castelli ST, Armand P, Tinarelli G, Duchenne C, Nibart M (2018) Validation of a Lagrangian particle dispersion model with wind tunnel and field experiments in urban environment. *Atmospheric Environment*, 193: 273–289
- Chubarenko IP, Esiukova EE, Bagaev AV, Bagaeva MA, Grave AN (2018) Three-dimensional distribution of anthropogenic microparticles in the body of sandy beaches. *Science of the Total Environment*, 628: 1340–1351
- Costa J (2025) Bridging the gap: A review on the interaction between (micro)plastics and climate change. *Philosophical Transactions of the Royal Society A*, 383(2307): 20240501 [<https://doi.org/10.1098/rsta.2024.0501>]
- Irfan T, Isobe A, Matsuura H (2024) A particle tracking model approach to determine the dispersal of riverine plastic debris released into the Indian Ocean. *Marine Pollution Bulletin*, 199: 115985 [<https://doi.org/10.1016/j.marpolbul.2023.115985>]
- Ko C-Y, Hsin Y-C, Jeng M-S (2020) Global distribution and cleanup opportunities for macro ocean litter: A quarter century of accumulation dynamics under windage effects. *Environmental Research Letters*, 15(10): 104063

- Lattanzi AM, Tavanashad V, Subramaniam S, Capecelatro J (2022) Stochastic model for the hydrodynamic force in Euler–Lagrange simulations of particle-laden flows. *Physical Review Fluids*, 7(1): 014301 [<https://doi.org/10.1103/PhysRevFluids.7.014301>]
- Lermusiaux PFJ, Doshi M, Kulkarni CS, Gupta A, Haley PJ, Mirabito C, Trotta F, Levang SJ, Flierl GR, Marshall J (2019) Plastic pollution in the coastal oceans: Characterization and modeling. IEEE
- Tong X, Jong M-C, Zhang J, You L, Gin KY-H (2021) Modelling the spatial and seasonal distribution, fate and transport of floating plastics in tropical coastal waters. *Journal of Hazardous Materials*, 414: 125502
- VanSwieten JH, Meyer I, Alsenas GM (2014) Evaluation of HYCOM as a tool for ocean current energy assessment
- Vinayachandran PNM, Masumoto Y, Roberts MJ, Huggett JA, Halo I, Chatterjee A, Amol P, Gupta GVM, Singh A, Mukherjee A (2021) Reviews and syntheses: Physical and biogeochemical processes associated with upwelling in the Indian Ocean. *Biogeosciences*, 18(22): 5967–6029
- Zhou X, Wang J, Zheng F, Wang H, Yang H (2023) An overview of coastline extraction from remote sensing data. *Remote Sensing*, 15(19): 4865

A participatory research approach for marine conservation in Bofa–Kilifi, Kenya

Jelvas Mwaura^{1*}, Siana Philips² and Thomas Sagimo²

¹Kenya Marine and Fisheries Research Institute, Oceanography & Hydrography Department, P.O. Box 81651–80100, Mombasa, Kenya,

²OceanSole Foundation, Karen Village, Ngong Road, Karen, Nairobi 00502

*Corresponding author Email: jmwaura@kmfri.go.ke

Abstract

Coral reefs in Bofa, Kilifi County, Kenya, are under growing pressure from overfishing, destructive fishing practices, live coral mining, and coral bleaching linked to climate change. This study reports a community-based citizen science initiative carried out by the Bofa community in partnership with KMFRI, the County Fisheries Department, and OceanSole Foundation. Seven local participants were trained in standard reef assessment methods to collect baseline data and strengthen community stewardship. Transect surveys were conducted at the inshore Mwamba wa Tasi reef (2 – 4 m depth) and the offshore Mwamba wa Nje reef (8 – 10 m depth). The surveys assessed benthic cover, reef fish density and diversity, and macroinvertebrate abundance. Results showed clear reef degradation at both sites. Mwamba wa Tasi had higher live coral cover (20%), mainly thermally tolerant *Porites*, but also showed signs of repeated bleaching. Mwamba wa Nje had very low coral cover (4%). Fish stocks were depleted, and most commercially important fish were small. Key macroinvertebrates, including sea cucumbers and lobsters, were scarce. These findings provide useful evidence for stakeholder engagement, reef restoration, low-impact ecotourism, and community-led conservation to support reef recovery, livelihoods, and food security.

Keywords: Citizen science; coral reefs; participatory monitoring; reef restoration; community-based conservation; fisheries management; Bofa; Kilifi; Kenya

Introduction

Marine and coastal ecosystems are among the most diverse and productive ecosystems in the world (Ray 1996). They support fisheries, shoreline protection, tourism, cultural values, and other services that coastal communities depend on. Across the Western Indian Ocean (WIO), these ecosystems are especially important because many households rely on the sea for food, income, and daily livelihoods (Cinner *et al.*, 2009; Obura *et al.*, 2017a). Despite this importance, reef habitats and coastal fisheries are declining in many areas (Graham *et al.*, 2017). The main drivers include pollution, overexploitation, destructive fishing practices, and climate change (Wenger *et al.*, 2015; McClanahan *et al.*,

2007; Obura *et al.*, 2017b). In Kenya, coral reefs are central to small-scale fisheries and coastal tourism, but they remain highly exposed to these pressures. Repeated coral bleaching events in 2016 and 2024 have added further stress to reefs that are already affected by fishing pressure and habitat disturbance. This is a serious concern for communities that depend on reef resources for food and income, as continued reef decline can reduce fish production, weaken livelihoods, and lower ecosystem resilience (Obura *et al.*, 2021). The UN Decade of Ocean Science for Sustainable Development (2021–2030) calls for stronger local and institutional capacity for marine conservation (UN, 2019). Effective management can improve reef resilience to future climate shocks, but many marine areas are still

poorly monitored. In many coastal locations, there is limited information on reef habitats, fish populations, and changes in ecosystem conditions over time. This weakens evidence-based decision-making, stakeholder engagement, and practical conservation action. In response, OceanSole Foundation has been working with local fishing communities to promote sustainable small-scale fisheries, improve local awareness of reef condition, and support conservation actions that can strengthen coastal livelihoods.

Marine citizen science can help fill monitoring gaps and build local stewardship of coastal and marine resources. In many reef areas, formal monitoring is limited by funding, logistics, and institutional capacity. This is especially important where communities depend on reef fisheries for food and income. By involving coastal communities in data collection, citizen science produces information that is locally relevant and useful for management. It also helps communities understand reef condition, ecological change, and conservation needs. This hands-on work supports marine citizenship by helping resource users observe local ecosystems, interpret change, and take part in decisions about the resources they depend on (Hyder *et al.*, 2015; Kelly *et al.*, 2019; Obura *et al.*, 2002a). Along the Kenyan coast, participatory and community-led management approaches are increasingly used to improve reef monitoring, encourage compliance, and build shared responsibility for marine conservation (Obura 2001; Obura *et al.*, 2002b). Programmes such as Reef Check show that community-led visual surveys can contribute to ecological databases and support policy and management decisions through repeated observations of reef condition (Poisson *et al.*, 2019). In Kenya, community-led management is also valued because it can support both conservation and coastal livelihoods when local ecological knowledge, scientific monitoring, and shared governance are combined (Kawaka *et al.*, 2017; Maina *et al.*, 2011).

This study presents a pilot community-based research initiative carried out with the Bofa community on the northern coast of Kenya. The work focused on two important local reef sites,

the inshore Mwamba wa Tasi reef and the off-shore Mwamba wa Nje reef. These sites were selected because they are used by local fishers, are known to the community, and have potential for future conservation and livelihood activities. The study aimed to generate a first quantitative ecological baseline for these reefs by documenting benthic habitat composition, reef fish density, and macroinvertebrate abundance. It is also aimed to show how local community members can take part in reef monitoring and use the results to guide practical conservation decisions. The findings were intended to support community discussion, improve understanding of reef condition, and identify possible interventions such as reef restoration, improved fisheries management, and low-impact marine-based livelihood activities. Specifically, the study sought to:

1. Train seven community members as citizen scientists and equip them with practical skills in standard reef assessment protocols.
2. Conduct participatory ecological surveys at two pre-selected reef sites using field methods that community members could understand and support.
3. Provide a preliminary assessment of Mwamba wa Tasi and Mwamba wa Nje by examining benthic habitat composition, fish density, and macroinvertebrate abundance.
4. Develop recommendations for marine conservation and livelihood interventions that respond to the survey findings and local community priorities.

Methods and approach

Seven reef rangers from the Bofa Beach Management Unit (BMU) and Ocean Sole Foundation staff participated in a four-day training programme. Participants were selected based on prior in-water experience from fishing or skin-diving. Training was led by a KMFRI marine scientist and followed standard reef-monitoring protocols adapted from Kawaka *et al.* (2017) (Annex i, ii). Sessions covered reef ecology, human and climate-related threats, conserva-

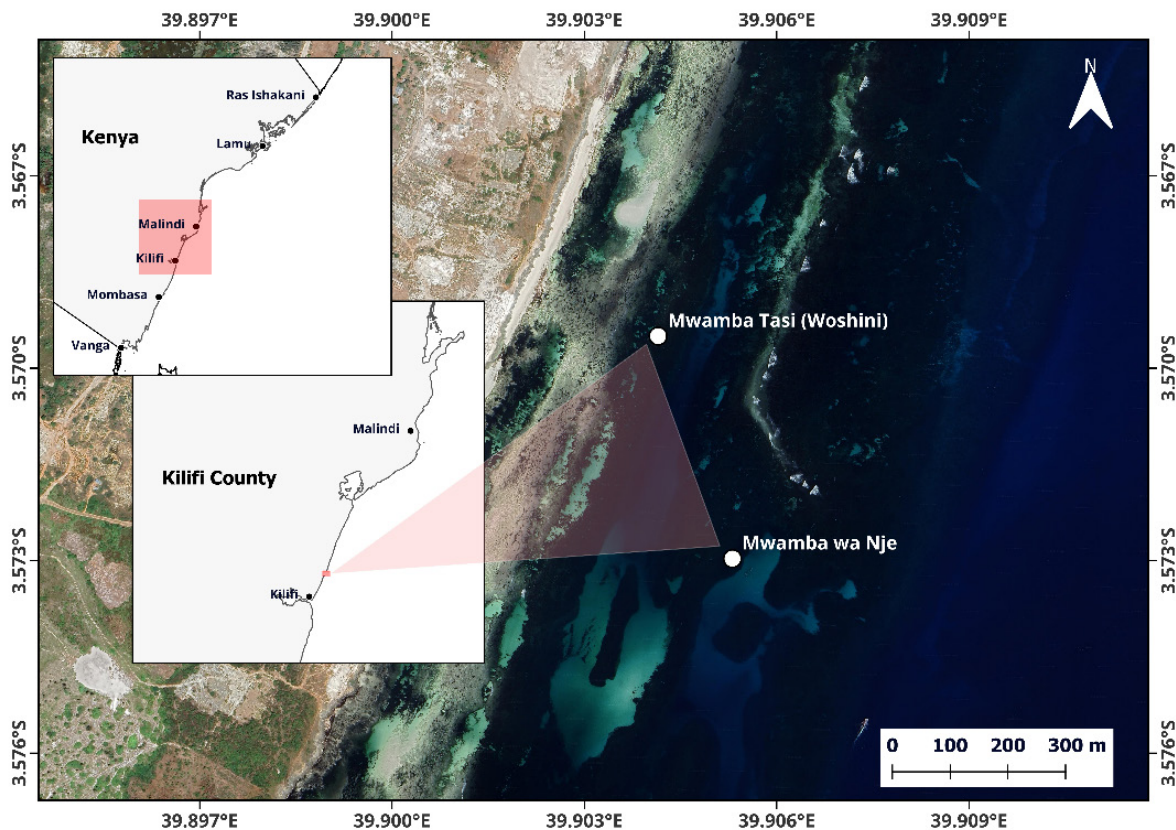


Figure 1. Survey locations showing the two reef sites surveyed, the inshore Mwamba wa Tasi and offshore Mwamba wa Nje (Source: Authors).

tion measures, survey design, indicator taxa, and field identification of benthic cover, reef fishes, and macroinvertebrates using common and local names. Practical training included beach-based field trials on site selection, data collection, and transect deployment. Fish visual census surveys were conducted by the KMFRI scientist, while community volunteers assisted with transect placement and macroinvertebrate counts. Ocean Sole staff collected benthic habitat images with minimal technical support. Survey sites were selected with community input based on accessibility, conservation potential, and local ecological knowledge (Fig. 1). Field surveys were conducted on 3 – 4 March 2025 during low spring tides to maximize in-water sampling time.

Ecological surveys

Ecological surveys were conducted at the two selected reef sites (Fig. 1; Table 1) using visual assessments of benthic substrate, reef fishes, and macroinvertebrates.

Fish and macroinvertebrate surveys

Indicator fish families and macroinvertebrates were recorded along 50 m transects using a 5 m-wide belt, with 2.5 m on each side of the transect line. Target taxa were selected because they indicate reef condition or have commercial value (Kawaka *et al.*, 2017) (Table 1). Parrotfish and butterflyfish were included because they play important roles in reef processes. Commercially important taxa included emperors, groupers, rabbitfish, surgeonfish, snappers, jacks/trevallies, and sweetlips.

Macroinvertebrate indicators included sea urchins, which act as grazers and bio-eroders, and octopuses and lobsters, which are both commercially and ecologically important predators. Giant clam (*Tridacna spp.*) density was also used as an indicator of reef condition and water quality because these taxa are sensitive to high temperature, nutrient enrichment, and pollution (Neo *et al.*, 2015).

Table 1. Indicator categories for fish, macroinvertebrates and benthic substrate (Kawaka *et al.*, 2017).

Fish families/local names	Trophic group	Macroinvertebrates/local names	Benthic substrate/local names
Rabbit fish/Tafi	Herbivores	Sea cucumbers/Jongoo	Live hard coral/Matumbawe
Parrot fish/Poo	Herbivores	Starfish/Kitic cha pweza	Soft corals/Matumbawe meroro
Triggerfish /Kikande/ Gona	Omnivores	Tiger cowrie/Kungugu	Rubble/Changarawe/kokoto
Emperor/changu	Omnivores	Lambis shell/Madole	Sand/Mchanga
Snapper/Mbavaa	Omnivores	Clams/Kigandamiza	Turf algae/Mwani
Sweetlip/Fute/Mleya	Omnivores	Bull mouth shell/Dondo jekundu	Macro algae/matarafa/Mitutu
Goat fish/Mkundaji	Omnivores	Octopus/Pweza	Seagrass/Manyasi
Butterfly fish/Kipepeo	Corallivores	Triton Shell/ Gunda fisi	Sponge/Spongi
Grouper/Tewa	Piscivores	Crown of thorns	
		Sea urchins/Vishimba	

During each survey, two divers entered the water first: one fish observer and one transect layer (Fig. 2). After the transect tape was secured, the fish observer recorded fish within the 5 m belt along the 50 m transect. A second two-person team followed five minutes and surveyed macroinvertebrates along the same transect. Macroinvertebrates were counted using a zigzag search pattern within the belt transect.

Benthic substrate assessment

Benthic substrate composition was used to de-

scribe reef structure and condition. Algae indicate primary production, seagrass beds provide habitat and food for juvenile fishes and invertebrates, and crustose coralline algae support coral recruitment, rubble stabilization, and reef framework development.

Benthic cover was assessed using the photo-quadrat method of Obura and Grimsditch (2009) (Fig. 3). Images of the substrate below the transect tape were taken at 2 m intervals, with at least 24 images collected per transect. Non-reef

habitats, such as seagrass beds and sandy bottoms, were avoided where possible. Images were analysed using Coral Point Count with Excel extensions (CPCe) software (Kohler and Gill, 2006). Cover was classified into nine categories: hard coral (HC), soft coral (SC), turf algae (TA), crustose coralline algae (CA), sand (S), sponge (SP), seagrass (SG), rubble (R), and macroalgae (AF).

Results

Mwamba wa Tasi (Inshore reef)

Benthic cover and corals

Mwamba wa Tasi (Woshini) is a shallow inshore reef located at 2 to 4 m depth. The site is characterized by reef bommies, scattered coral

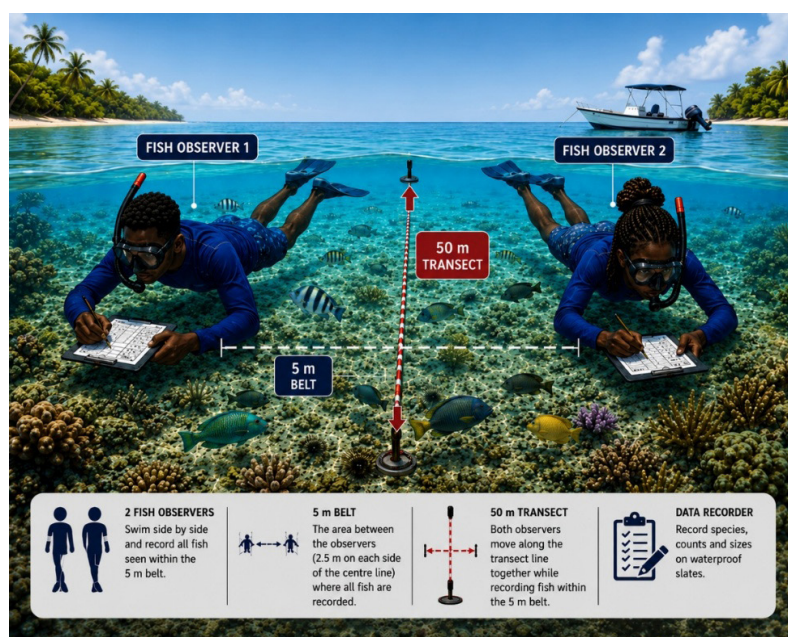


Figure 2. A conceptual standard belt transect survey with two fish observers conducting fish and macroinvertebrate assessments along the same 50 m belt transect. The fish observers record fish and macroinvertebrates abundance within a 5 m-wide belt.

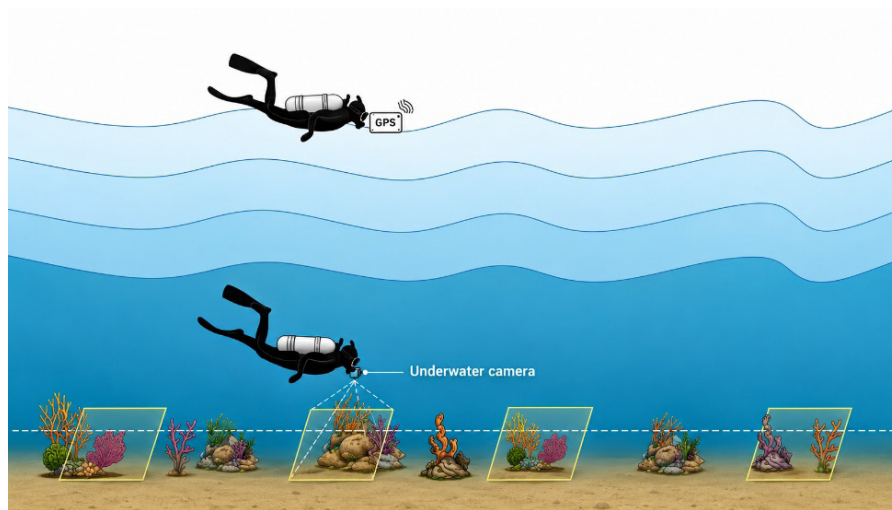


Figure 3. Divers capturing benthic substrate images approximately 0.7–1 m above the seabed using the photo-quadrat method.

patches, extensive seagrass beds, sandy areas, and large stands of brown macroalgae. The shallowest sections, at about 1 – 2 m depth, were mainly covered by seagrass, particularly *Thalassodendron ciliatum*, with smaller areas of exposed sand. Across the three transects, live hard coral, sand patches, and algal turf on rocky reef were the main benthic substrate types and together accounted for 54% of total cover (Fig. 4). The coral community was dominated by massive coral genera, including *Porites*, *Turbinaria*, *Platygyra*, *Favia*, and *Favites*. These forms were more common than foliose and branching corals such as *Galaxea*, *Acropora*, and *Pocillopora*.

This pattern suggests that the reef is largely composed of stress-tolerant coral forms that can persist under shallow, disturbed conditions. However, a high proportion of the coral framework showed signs of degradation. Approximately 60% of the observed coral appeared dead and was overgrown by turf algae and macroalgae, including *Sargassum* spp. The high cover of algal growth on dead coral skeletons indicates reduced live coral condition and suggests that recovery may be limited without active management to reduce local stressors and support coral recruitment.

Reef fish

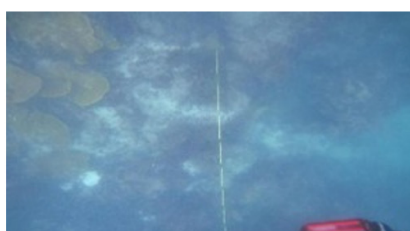
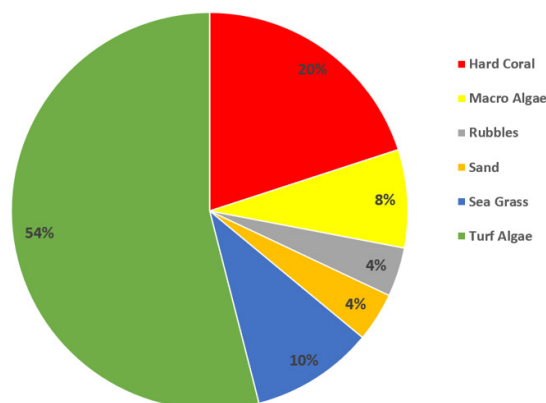


Figure 4. Benthic cover composition and representative underwater images of Mwamba wa Tasi.

Mwamba wa Tasi supported relatively higher densities of commercially important reef fishes compared with the offshore site, with surgeonfish and wrasses being the most abundant groups recorded (Fig. 5). this reef.

Damselfish were also present at relatively high densities within coral bommies, probably reflecting low fishing pressure on this group. In contrast, highly targeted families, including groupers, snappers, sweetlips, and goatfish, occurred at low densities (<25 individuals per 250 m²) and were generally represented by small-bodied individuals. The occurrence of butterflyfish, a corallivorous group, indicates the continued presence of suitable coral habitat at

Macroinvertebrates

Long-spined sea urchins were the dominant macroinvertebrates recorded at Mwamba wa Tasi, occurring mainly in sandy-bottom areas (Fig. 6). Other macroinvertebrates, including sea cucumbers, were observed at very low densities, typically 2–3 individuals per 250 m² transect.

Mwamba wa Nje (Offshore reef)

Benthic cover and corals

Mwamba wa Nje is an offshore fore-reef located beyond the fringing reef, with a reef-slope extending to approximately 8 – 15 m depth. The site was dominated by soft corals and relatively high macroalgal cover (32%), with only a few scattered massive *Porites* colonies recorded (Fig. 7). Sand patches and pockets of soft coral were frequently observed along the transects.

Reef fish

Mwamba wa Nje had very low abundances of commercially important reef fish (Fig. 8). Wrasses and parrotfish were the most frequently recorded groups, although overall abundance remained low. Few juvenile surgeonfish and goatfish were also observed along the transects.

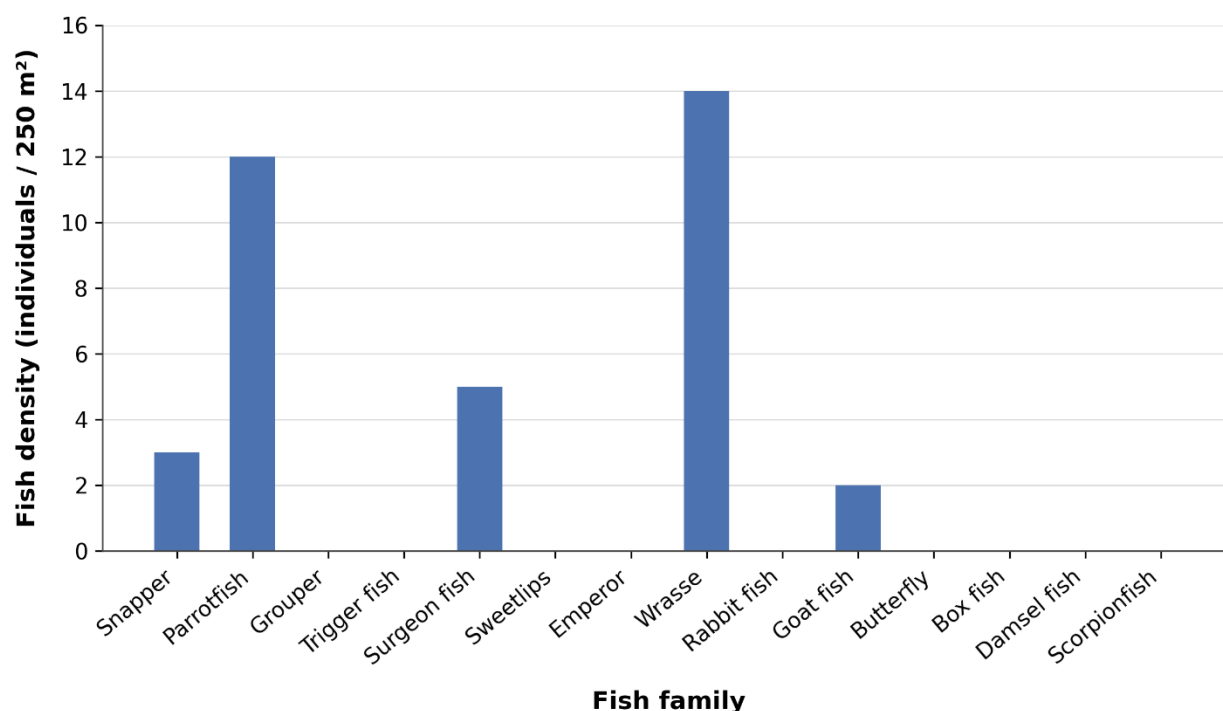


Figure 5. Average fish densities of common fish observed during the survey

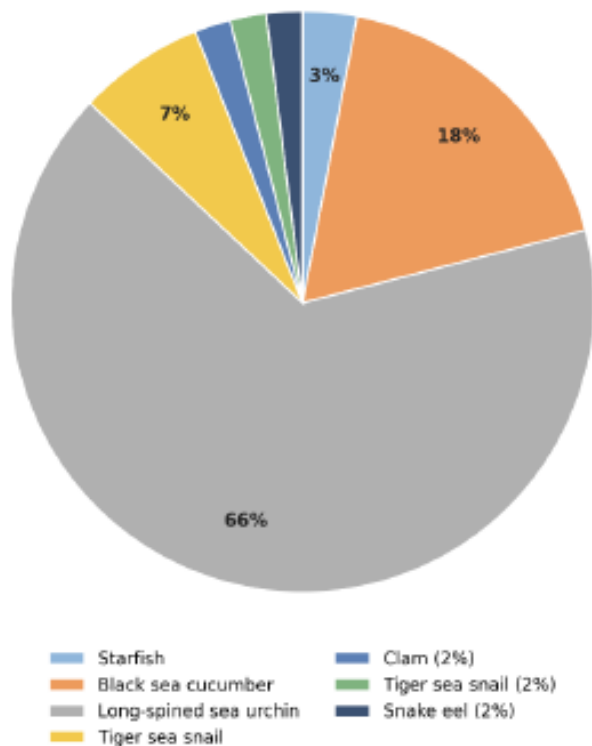


Figure 6. Relative composition of macroinvertebrates recorded at Mwamba wa Tasi.

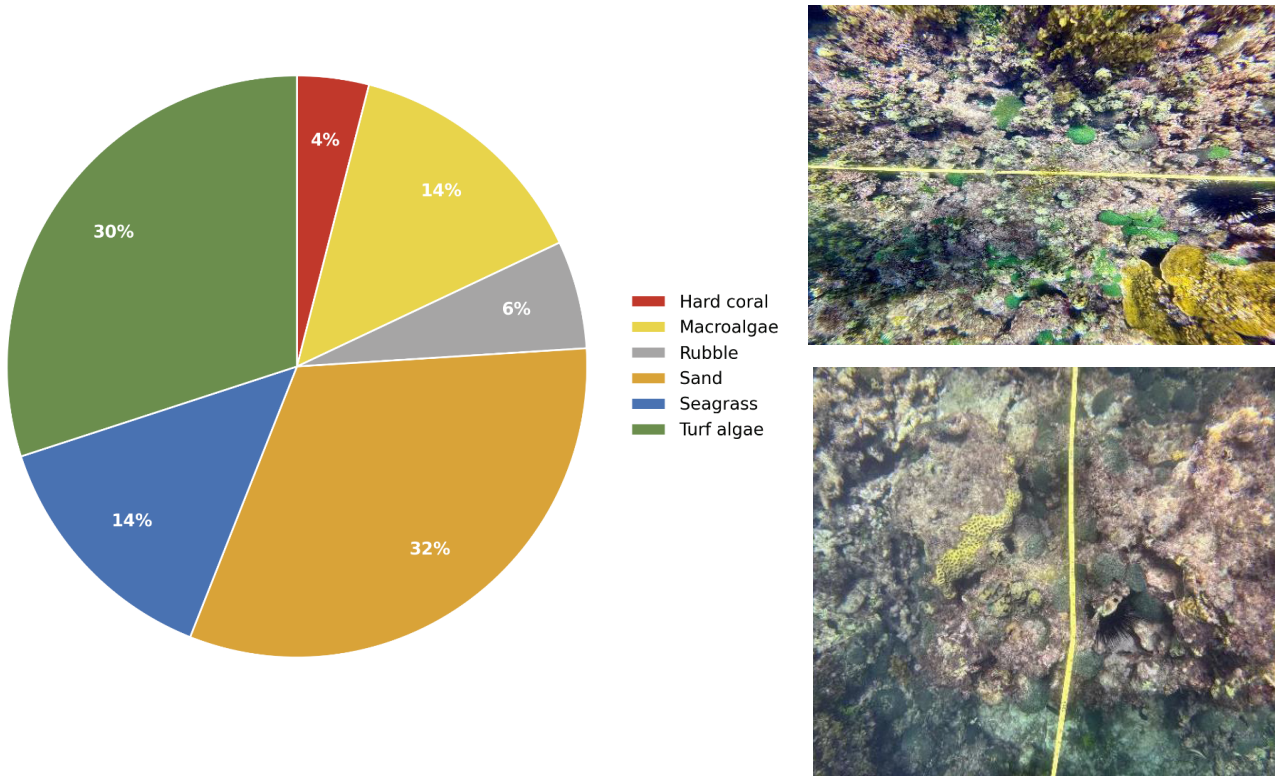


Figure 7. Benthic cover composition and representative underwater images of Mwamba wa Nje.

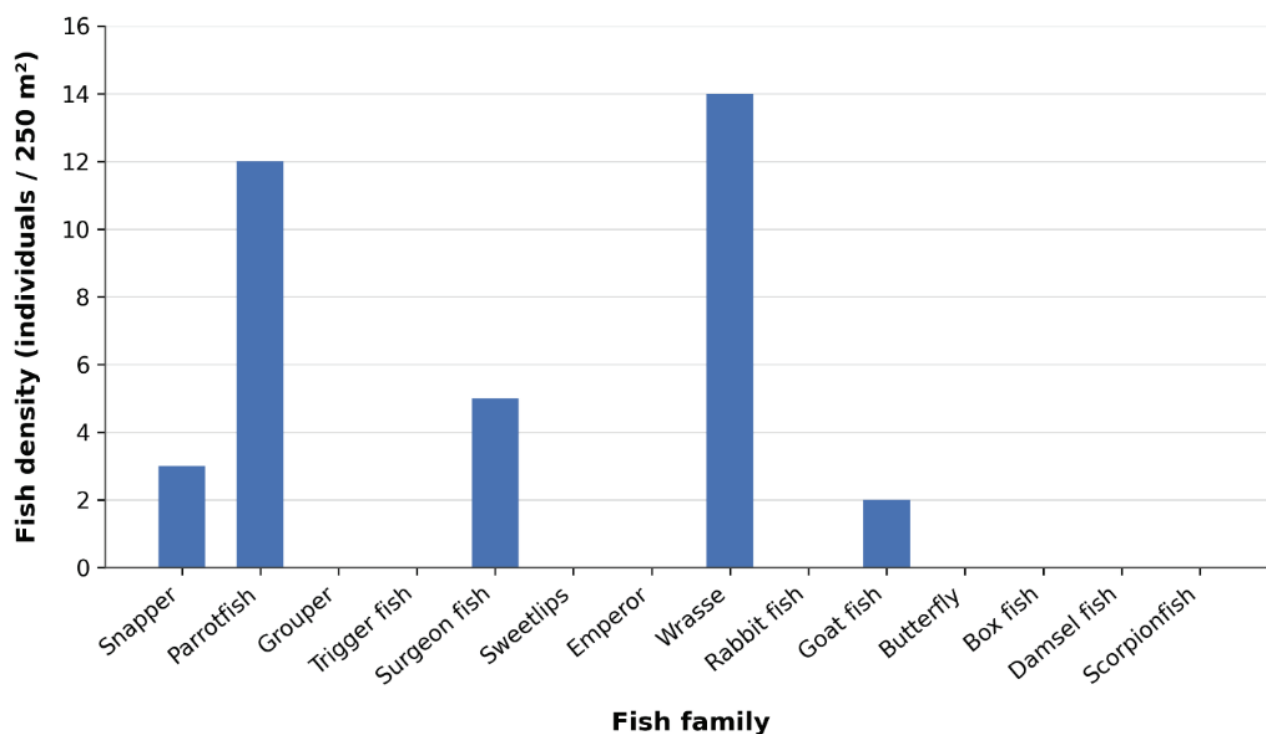


Figure 8. Average fish densities of common fish observed during the survey

Macroinvertebrates

Macroinvertebrate abundance at Mwamba wa Nje was very low across the surveyed transects (Fig. 9). Sea cucumbers were the most frequently recorded macroinvertebrates, followed by tiger shells and starfish, but all were observed in low numbers. Only one cephalopod, a cuttlefish, was recorded at the site. No lobsters or octopuses were observed during the survey. The low occurrence of commercially and ecologically important macroinvertebrates suggests a depleted macroinvertebrate community and indicates limited habitat function or possible harvesting pressure at the offshore reef.

Climate change and coral reefs

Rising sea surface temperatures remain a major threat to coral reef ecosystems globally. Extreme thermal events, particularly those associated with El Niño episodes in 1998, 2010, and 2016, have caused widespread coral bleaching. In Kilifi County, previous bleaching events resulted in coral mortality exceeding 80% (Fig. 10). The increasing frequency and intensity of bleaching

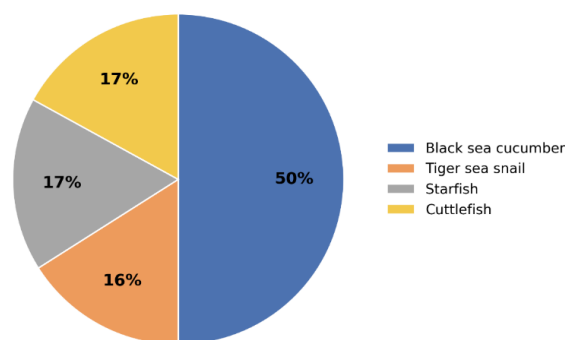


Figure 9. Proportion of macro-invertebrates observed in Mwamba wa Nje

events highlight the need for proactive management and restoration measures to reduce further ecological degradation and support recovery of already impacted reef systems.

Discussions

Participatory research can support local communities to take a more active role in marine conservation. It also helps build trust between resource users, scientists, and management agencies. When communities are involved in data collection, they are more likely to understand the condition of local ecosystems and support conservation actions that respond to observed changes (Toomey and Domro-



Coral bleaching observed during elevated sea surface temperatures in March 2024



Post-bleaching coral mortality observed in January 2025

Figure 10. Coral bleaching is associated with elevated sea surface temperatures and subsequent post-bleaching coral mortality.

ese, 2013). In this study, the involvement of the Bofa community provided practical insights into the condition of their reefs and helped create a shared understanding of the ecological challenges facing these habitats (Johnson and Jackson 2015). The collaboration among community members, researchers, OceanSole Foundation, and government agencies produced baseline information that can support future conservation planning, local awareness, and collective decision-making.

The ecological surveys showed clear signs of stress at both the inshore and offshore reefs in Bofa. This indicates the need for management actions that address both local and climate-related pressures. The condition of the nearshore reef, including high macroalgal cover and reduced live coral condition, is consistent with reefs affected by overfishing, habitat disturbance, and repeated warming events (Hughes *et al.*, 2018; Eakin *et al.*, 2019). Macroalgal dominance can reduce space available for coral settlement and may slow reef recovery after disturbance. It may also indicate changes in the reef food web, especially where herbivorous fish have been reduced by fishing pressure. Herbivores play an important role in controlling algal growth and maintaining space for coral recruitment. Their decline can therefore increase algal cover and reduce the ability of reefs to recover after bleaching or physical disturbance (McClanahan *et al.*, 2012; Knoester *et al.*, 2023).

Although Mwamba wa Tasi had higher coral cover than the offshore reef, the widespread presence of dead coral skeletons suggests strong and lasting effects of repeated bleaching events (Obura, 2005; Eakin *et al.*, 2019). Bleaching weakens corals by disrupting the relationship between corals and their symbiotic algae. If high temperature stress persists, bleached corals may die and leave behind bare skeletons that are later colonized by turf algae and macroalgae. This process appears to be occurring at Mwamba wa Tasi, where many dead coral surfaces were covered by algal growth. The fish survey results also point to heavy fishing pressure. Commercially important species, including groupers, snappers, sweetlips, and goatfish, were scarce and mostly small-bodied. This pattern suggests that larger individuals have been removed from the reef, reducing breeding potential and weakening fish population recovery. These findings are consistent with earlier concerns that Kenya's artisanal reef fisheries were approaching a critical threshold (Samoilys *et al.*, 2017). Past destructive fishing practices, including beach seining, may have further contributed to reef degradation by damaging benthic habitats and removing fish across different size classes, including mature breeding individuals.

Conclusion and recommendations

This study successfully provided critical baseline information to support local management initiatives for Bofa's near-shore reefs. While the current condition of these reefs is poor, their resilience should not be underestimated. The presence of large and scattered *Porites* coral stands, known for their high thermal tolerance, suggests potential for recovery from future warming events. The inshore reef's unique physical features, including channels and rocky gaps, may also serve as important habitats for endangered species and fish spawning aggregations, making it a priority for protection (Colin 2012). The implementation of strategic no-take zones that are co-managed with communities and resorts are an ideal approach to protect both coral habitat and fish populations (Kawaka *et al.*, 2017; Estradivari *et al.*, 2022).

The participatory approach employed here is not just a data collection method; it demonstrates an opportunity to engage the fishing community and foster their community reef stewardship needed for successful management plans and adaptive practices. The trained fishermen can play a useful role as reef stewards who take responsibility for safeguarding marine biodiversity as well as fisheries management in community protected or conserved areas and wider seascapes (Obura *et al.*, 2002b).

By training and involving local fishermen as "reef stewards," this initiative has fostered a strong sense of ownership and responsibility for protecting the coral reefs (Cruz *et al.*, 2018). Through awareness sessions and basic training in coral biology and environmental care, community members gain a clearer understanding of reef ecology and why these ecosystems matter—leading to growing acceptance and support for conservation practices (Kawaka *et al.*, 2017; Mwaura *et al.* 2022). This in turn may encourage and inspire them to take the initiative to look after their protected area and carry out activities that will generate ecological benefits such as enhanced coral cover and commercially important fish populations.

Given the heavy reliance of local communities on reef resources for both food and income and, the widespread impact of the 2016 coral bleaching event across the Western Indian Ocean (Gudka *et al.*, 2018), it is likely that reef conditions in Bofa are in decline. The findings from these participatory surveys offer a strong scientific foundation for addressing both local and global conservation challenges, while also strengthening long-term community engagement and ownership in protecting reef ecosystems. Although the inshore reefs are in poor health conditions, being characterized by low coral cover (<20%) and depleted fish populations, there is still potential for recovery. Coastal fisheries exist in a complex socio-ecological system that involves many factors that determine the success of a particular management regime, but two major factors are compliance with fishery regulations and availability of nursery habitat (Marriott *et al.*, 2021). Active intervention such as deployment of artificial reefs can serve as new habitat to facilitate speedy recovery of corals and fish, as well as lobsters and octopus that are crucial for socio-economic welfare of nearby communities. Artificial reef interventions have been practiced and proved successful which include coral restoration or substrate stabilization, along with full banning of destructive fishing practices such as use of beach seine nets and near shore ring nets (Mwaura *et al.*, 2022).

References

- Agung MF, Adhuri DS, Ferse SCA, Sualia I, Andradi-Brown DA, Campbell SJ, Iqbal M, Jonas HD, Lazuardi ME, Nanlohy H, Pakiding F (2022) Marine conservation beyond MPAs: Towards the recognition of other effective area-based conservation measures (OECMs) in Indonesia. *Marine Policy*, 137: 104939 [<https://doi.org/10.1016/j.marpol.2021.104939>]
- Cinner JE, McClanahan TR, Daw TM, Graham NAJ, Maina J, Wilson SK, Hughes TP (2009) Linking social and ecological systems to sustain coral reef fisheries. *Current Biology*, 19(3): 206–212

- Colin PL (2012) Timing and location of aggregation and spawning in reef fishes. In Sadovy de Mitcheson Y and Colin PL (Eds.), *Reef fish spawning aggregations: Biology, research and management* (pp. 117–158). Springer
- Cruz DW, Villanueva RD, Baria MV (2014) Community-based, low-tech method of restoring a lost thicket of *Acropora* corals. *ICES Journal of Marine Science*, 71(7): 1866–1875
- Eakin CM, Sweatman HPA, Brainard RE (2019) The 2014–2017 global-scale coral bleaching event: Insights and impacts. *Coral Reefs*, 38: 539–545 [<https://doi.org/10.1007/s00338-019-01844-2>]
- Govan H (2009) Achieving the potential of locally managed marine areas in the South Pacific. *SPC Traditional Marine Resource Management and Knowledge Information Bulletin*, 25: 16–25
- Graham NAJ, McClanahan TR, MacNeil MA, Wilson SK, Cinner JE, Huchery C et al. (2017) Human disruption of coral reef trophic structure. *Current Biology*, 27: 231–236 [<https://doi.org/10.1016/j.cub.2016.10.062>]
- Gudka M, Obura DO, Mwaura J, Porter S, Yahya S, Mabwa R (2018) Impact of the 3rd global coral bleaching event on the Western Indian Ocean in 2016. Global Coral Reef Monitoring Network/Intergovernmental Oceanographic Commission [<https://doi.org/10.13140/RG.2.2.32306.71365>]
- Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Baird AH, Baum JK, Berumen ML, Bridge TCL, Claar DC (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, 359(6371): 80–83 [<https://doi.org/10.1126/science.aan8048>]
- Hyder K, Townhill B, Anderson LG, Delany J, Pinnegar JK (2015) Can citizen science contribute to the evidence-base that underpins marine policy? *Marine Policy*, 59: 112–120 [<https://doi.org/10.1016/j.marpol.2015.04.022>]
- Johnson AE, Jackson JBC (2015) Fisher and diver perceptions of coral reef degradation and implications for sustainable management. *Global Ecology and Conservation*, 3: 890–899
- Kawaka JA, Samoilys MA, Murunga M (2017) Coral reef monitoring in Eastern Africa: A guide for communities. TNC/CORDIO
- Kelly R, Fleming A, Pecl GT (2019) Citizen science and social licence: Improving perceptions and connecting marine user groups. *Ocean & Coastal Management*, 178: 104855 [<https://doi.org/10.1016/j.ocecoaman.2019.104855>]
- Knoester EG, Plug VE, Murk AJ, Sande SO, Osinga R (2023) Fisheries restrictions and their cascading effects on herbivore abundance and macroalgae removal at Kenyan coral reefs. *Journal of Experimental Marine Biology and Ecology*, 559: 151850
- Kohler KE, Gill SM (2006) Coral point count with Excel extensions (CPCe): A Visual Basic program for the determination of coral and substrate coverage using random point count methodology. *Computers & Geosciences*, 32: 1259–1269
- Madi M, Ravinia I, Razafindrainibe H, Yahya S, Zivane F (2021) Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. Nature Sustainability. Advance online publication [<https://doi.org/10.1038/s41893-021-00817-0>]
- Maina GW, Osuka KE, Samoilys ME (2011) Opportunities and challenges of community-based marine protected areas in Kenya. CORDIO Status Report, 2011: 6
- Marriott SE, Cox C, Amolo RC, Apistar D, Mancao RH, de Mutsert K (2021) Implications of community-based management of marine reserves in the Philippines

- for reef fish communities and biodiversity. *Frontiers in Marine Science*, 8: 731675 [<https://doi.org/10.3389/fmars.2021.731675>]
- McClanahan TR, Ateweberhan M, Graham NAJ, Wilson SK, Sebastián CR, Guillaume MM, Bruggemann JH (2007) Western Indian Ocean coral communities: Bleaching responses and susceptibility to extinction. *Marine Ecology Progress Series*, 337: 1–13
- Mwaura JM, Murage D, Karisa JF, Otswana LM, Said HO (2022) Artificial reef structures and coral transplantation as potential tools for enhancing locally managed inshore reefs: A case study from Wasini Island, Kenya. *Western Indian Ocean Journal of Marine Science*, 21(2): 83–94
- Neo ML, Eckman W, Vicentuan K, Teo SLM, Todd PA (2015) The ecological significance of giant clams in coral reef ecosystems. *Biological Conservation*, 181: 111–123
- Obura DO (2001) Participatory monitoring of shallow tropical marine fisheries by artisanal fishers in Diani, Kenya. *Bulletin of Marine Science*, 69(2): 777–791
- Obura DO (2005) Resilience and climate change: Lessons from coral reefs and bleaching in the Western Indian Ocean. *Estuarine, Coastal and Shelf Science*, 63(3): 353–372
- Obura D, Grimsditch G (2009) Resilience assessment of coral reefs: Assessment protocol for coral reefs, focusing on coral bleaching and thermal stress. IUCN
- Obura DO, Smits M, Chaudhry T, McPhillips J, Beal D, Astier C (2017a) Reviving the Western Indian Ocean economy. WWF International
- Obura D, Gudka M, Rabi FA, Gian SB, Bijoux J, Freed S, Maharavo J, Mwaura J, Porter S, Sola E, Wickel J (2017b) Coral reef status report for the Western Indian Ocean. Global Coral Reef Monitor-
ing Network/International Coral Reef Initiative [<https://doi.org/10.13140/RG.2.2.20642.07366>]
- Obura DO, Wanyonyi IN, Mwaura JM, Africa CE (2002) Participatory monitoring of an artisanal fishery in Kenya. In Coral reef degradation in the Indian Ocean (p. 70)
- Obura DO, Wells S, Church J, Horrill C (2002) Monitoring of fish and fish catches by local fishermen in Kenya and Tanzania. *Marine and Freshwater Research*, 53(2): 215–222
- Poisson AC, McCullough IM, Cheruvellil KS, Elliott KC, Latimore JA, Soranno PA (2020) Quantifying the contribution of citizen science to broad-scale ecological databases. *Frontiers in Ecology and the Environment*, 18(1): 19–26 [<https://doi.org/10.1002/fee.2128>]
- Ray GC (1996) Coastal-marine discontinuities and synergisms: Implications for biodiversity conservation. *Biodiversity and Conservation*, 5: 1095–1108 [<https://doi.org/10.1007/BF00052719>]
- Samoilys MA, Osuka K, Maina GW, Obura DO (2017) Artisanal fisheries on Kenya's coral reefs: Decadal trends reveal management needs. *Fisheries Research*, 186: 177–191
- Toomey AH, Domroese MC (2013) Can citizen science lead to positive conservation attitudes and behaviors? *Human Ecology Review*, 20(1): 50–62
- Wenger AS, Fabricius KE, Jones GP, Brodie JE (2015) Effects of sedimentation, eutrophication, and chemical pollution on coral reef fishes. In Mora C (Ed.), *Ecology of fishes on coral reefs* (pp. 145–153). Cambridge University Press [<https://doi.org/10.1017/CBO9781316105412.017>]

Nile tilapia (*Oreochromis niloticus*) invasion of a saline–alkaline meromictic crater lake in Kenya’s Great Rift Valley: implications for management and conservation

Edna Waithaka^{1*}, James Last Keyombe², Alice Mutie¹, Salima Otieno¹

¹Kenya Marine and Fisheries Research Institute, Naivasha Station, Naivasha, Kenya

²Kenya Marine and Fisheries Research Institute, Kisumu Centre, Kisumu, Kenya

*Corresponding author E-mail: kerubowaithaka@gmail.com

Abstract

Lake Sonachi (Crater Lake) is a small saline–alkaline meromictic lake in Kenya’s Great Rift Valley that has historically been fishless and important for soda-lake birdlife. Recent reports of fish prompted this baseline survey of the lake’s water quality and fish status. Physicochemical measurements indicated a marked decrease in salinity, from historical saline conditions (~15.6 ppt) to 2.7–3.3 ppt, signalling a shift toward freshwater. Total dissolved solids ranged from 3,289 to 3,757 mg/L, reflecting the lake’s mineral-rich waters. Eighty-five fish were sampled, comprising Nile tilapia (*Oreochromis niloticus*, 84%) and a suspected hybrid (16%); condition factors above 1 indicated fish in good condition. The establishment of Nile tilapia is an ecological concern: beyond its likely collapse should saline conditions return, it may compete with specialised soda-lake biota and alter primary productivity. Heavy-metal analysis showed iron (0.5–2.5 mg/L) and arsenic (10–30 µg/L) above WHO drinking-water guidelines. To safeguard the lake, we recommend integrated catchment management to regulate freshwater inflow and community-led monitoring of the invasive fish population.

Keywords: Lake sonachi, nile tilapia, invasive species, soda lake, water quality, conservation

Introduction

Rift Valley lakes form distinct freshwater ecoregions, often including alkaline waters, and are recognised as global biodiversity hotspots that support a disproportionately large share of the world’s species. Freshwater ecosystems hold roughly 6% of all described species despite occupying only about 0.8% of the Earth’s surface (Dudgeon *et al.*, 2006).

Crater Lake Game Sanctuary, commonly known as Lake Sonachi, is a small but ecologically significant saline–alkaline lake in Kenya’s Great Rift Valley, on the western side of Lake Naivasha in Nakuru County. Formed within a volcanic cra-

ter, it lies at about 1,892 m above sea level and covers roughly 0.62 km². The surrounding vegetation, particularly dense stands of yellow fever trees (*Acacia xanthophloea*), is characteristic of the riparian zones of this part of the Rift Valley and provides habitat for diverse fauna.

The lake is meromictic: its water layers do not mix vertically, so the deeper water remains isolated and stagnant, producing strong gradients in oxygen and chemistry between the surface and bottom. Its saline and alkaline waters have historically made it unsuitable for fish but ideal for birds, and it is well known for the lesser flamingo (*Phoeniconaias minor*), which feeds on the cyanobacteria that thrive in its alkaline wa-

ters (Fazi *et al.*, 2021). Lake Sonachi is essentially ombrotrophic, receiving water mainly from precipitation and surface runoff from the surrounding crater walls, with no known surface inlets or outlets (Gaudet and Melack, 1981); it is also fed by groundwater from nearby Lake Naivasha (Verschuren, 1999). Over the past decade the lake has shown large natural water-level fluctuations exceeding 2.5 m, reshaping its ecosystem and altering surrounding habitats (Woolway *et al.*, 2022).

The sanctuary supports diverse wildlife, with over 150 bird species recorded, including flamingos, yellow-billed storks, African fish eagles and pied avocets (BirdLife International, 2024). The surrounding forest provides habitat for black-and-white colobus monkeys (*Colobus guereza*) and antelopes such as impala (*Aepyceros melampus*) and Thomson's gazelle (*Eudorcas thomsonii*). Although the lake was long considered fishless because of its high salinity and alkalinity, local communities and researchers have recently reported birds feeding on fish, raising concern about the introduction of fish into the lake. Nile tilapia (*Oreochromis niloticus*), a species usually associated with freshwater, is suspected to have entered the lake despite its saline conditions, raising questions about its im-

pact on the lake's delicate ecological balance and its suitability for human consumption.

In response, the Kenya Marine and Fisheries Research Institute (KMFRI) initiated a baseline survey to assess the presence of fish and the broader ecological implications of this unexpected invasion, including whether the lake can sustainably support fish and whether the fish are safe to eat. Given the lake's importance as a bird sanctuary and the fragility of its ecosystem, the introduction of fish into such a closed-basin lake could disrupt existing biodiversity (BirdLife International, 2024).

This study provides a baseline analysis of the ecological dynamics of Lake Sonachi, focusing on the current status of fish populations and the lake's water quality. It identifies and quantifies the fish species present and measures key water quality parameters – including temperature, pH, dissolved oxygen and trace elements – to evaluate the lake's suitability for aquatic life. Because the lake is meromictic, these measurements are especially important for understanding how stratification and deep-water anoxia influence fish habitat and water chemistry. The findings will inform future conservation and management of Crater Lake Game Sanctuary.

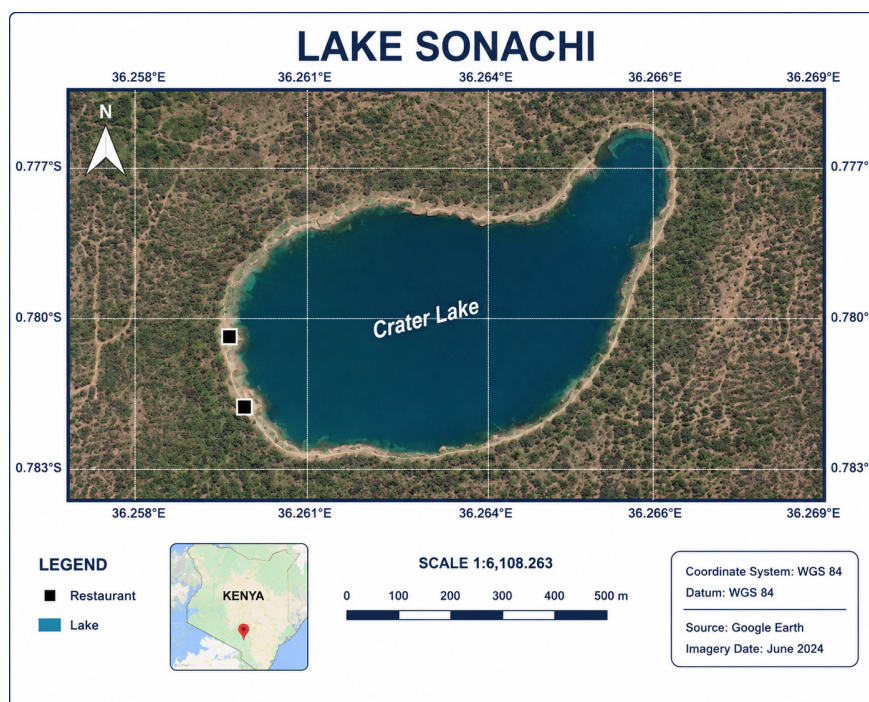


Figure 1. Schematic location map of Lake Sonachi (Crater Lake), west of Lake Naivasha in Kenya's Great Rift Valley, showing the four sampling sites (A–D).

Materials and methods

Study area

The study was carried out in Lake Sonachi, a crater lake on the western side of Lake Naivasha in Nakuru County, Kenya (Fig. 1). Water samples were taken at four sites within the lake.

Data collection

At each of the four sampling sites, *in situ* measurements and water samples were collected to obtain a representative profile of the lake. Two replicate samples were taken at each site to allow vertical depth profiling, giving eight samples in total. At each site, 2 L of water were collected in clean plastic containers for the analysis of nutrients and total suspended solids (TSS).

Physicochemical parameters

Physicochemical parameters were measured *in situ* using a calibrated portable YSI multiparameter water quality meter. The parameters recorded were temperature (°C), dissolved oxygen (DO; mg/L), pH, electrical conductivity (µS/cm), total dissolved solids (TDS; mg/L), salinity (ppt), pressure and oxidation–reduction potential (ORP; mV). Measurements were taken at the water surface after allowing the probe to stabilise for about 2–3 minutes at each station to minimise sensor drift. All sensors were calibrated before deployment following the manufacturer's guidelines.

Turbidity was measured *in situ* with a portable turbidity meter. Water was gently collected into clean sample cells to avoid air bubbles and sediment disturbance, the instrument was zeroed with standard calibration solutions, and turbidity was recorded in nephelometric turbidity units (NTU). *In situ* chlorophyll-*a* was measured with a YSI 600 OMS meter lowered through the water column at each station, with readings taken after sensor stabilisation to assess phytoplankton biomass.

Water transparency, depth and total suspended solids

Water transparency was measured with a 20 cm diameter Secchi disc painted alternately black and white, lowered on the shaded side of the vessel until it disappeared and then raised until it reappeared; the mean of the two depths was recorded as the Secchi depth (m). Water depth at each station was measured with a portable depth finder, taking multiple readings to account for spatial variability. TSS were determined gravimetrically following APHA (2005): a known volume of water was filtered through pre-weighed glass-fibre filters under vacuum, and the filters were oven-dried at 104 °C for 24 h, cooled in a desiccator and re-weighed, with TSS calculated from the weight difference per volume filtered and expressed as mg/L.

Soluble reactive phosphorus and nitrate

Water for soluble reactive phosphorus (SRP) analysis was filtered through 0.45 µm membrane filters and analysed by the molybdenum-blue method following APHA (2005), with absorbance read on a spectrophotometer against calibration standards. Nitrate was analysed with a Palintest Photometer 7500 (Wagtech Potalab) direct-reading spectrophotometer; filtered samples were reacted with high-range nitrate reagent (NitraVer 5) following the manufacturer's protocol, and nitrate-nitrogen (NO₃⁻-N) was computed by the instrument.

Fisheries

Fish were collected using multifilament and monofilament gill nets of mesh sizes ranging from 2 to 4 inches, with an average soak time of 3 h, to determine the catch rate.

Microbial contaminants (total and faecal coliforms)

Coliforms were determined by membrane filtration. At each station, surface water was collected in a sterile cup, and 10 mL was vacuum-filtered through a 47 mm membrane filter (0.45 µm porosity) to trap coliforms. The filter was transferred to a Petri dish containing an absorbent pad soaked in m-lauryl sulphate broth and

incubated for 24 h at 37 °C for total coliforms and at 44.7 °C for faecal coliforms. Yellow colony-forming units were counted manually using membrane grids (US EPA, 2002).

Elemental analysis

Water samples were collected at different depths to capture vertical stratification, using acid-cleaned polyethylene bottles to avoid contamination. Samples were immediately acidified with ultrapure nitric acid (HNO₃) to preserve dissolved metals and filtered through 0.45 µm membrane filters to separate the dissolved fraction. Trace elements (e.g. Fe, Mn, Zn, Cu, Pb, Cd, As) were quantified by inductively coupled plasma mass spectrometry (ICP-MS), and major cations and higher-concentration trace metals by inductively coupled plasma optical emission spectrometry (ICP-OES). Calibration standards were prepared from certified reference materials, and blanks and replicates were included to check for contamination and reproducibility, with detection limits reported for each element. Concentrations were compared with background levels in other Rift Valley lakes, trace-metal-to-major-ion ratios were used to infer geochemical sources (hydrothermal input versus catchment runoff), and heavy-metal enrichment factors were calculated relative to crustal averages (Butturini *et al.*, 2020).

Results and discussion

Physicochemical characteristics

The physicochemical parameters indicated a substantial reduction in salinity, from historical levels toward current values of 2.7–3.3 ppt, marking a transition toward freshwater conditions (Butturini *et al.*, 2020). TDS ranged from 3,289 to 3,757 mg/L, reflecting the lake's mineral content and nutrient inputs (Table 1).

Table 1. Mean (± SD) values of surface-water variables in Lake Sonachi, June 2024.

Parameter	Mean (± SD)	Range
Temperature (°C)	22.1 ± 0.14	21.2–22.2
Conductivity (mS/cm)	4.79 ± 0.05	4.72–4.87
Dissolved oxygen (mg/L)	3.1 ± 1.26	1.4–4.4
Salinity (ppt)	2.73 ± 0.01	2.72–3.3
Turbidity (NTU)	25.9 ± 3.11	23.7–30.3
pH	8.10 ± 0.34	7.63–8.39
Total dissolved solids (mg/L)	3301.8 ± 9.08	3289–3757
Pressure (mmHg)	587.37 ± 0.17	587.3–587.7
Depth (m)	4.63 ± 0.40	4.3–5.2
Secchi depth (m)	23.17 ± 0.94	22.5–24.5
Chlorophyll- <i>a</i> (µg/L)	9.57 ± 0.31	—
Total suspended solids (mg/L)	31.33 ± 4.04	27–35
Alkalinity (mg/L)	324 ± 133.1	205–470
Nitrate (NO ₃ ⁻ ; mg/L)	0.004 ± 0.003	—
Phosphate (PO ₄ ³⁻ ; mg/L)	0.022 ± 0.009	—
Total coliforms (cfu/100 mL)	125	—
Faecal coliforms (cfu/100 mL)	22	—

The salinity of Lake Sonachi has shifted notably in recent years. Historically the lake was strongly saline (approximately 24.6 ppt), consistent with the high-salinity phases documented for Rift Valley soda lakes (Vareschi and Vareschi, 1984). A similar transition has been observed in neighbouring Lake Nakuru, where flooding reduced salinity from typically >30 ppt to <5 ppt, markedly altering the food web: the salt-tolerant tilapia *Oreochromis alcalicus grahami* declined while the freshwater-tolerant *Oreochromis niloticus* increased, and the cyanobacterium *Arthrospira fusiformis* (spirulina) disappeared, triggering large-scale emigration of lesser flamingos (Opiyo *et al.*, 2019). Such freshening can substantially alter species composition, nutrient cycling and aquatic-life dynamics (Mulama and Ondieki, 2023).

The TDS values (3,289–3,757 mg/L) indicate that, although the lake is freshening, it remains rich in dissolved minerals, probably owing to its volcanic geology and localised nutrient loading; high TDS typically signals elevated dissolved ions such as sodium, potassium and chloride, characteristic of volcanic lakes (Onzere *et al.*, 2022). These changes alter the lake's biogeochemistry by affecting nutrient solubility and reducing carbonate buffering capacity. The resulting freshening favours invasion by *O. niloticus* while imposing osmotic stress on specialised alkaline-adapted taxa, with the potential for permanent loss of the lake's unique soda-lake biodiversity.

Dissolved oxygen showed a clear vertical gradient, decreasing with depth at all sampling points. Higher concentrations occurred in surface and near-surface waters, while deeper layers were consistently oxygen-poor. This decline reflects microbial decomposition of organic matter (from runoff and settling material) that consumes oxygen at depth, together with the lake's meromictic stratification, which limits vertical mixing and oxygen diffusion to deeper layers and can produce anoxic conditions. Such oxygen gradients are characteristic of stratified, meromictic systems with limited circulation and high organic inputs (Wetzel, 2001), and comparable depth-related oxygen depletion has been reported for small alkaline Rift Valley lakes (Gikuma-Njuru *et al.*, 2013).

Trace metals and nutrients

Trace-metal analysis showed dominance of iron (Fe) and manganese (Mn), moderate zinc (Zn) and copper (Cu), and trace but notable lead (Pb), cadmium (Cd) and arsenic (As) (Table 2). Fe and Mn enrichment reflects hydrothermal activity and the anoxic conditions of the deeper layers. Although Pb and Cd were low, they raise ecological concern for waterbirds and benthic organisms, and As exceeded WHO drinking-water guidelines, indicating potential risk if the lake water were used for human consumption. Overall, Sonachi's trace-metal profile is consistent with the geothermal influence of other Rift Valley soda lakes, but with somewhat higher As and Pb.

Table 2. Average concentrations of trace elements from the surface (0 m) to the bottom (4 m) of the water column in Lake Sonachi.

Element	Concentration range	Comments
Iron (Fe)	0.5–2.5 mg/L	Elevated, reflecting hydrothermal/geo-thermal inputs
Manganese (Mn)	0.2–1.0 mg/L	Linked to reducing conditions in bottom waters
Zinc (Zn)	20–80 µg/L	Moderate enrichment relative to background soda lakes
Copper (Cu)	10–40 µg/L	Detected mainly in surface waters
Lead (Pb)	5–15 µg/L	Low but above natural crustal averages
Cadmium (Cd)	1–5 µg/L	Trace levels; potential ecological concern
Arsenic (As)	10–30 µg/L	Elevated relative to WHO drinking-water guidelines

Chlorophyll-*a* levels were low, which may reflect water movement, lake depth or nutrient limitation, while nitrate and phosphate were within acceptable environmental ranges (Wetzel, 2001) (Table 3).

Table 3. Mean nutrient levels at three sampling points in Lake Sonachi.

Point	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (µg/L)	Chlorophyll- <i>a</i> (µg/L)
A	0.3	15.1	9.5
B	0.7	32.6	9.3
C	0.1	19.0	9.0

Fish abundance and composition

In total, 85 fish were caught and measured for length (cm) and weight (g), comprising *Oreochromis niloticus* (84%, *n* = 71) and a suspected hybrid (16%, *n* = 14) thought to have originated from outside the basin (Fig. 2). Molecular characterisation will be needed to confirm the identity of the hybrid.

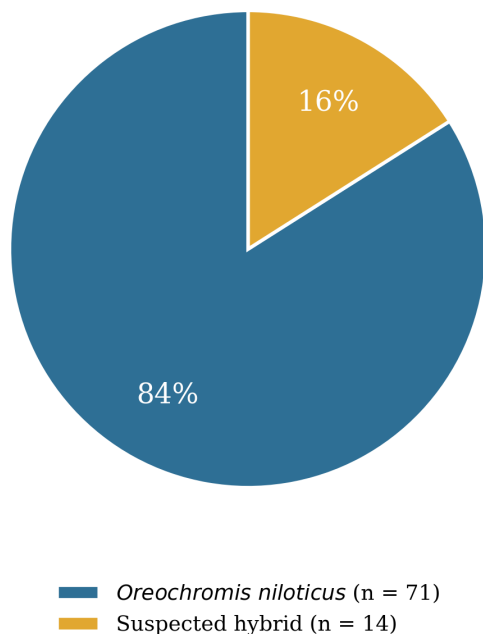


Figure 2. Percentage species composition of fish sampled in Lake Sonachi.

The total length (TL) of *O. niloticus* ranged from 10 to 29 cm (mean 17.1 ± 4.98 cm), whereas the hybrid ranged from 15 to 27.6 cm (mean 20.9 ± 3.5 cm) (Table 4). The condition factor (K) of *O. niloticus* exceeded 1 in all samples, indicating fish in good condition and conditions in the lake favourable for growth.

Table 4. Characteristics of fish caught in Lake Sonachi.

Measure	Sample size	Range	Mean ($\pm$ SD)
Suspected hybrid			
Length (cm)	14	15–27.6	20.9 ± 3.5
Weight (g)	14	84–434	212.7 ± 96.5
Condition factor (K)	14	1.67–3.85	2.37 ± 1.00
<i>Oreochromis niloticus</i>			
Length (cm)	71	10–29	17.1 ± 4.98
Weight (g)	71	39–521	168.8 ± 100.34
Condition factor (K)	71	1.6–5.44	3.41 ± 1.13

Gut-content analysis showed that *O. niloticus* feeds opportunistically (Table 5). Algae (cyanobacteria) were the dominant gut item (66.7% of items recorded), followed by copepods (33.3%), reflecting a flexible diet adapted to available food resources.

Table 5. Gut contents of *Oreochromis niloticus* in Lake Sonachi.

Gut content	No.	%
Algae	54	66.7
Copepods	27	33.3
Total	81	100

The sex ratio was male-skewed, at 1:0.6 for *O. niloticus* and 1:0.4 for the suspected hybrid. A skewed sex ratio may limit spawning opportunities and reduce reproductive success, potentially affecting population dynamics. These findings underline the need for continued monitoring and for molecular characterisation of the hybrid to better understand the ecology of the lake’s fish populations.

This study represents the first documented occurrence of fish in Lake Sonachi and reveals ecological change likely linked to recent shifts in water quality. The presence of *O. niloticus* and its suspected hybrids suggests that the lake has recently become more suitable for fish, probably owing to increased precipitation and associated environmental change. However, the persistence of these populations is uncertain given the lake’s fluctuating water levels: a return toward saline–alkaline conditions would likely cause mass mortality, as observed in other Rift Valley lakes where salinity thresholds (e.g. >13 ppt) impose osmotic and physiological stress on less-tolerant species (Kevrekidis *et al.*, 2020).

Conclusions and recommendations

This survey documents the first recorded occurrence of fish in Lake Sonachi, against a backdrop of declining salinity and a transition toward freshwater conditions. The establishment of *O. niloticus* and a suspected hybrid, together with

elevated arsenic and iron, signals important ecological change in this fragile soda-lake ecosystem. We recommend a systematic monitoring programme for water quality and nutrients to track ongoing change and possible contamination; habitat management focused on preserving and restoring habitats that support sensitive, soda-lake-adapted species; the involvement of local communities in conservation, sustainable fishing and socio-economic resilience; and comprehensive studies of the introduced fish, including genetic characterisation to clarify hybridisation and its implications for biodiversity.

Acknowledgements

The authors thank the Kenya Marine and Fisheries Research Institute (KMFRI) for the institutional, technical and logistical support that made this baseline survey possible, and the field and laboratory staff who assisted with sampling and analysis.

Funding

This study was supported by the Kenya Marine and Fisheries Research Institute (KMFRI).

References

- American Public Health Association (2005) Standard methods for the examination of water and wastewater (21st ed.). American Public Health Association
- BirdLife International (2024) Lake Naivasha – Important Bird Area factsheet. BirdLife Data Zone. [<https://datazone.birdlife.org/site/factsheet/lake-naivasha-iba-kenya>]
- Butturini A, Amalfitano S, Herzsprung P, Lechtenfeld OJ, Venturi S, Olaka LA, Pacini N, Harper DM, Tassi F, Fazi S (2020) Dissolved organic matter in continental hydro-geothermal systems: Insights from two hot springs of the East African Rift Valley. *Water*, 12(12): 3512 [<https://doi.org/10.3390/w12123512>]
- Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews*, 81(2): 163–182 [<https://doi.org/10.1017/S1464793105006950>]
- Fazi S, Amalfitano S, Venturi S, Pacini N, Vázquez E, Olaka LA, Tassi F, Crognale S, Herzsprung P, Lechtenfeld OJ, Cabassi J, Capecechiacci F, Rossetti S, Yakimov MM, Vaselli O, Harper DM, Butturini A (2021) High concentrations of dissolved biogenic methane associated with cyanobacterial blooms in East African lake surface water. *Communications Biology*, 4: 845 [<https://doi.org/10.1038/s42003-021-02365-x>]
- Gaudet JJ, Melack JM (1981) Major ion chemistry in a tropical African lake basin. *Freshwater Biology*, 11(4): 309–333
- Gikuma-Njuru P, Hecky RE, Guildford SJ (2013) Oxygen and nutrient dynamics in alkaline Rift Valley lakes: Implications for ecosystem health
- Kevrekidis T, Mogias A, Gkoltsiou A (2020) Long-term hydrologic fluctuations and dynamics of primary producers in a tropical crater lake. *Journal of Limnology*, 79: 215–228 [<https://doi.org/10.4081/jlimnol.2020.215>]
- Mulama R, Ondieki J (2023) Assessment of spatial expansion of Rift Valley lakes using satellite data. *Advances in Remote Sensing*, 12: 88–98 [<https://doi.org/10.4236/ars.2023.123005>]
- Onzere E (2022) Hydrological shifts and biodiversity in Kenyan Rift Valley lakes
- Opiyo MA (2019) Physicochemical parameters and their influence on the composition and abundance of phytoplankton in Lake Nakuru, Kenya. *African Journal of Aquatic Science*

United States Environmental Protection Agency
(2002) Method 1604: Total coliforms and
Escherichia coli in water by membrane
filtration. U.S. Environmental Protection
Agency

Vareschi E, Vareschi A (1984) The ecology of
Lake Nakuru (Kenya). IV. Biomass and
distribution of consumer organisms.
Oecologia, 61(1): 70–82 [[https://doi.
org/10.1007/BF00379091](https://doi.org/10.1007/BF00379091)]

Verschuren D (1999) Sedimentation controls
on the preservation and time resolution
of climate-proxy records from shallow
fluctuating lakes. *Quaternary Science
Reviews*, 18(6): 821–837 [[https://doi.
org/10.1016/S0277-3791\(98\)00065-1](https://doi.org/10.1016/S0277-3791(98)00065-1)]

Wetzel RG (2001) Limnology: Lake and river eco-
systems (3rd ed.). Academic Press

Woolway RI, Sharma S, Smol JP (2022) Lakes in
hot water: The impacts of a changing
climate on aquatic ecosystems. *Bio-
Science*, 72(11): 1050–1061 [[https://doi.
org/10.1093/biosci/biac052](https://doi.org/10.1093/biosci/biac052)]

Structure and organization of Omena (*Rastrineobola argentea*) fishing enterprises in Lake Victoria, Kenya: labour, income distribution and gender dynamics

Susan Atieno Wandago^{1*}, Christopher Mulanda Aura¹, Chrispine S. Nyamweya¹, Venny Mziri¹, FondaJane Awuor¹, Patrick Wanguche Otuo¹, Victor Kevin Onsongo¹, Melckzedek Osore², Paul S. Orina²

¹Kenya Marine and Fisheries Research Institute, P.O. Box 1881–40100, Kisumu, Kenya

²Kenya Marine and Fisheries Research Institute, P.O. Box 81651–80100, Mombasa, Kenya

*Corresponding author E-mail: suemeracy28@gmail.com

Abstract

This study examines the structure, labour organisation, income distribution and gender dynamics of Omena (*Rastrineobola argentea*) fishing enterprises on the Kenyan shores of Lake Victoria. Based on a survey of 114 enterprises (55 traders, 28 processors, 31 producers), it reveals a highly gendered, hierarchical system. Producer enterprises employ an average of 14 workers, mainly male fishers, whereas processors and traders rely on smaller, often female-dominated teams (means of 3 and 1 workers). Income is uneven and seasonal: boat owners earned a mean of KES 126,000 monthly in the high season, compared with KES 24,623 for fishers and KES 8,688 for seasonal labourers. The Gender Concentration Index (GCI) shows stark divisions – capture fishing is male-dominated (GCI = 0.89), while processing (GCI = 1.00), trading (GCI = 0.85) and financial management (GCI = 0.67) are female-dominated. Safety practices are tiered, with boat crews reporting multiple precautions and processors only basic protective equipment. Governance challenges persist, with harassment from authorities ranking highest (average weighted score = 1.47). The findings show that Omena enterprises are complex socio-economic systems in which informal co-management, embedded gender roles and seasonal variability shape livelihoods, equity and sustainability in this vital freshwater fishery.

Keywords: Omena fishery, Lake Victoria, enterprise structure, gender dynamics, income distribution, co-management

Introduction

The global significance of small-scale fisheries extends far beyond mere food production, constituting a fundamental pillar of livelihood security, poverty alleviation, and cultural identity for hundreds of millions of people worldwide. These fisheries are estimated to contribute over half of the global fish catch destined for direct human consumption and provide employment for more than 90% of all capture fishers and fish workers (FAO, 2018). However, this critical sector operates within a complex and often precarious

socio-ecological framework. The organizational structures of these enterprises are typically informal, adaptive, and deeply embedded in local social and cultural norms, which govern everything from labor recruitment to the distribution of benefits (Crona *et al.*, 2016). This informality, while offering flexibility, often renders the sector and its workers vulnerable to external shocks, including climate variability, market fluctuations, and resource depletion, challenging conventional top-down management approaches (Béné *et al.*, 2016). A central feature of these enterprises globally is the prevalence of share

systems or “lays” as a primary income-sharing mechanism. This model, which allocates a portion of the catch value or profit among the boat owner, crew, and sometimes creditors, functions as a risk-sharing arrangement that aligns incentives in an inherently uncertain profession (Platteau *et al.*, 1992). Concurrently, a robust body of international scholarship has systematically deconstructed the notion of fishing as a purely male domain, illuminating the extensive yet frequently undervalued and unseen roles of women. While men dominate capture fishing, women are integral to post-harvest activities processing, marketing, and net maintenance and are crucial in managing household income from fisheries, thereby underpinning both food and economic security (Harper *et al.*, 2020). The failure to account for these gendered divisions of labor and access to resources has been shown to compromise the effectiveness, efficiency, and equity of fisheries policies and development interventions (Kleiber *et al.*, 2015).

In the East African regional context, inland fisheries are not merely economic activities but are central to the food systems and socio-economic fabric of the Great Lakes region. Lake Victoria, as the continent’s largest freshwater body, epitomizes this importance, sustaining livelihoods for an estimated three million people directly and indirectly across Kenya, Tanzania, and Uganda (Njiru *et al.*, 2018). The lake’s fishery has been characterized by dramatic ecological shifts, most notably the introduction of Nile perch (*Lates niloticus*) and the subsequent expansion of a lucrative export-oriented fillet industry. Within this transformed ecosystem, the Omena (*Rastrineobola argentea*) fishery has emerged as a resilient and socio-economically vital sector. Omena, a small, nutrient-rich pelagic fish, serves as a critical source of affordable animal protein for low-income populations and a buffer against food insecurity, while its fishery provides essential employment, particularly for those without the capital to engage in the large Nile perch venture (Taabu-Munyaho *et al.*, 2016). The fishery’s operational model, relying on nocturnal fishing with lift nets and kerosene or pressure lamps for attraction, creates distinct labor demands and seasonal patterns. Regionally, stud-

ies have documented the highly mobile nature of Omena fishing crews, complex pre-financing arrangements between traders and boat owners, and the pervasive use of share systems. However, these studies also highlight concerns regarding working conditions, indebtedness among crew, and the environmental pressures of the fishery, including the ecological impacts of using mosquito nets and the competition for fishery resources (Nunan *et al.*, 2015). The trans-boundary nature of the resource further complicates management, requiring coordination that often struggles to account for these intricate local-level socio-economic structures.

Examining the broader African continent reveals that small-scale fisheries governance is increasingly moving towards co-management paradigms, which seek to blend community-based institutions with state regulatory frameworks. The success of such approaches is heavily contingent on a deep understanding of existing local organizations, norms, and economic relationships (Chuenpagdee and Jentoft, 2019). Across African fisheries, informal and customary institutions frequently hold more sway than formal laws in regulating access, resolving disputes, and structuring economic exchanges within fishing enterprises (Belhabib *et al.*, 2015). The share system, while common, exhibits local variations in the distribution formulae, reflecting historical precedent, power dynamics, and the specific capital inputs required (Jul-Larsen *et al.*, 2003). A continent-wide analysis of gender roles consistently reveals a persistent dichotomy: men are predominantly the owners of capital assets like boats and engines and are seen as the primary harvesters, while women are overwhelmingly concentrated in the post-harvest sector. This includes activities such as smoking, drying, frying, and petty trading, which are characterized by informality, low profit margins, and high physical burdens (Frangoudes and Gerrard, 2018). Despite generating substantial income and ensuring food reaches consumers, women’s work is often perceived as an extension of domestic responsibilities rather than as formal economic labor, limiting their access to credit, technology, and representation in formal decision-making bodies (Onyango and Luomba, 2017). This systemic marginalization means that fisheries policies and development programs,

even those aimed at community participation, often bypass or inadvertently harm women's interests, thereby undermining both social justice and the potential for holistic resource management (Okeke-Ogbuafor *et al.*, 2020).

Focusing on the Kenyan portion of Lake Victoria, the Omena fishery has become a linchpin of the local economy in counties like Siaya, Homa Bay, Migori, and Kisumu. Its growth is attributed to the relative stability of Omena stocks compared to some other species, its lower barriers to entry in terms of gear cost compared to motorized Nile perch fishing, and its role as a employer for youth and migrant laborers (Manyala and Ojuok, 2007). The Kenyan government, through the State Department for Fisheries and with research support from the Kenya Marine and Fisheries Research Institute (KMFRI), has implemented regulatory measures such as annual two-month fishing bans to protect breeding stocks and restrictions on illegal gear (Obiero *et al.*, 2015). Nevertheless, the internal social architecture of Omena enterprises how labor is organized, how income is shared, and how gender shapes participation remains inadequately mapped and understood. Existing literature points to a multi-tiered actor network involving absentee boat owners, captains who are often experienced crew, migratory crew members with precarious employment, and a downstream chain of traders, processors, and transporters (Abila *et al.*, 2009). Labor patterns are intimately tied to lunar cycles and weather, with peak fishing activities around the dark moon phases, leading to periods of intense work followed by lulls, affecting income regularity and labor stability (Ojwang *et al.*, 2014). The income-sharing model, though ostensibly designed for fairness, is often opaque. Power asymmetries based on ownership, debt relationships where crew are advanced nets or food, and access to market information can lead to exploitative practices where the crew's share is minimized after deductions (Onyango, 2017). In Kenyan fishing communities, gender roles are sharply delineated. Women are the backbone of the post-harvest Omena value chain, engaging in sun-drying on raised racks, sorting, grading, bulking, and local trading. These activities expose

them to occupational health hazards, including respiratory problems from dust and musculoskeletal injuries, and offer minimal financial returns relative to their labor input (Odhon et al., 2020). Critically, despite their economic significance, women's participation in formal governance structures like Beach Management Units (BMUs) the cornerstone of fisheries co-management in Kenya is markedly low. Their exclusion from these forums means that management decisions, including those on access rules, closure periods, and infrastructure development, are made without considering their specific needs and constraints, perpetuating a cycle of marginalization (Etiegni *et al.*, 2017).

Therefore, a systematic investigation into the organizational structure and operational dynamics of Omena fishing enterprises in the Kenyan Lake Victoria basin is both timely and necessary. This study seeks to characterize how these enterprises are internally organized by documenting the structure of labor arrangements and the seasonal rhythms that shape fishing operations and employment stability. This study focuses specifically on three core enterprise types that constitute the fishery's value chain: producers (capture fishing units), processors, and traders. It seeks to characterize how these enterprises are internally organized by documenting the structure of labor arrangements and the seasonal rhythms that shape fishing operations and employment stability. It further examines the income-sharing mechanisms that govern the distribution of benefits among boat owners, crew members, and other key actors, paying particular attention to how power relations, indebtedness, and access to capital influence outcomes. Finally, the study interrogates the gendered dimensions of Omena fisheries by analyzing the roles of men and women across production, post-harvest processing, household decision-making, and participation in governance structures. By integrating labor organization, economic relations, and gender dynamics within a single analytical framework, the study generates evidence critical for informing more inclusive, equitable, and context-responsive fisheries management and development interventions in Kenya's portion of Lake Victoria.

Materials and methods

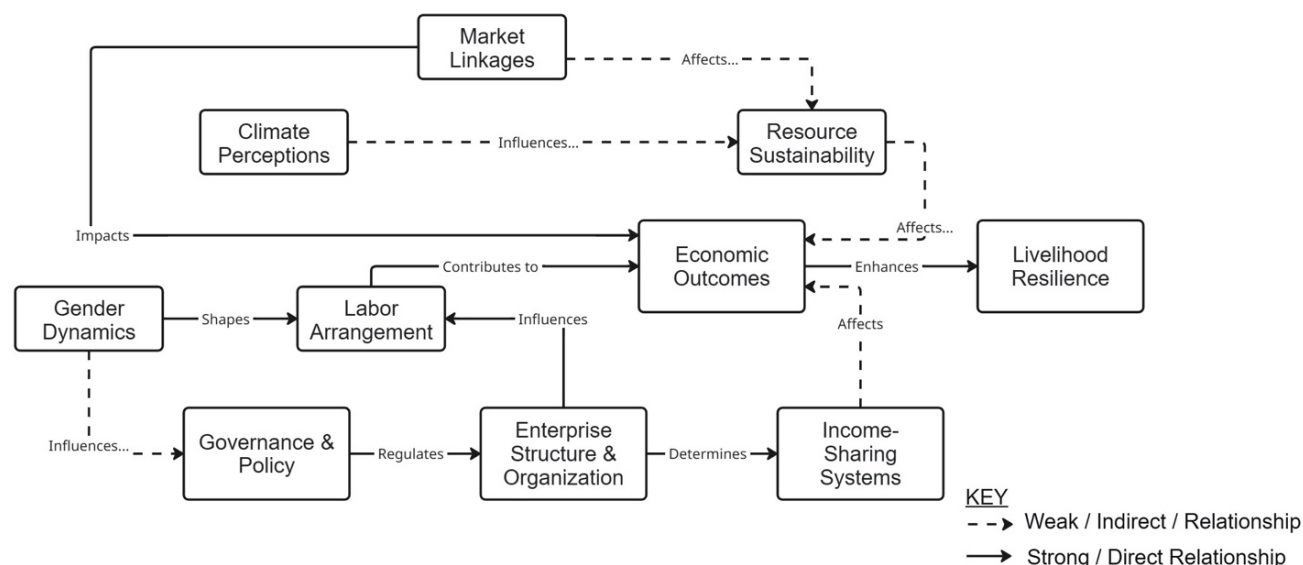


Figure 1. Conceptual framework linking gender dynamics, enterprise organisation, market linkages and livelihood outcomes in the Lake Victoria Omena fishery.

Study area and context

This study was conducted within the Kenyan portion of the Lake Victoria basin, a major inland fishery system that supports extensive capture fisheries, trade networks, and lakeshore livelihoods (Njiru *et al.*, 2018). The focus was on the Omena (*Rastrineobola argentea*) fishery, a small pelagic species that plays a central role in food security, income generation, and employment across riparian communities, particularly in the context of ecological and economic changes in the lake (Tumwebaze *et al.*, 2007). Data collection was purposively concentrated on key Omena landing sites and associated market centers distributed across the main Kenyan riparian counties of Migori, Homa Bay, Kisumu, Busia and Siaya, which together form the core of Kenya's Omena production zone (Manyala and Ojuok, 2007). The selected beaches included Ngore, Kibiro, and Sori in Migori County; Sindo and Litare in Homa Bay County; Dunga and Asat in Kisumu County, Uhanya in Siaya County and Marenga in Busia County (Figure 2). These sites represent well-established landing points characterized

by intensive night fishing, lift-net operations, and high volumes of daily landings. In addition to landing sites, the study incorporated major inland and lakeside fish markets that structure Omena trade and distribution. These included Dunga Beach market, Kibuye Market Kisumu, Suneka Market, Daraja Mbili Market Kisii, Eldoret Main Market, and Wakulima Market Nakuru, capturing both proximal and extended market linkages beyond the immediate lakeshore. The inclusion of inland urban markets reflects the spatial reach of Omena value chains and the integration of fishing communities with regional consumption centers. This spatial coverage allowed the study to capture variation in enterprise organization, labor use, and income flows across beach-based production nodes and downstream market destinations. By combining lakeshore landing sites with inland trading hubs, the study area design reflects the functional geography of the Omena fishery and provides a robust basis for analyzing enterprise dynamics, gendered roles, and market interactions within the Kenyan Lake Victoria fishery system.

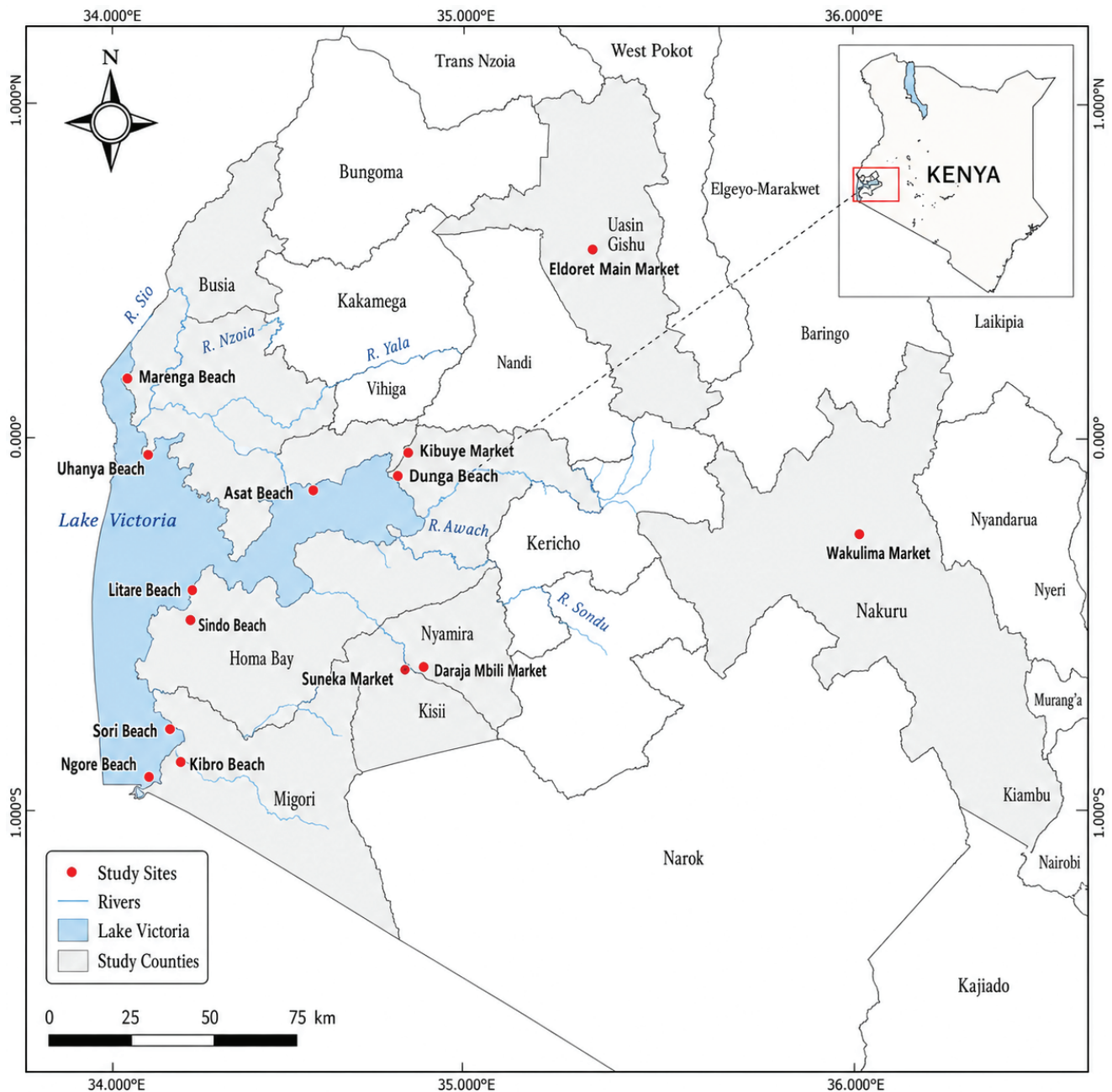


Figure 2. Spatial distribution of *Omena (Rastrineobola argentea)* landing sites and associated inland markets in the Kenyan Lake Victoria basin.

Survey design and instrument development

A comprehensive, structured questionnaire was developed to collect both quantitative and qualitative data directly aligned with the study's specific objectives. The instrument's design was informed by established frameworks for analyzing small-scale fisheries economics and social organization, particularly concerning informal labor and benefit-sharing arrangements

(Jul-Larsen *et al.*, 2003; Platteau *et al.*, 1992). The survey contained discrete but interlinked modules. The labour module captured detailed employment figures, distinguishing permanent from seasonal workers and high from low fishing seasons as experienced by fishers. Based on responses across enterprises, high fishing seasons were predominantly reported to occur between February and June, with peak activity commonly observed in April and May, while

low fishing seasons were most frequently associated with the period between August and December, particularly November through January. The instrument also allowed respondents to indicate variability and overlapping seasons, recognizing that fishing intensity may fluctuate across locations, lunar cycles, and years. The income-sharing module quantified the percentage distribution of catch value among key inputs (boat, gear, lamp) and actors (owner, crew), complemented by an open-ended question for nuanced description. The gender module utilized a household task-allocation roster to identify the primary responsible gender for activities from capture to financial management, a method validated in gendered fisheries research (Kleiber *et al.*, 2015). Additional modules on assets, operational costs, catch volumes, and post-harvest losses provided the necessary contextual data to understand enterprise viability and embeddedness within the broader value chain (Abila *et al.*, 2009).

Data collection and sampling strategy

Primary data were collected through face-to-face interviews using Computer-Assisted Personal Interviewing (CAPI) on the Survey Solutions platform from November to December 2025. The CAPI approach improves data accuracy by implementing real-time validation checks and complex skip logic, reducing errors common in paper-based surveys (Beaumont, 2020). The unit of analysis was the Omena fishing enterprise, with the owner or primary operator serving as the key informant. A purposive sampling strategy was employed, which is a recognized and practical method for accessing specific, knowledgeable populations in small-scale fisheries research where comprehensive sampling frames are often unavailable (Nunan *et al.*, 2015). The study acknowledges that purposive sampling might not be fully statistically representative of all enterprises but it was the

most feasible and appropriate method to capture knowledgeable informants across the key segments of the value chain in strategic locations. With facilitation from local Beach Management Unit (BMU) officials, researchers identified and recruited active enterprise owners at each site. The final sample comprised 114 complete interviews, including 55 traders, 28 processors and 31 producers enabling a preliminary examination of potential gendered differences in enterprise structure across both high (January – June) and low (July – December) fishing seasons.

Data analysis

Data analysis followed a convergent parallel mixed-methods design, in which quantitative and qualitative data streams were analyzed separately before being integrated in the final interpretation (Creswell and Plano Clark, 2017). Quantitative data from the structured surveys were processed and analyzed using SPSS Statistics (Version 28). Descriptive statistics, including means, standard deviations, and confidence intervals, were computed to characterize key variables such as labor size, seasonal incomes, and respondent demographics. To quantify the gendered division of labor within household and enterprise activities, a Gender Concentration Index (GCI) was calculated for specific roles using the formula: $GCI = (M - W) / (M + W)$,

where M represents the count of responses indicating “Mainly men” and W represents the count for “Mainly women.” This index provides a standardized measure of occupational segregation, with values interpreted as:

- 0.00 – 0.24 (low/gender-balanced),
- 0.25 – 0.49 (moderate concentration),
- 0.50 – 0.74 (high concentration), and
- ≥ 0.75 (very high concentration).

Perceptions of governance-related challenges, captured via Likert-type scales (Never, Sometimes, Often), were analyzed by calculating Total

Weighted Scores (TWS) and Average Weighted Scores (AWS) for ranking. The TWS was derived as $(1 \times \text{Never}) + (2 \times \text{Sometimes}) + (3 \times \text{Often})$, and the AWS as TWS / N , a method established for analyzing ordinal attitudinal data (Joshi *et al.*, 2015). For spatial and seasonal analysis, enterprise-level data on income and operation were aggregated and visualized to compare trends across counties and between high (February–June) and low (August–December) fishing seasons. Qualitative data from open-ended responses were analyzed using inductive thematic analysis (Braun and Clarke, 2006). This process involved repeated reading of responses, initial coding, and the identification of emergent themes related to income-sharing mechanisms, seasonal adaptation strategies, safety practices, and gendered experiences in the fishery. In the final synthesis phase, these qualitative themes were used to contextualize and explain the quantitative patterns such as linking reported income disparities to narratives of customary share systems and power dynamics ensuring a robust, nuanced understanding of the Omena fishery's organizational structure.

Results and discussion

Socio-demographics and fishing operations

Findings indicate a strong female predominance among respondents, with women accounting for 70.20% of the sample compared to 29.80% men (Table 1). This gender composition reflects the structure of the Omena fishery, where women are highly represented in downstream activities but remain less visible in capture-oriented roles. Similar gender patterns have been documented in Lake Victoria fisheries, where women's participation is substantial yet unevenly reflected in formal sector statistics and management

narratives (Abila *et al.*, 2009). Occupational patterns reveal a clearly gender-segmented value chain. Fish processing is overwhelmingly female-dominated, with women representing 23.70% of respondents compared to 0.90% men, while trading is also strongly feminized, with women accounting for 38.60% compared to 9.60% men (Table 1). In contrast, production roles show a male bias, with men constituting 19.30% of producers compared to 7.90% women. These divisions align with widely observed gendered labor arrangements in small-scale fisheries, where capture activities are predominantly male and post-harvest functions are socially assigned to women (Kleiber *et al.*, 2015).

Spatially, respondents are distributed across multiple counties associated with Lake Victoria, with the highest combined representation in Migori (29.80%), Homa Bay (22.00%), and Kisumu (17.60%) counties (Table 1). These areas are well-established Omena production and trading hubs, characterized by dense fishing activity and strong market linkages within the basin. The consistently higher representation of women across counties highlights the geographically extensive nature of women's engagement in the Omena value chain (Njiru *et al.*, 2018). Membership in trade or business associations is relatively high, with 75.50% of respondents reporting participation, and women forming the majority of members (Table 1). This pattern suggests that collective organization plays a critical role in facilitating market access and livelihood security, particularly for women operating in an economically volatile and informally governed fishery. Collective action has been identified as an important mechanism for strengthening inclusion and resilience within small-scale fisheries governance systems (Chuenpagdee and Jentoft, 2019).

Table 1. Socio-Demographic Characteristics and Fishing Operations of Respondents in the Omena (*Rastrineobola argentea*) Fishery, Lake Victoria, Kenya (N = 114).

Characteristic	Category	Gender	Counts	% of Total	Cumulative %
Total distribution	Total	Female	80	70.20	70.20
		Male	34	29.80	100.00
Occupation	Processor	Female	27	23.70	23.70
		Male	1	0.90	24.60
	Producer	Female	9	7.90	32.50
		Male	22	19.30	51.80
	Trader	Female	44	38.60	90.40
		Male	11	9.60	100.00
County distribution	Busia	Female	8	7.00	7.00
		Male	4	3.50	10.50
	Eldoret	Female	3	2.60	13.20
		Male	0	0.00	13.20
	Homa Bay	Female	15	13.20	26.30
		Male	10	8.80	35.10
	Kisii	Female	5	4.40	39.50
		Male	1	0.90	40.40
	Kisumu	Female	14	12.30	52.60
		Male	6	5.30	57.90
	Migori	Female	27	23.70	81.60
		Male	7	6.10	87.70
	Nakuru	Female	1	0.90	88.60
		Male	2	1.80	90.40
Are you a member of a trade / business association or a chain?	No	Female	18	15.80	15.80
		Male	10	8.80	24.60
	Yes	Female	62	54.40	78.90
		Male	24	21.10	100.00

The sample comprises 80 female and 34 male respondents (Table 2). The mean age of female respondents is 41.80 ± 10.30 years, while male respondents have a higher mean age of 45.10 ± 8.56 years, indicating modest gender differences in age profiles within the fishery. This age structure reflects the mature and experience-dependent nature of participation in small-scale fisheries, where entry and sustained engagement often increase with age and accumulated social and economic capital (Onyango, 2017). Years

of involvement in the Omena enterprise further highlight gendered differences in participation trajectories. Female respondents report a Mean $\pm$ SD involvement of (13.30 ± 9.27) years, compared to (15.20 ± 9.79) years among male respondents (Table 2). This pattern suggests that men, on average, remain engaged in the fishery for longer periods, which may reflect earlier entry into capture-related activities and greater continuity in roles tied to fishing assets such as boats and gear (Onyango, 2017).

The confidence intervals for mean age show limited overlap between genders, with female respondents ranging from 39.50 to 44.10 years, and male respondents from 42.10 to 48.10 years (Table 2). Similarly, the 95% confidence intervals for years of involvement indicate that men tend to accumulate longer experience in the fishery, with upper bounds reaching 18.70 years compared to 15.40 years for women. These patterns point to gendered pathways of entry and retention, consistent with evidence that men often establish long-term engagement in production roles, while women's participation may be more responsive to household needs, market opportunities, and life-course dynamics (Béné *et al.*, 2010). The age and experience profiles presented in Table 2 suggest that the Omena fishery is sustained by an experienced workforce, with both women and men demonstrating long-term engagement. However, the observed gender differences in mean age and years of involvement reinforce broader findings that men tend to accumulate longer fishing careers, while women's participation, though extensive, is shaped by differentiated access to assets and socially defined roles within the fishery (Kleiber *et al.*, 2015).

Labour organisation and working conditions

The results show marked variation in labor intensity by role. Producer-based enterprises exhibit the highest labor engagement, with a mean of

14.00 workers, compared to 3.00 workers for processors and 1.00 worker for traders. This highlights the centrality of capture activities in shaping enterprise scale and labor demand within the Omena fishery. The confidence intervals further illustrate differences in labor organization across occupations. Producer enterprises show a wide 95% confidence interval ranging from 10.00 to 18.00 workers, reflecting substantial heterogeneity in enterprise size and labor mobilization. In contrast, processing activities involve smaller and more stable labor units, with a confidence interval of 2.00 to 4.00 workers, while trading activities remain consistently small, with both lower and upper confidence bounds fixed at 1.00 worker. This pattern reflects differentiated capital requirements and task specialization across segments of the value chain (Bjorndal *et al.*, 2014).

The relatively large labor size observed among producers underscores the collective nature of capture fisheries on Lake Victoria, where fishing operations require coordinated crew arrangements for boat handling, net deployment, hauling, and post-harvest handling. Such labor structures are characteristic of small-scale fisheries operating under shared-risk and shared-return arrangements, particularly in pelagic fisheries such as *Rastrineobola arge**ntea** (Platteau and Nugent, 1992).

Table 2. Age and Experience Characteristics of Respondents in the Omena (*Rastrineobola argentea*) Fishery, Lake Victoria, Kenya (N = 114).

Descriptive	Gender	Age	Years involved in this enterprise
N	Female	80	80
	Male	34	34
Mean	Female	(Mean ± SD) 41.80 ± 10.30	(Mean ± SD) 13.30 ± 9.27
	Male	(Mean ± SD) 45.10 ± 8.56	(Mean ± SD) 15.02 ± 9.79
95% CI mean lower bound	Female	39.50	11.30
	Male	42.10	11.80
95% CI mean upper bound	Female	44.10	15.40
	Male	48.10	18.70

The labor patterns observed in Table 3 indicate that Omena fishing enterprises are structurally heterogeneous, with capture-oriented enterprises acting as the primary employers within the sector. The dominance of producer labor highlights the fishery's role as a critical source of employment in Lake Victoria communities, reinforcing its socio-economic importance beyond income generation alone (Béné *et al.*, 2016).

Table 3. Labor Size and Occupational Composition of Omena (*Rastrineobola argentea*) Fishing Enterprises in Lake Victoria, Kenya (N = 114).

How many employees are involved in your enterprise, including yourself?	Occupation	Counts
Mean	Processor	3.00
	Producer	14.00
	Trader	1.00
95% CI mean lower bound	Processor	2.00
	Producer	10.00
	Trader	1.00
95% CI mean upper bound	Processor	4.00
	Producer	18.00
	Trader	1.00

Table 4 presents key labor condition indicators across Omena fishing enterprises, disaggregated by enterprise. With respect to seasonal variation in labor size, 50.90% of the respondents report that the number of employees varies by season, while 49.10% indicate no seasonal variation. Seasonal variability is most pronounced among processors (19.30%) and producers (16.70%), reflecting the highly seasonal nature of Omena availability and associated fluctuations in processing and capture activities. This pattern is consistent with the flexible and adaptive labor arrangements characteristic of small-scale fisheries in Lake Victoria (Abila *et al.*, 2009). 93.00% of the re-

spondents report no involvement of workers under the age of 18, while 7.00% acknowledge a small level of underage participation across all occupational categories. Although the proportion reporting underage involvement is relatively low, its occurrence among processors (2.60%), producers (1.80%), and traders (2.60%) suggests that family-based labor contributions may persist within the fishery, particularly during seasons when schools are closed. Such arrangements are commonly observed in small-scale fisheries where household labor plays a complementary role in enterprise functioning (Béné *et al.*, 2010).

Safety practices exhibit substantial variation by occupation. While 27.00% of producers report regular use of safety measures or equipment, no traders and only 3.00% of processors indicate the use of such measures. Overall, 70.00% of respondents report the absence of regular safety equipment. This uneven distribution reflects occupational differences in exposure to physical risk, with producers operating on water more likely to recognize and adopt safety practices compared to shore-based activities such as trading and processing (Njiru *et al.*, 2018). The results also indicate relatively high levels of institutional awareness and informal labor regulation within the enterprises. A majority of respondents (62.20%) report having written or clearly agreed terms of work, particularly among producers (22.80%) and processors (19.30%). In addition, 97.40% of respondents indicate that there is an authority they can approach in cases of disputes, injuries, or regulatory issues (Table 4). This suggests that despite the largely informal nature of employment arrangements, Omena enterprises are embedded within broader co-management and governance structures that provide avenues for redress and support (Nunan *et al.*, 2015).

Table 4. Labor Conditions, Employment Practices, and Welfare Characteristics of Omena (*Rastrineobola argentea*) Fishing Enterprises in Lake Victoria, Kenya (N = 114).

Characteristic	Category	Occupation	Counts	% of Total	Cumulative %
Does no of employees vary by season?	No	Processor	6.00	5.30	5.30
		Producer	12.00	10.50	15.80
		Trader	38.00	33.30	49.10
	Yes	Processor	22.00	19.30	68.40
		Producer	19.00	16.70	85.10
		Trader	17.00	14.90	100.00
In your enterprise, are there any workers under the age of 18 involved in fishing or related activities?	No	Processor	25.00	21.90	21.90
		Producer	29.00	25.40	47.40
		Trader	52.00	45.60	93.00
	Yes	Processor	3.00	2.60	95.60
		Producer	2.00	1.80	97.40
		Trader	3.00	2.60	100.00
Are there any safety measures or equipment regularly used in the enterprise (e.g. life jackets, first aid kit)?	No	Processor	25.00	22.00	22.00
		Producer	0.00	0.00	22.00
		Trader	55.00	48.00	70.00
	Yes	Processor	3.00	3.00	73.00
		Producer	31.00	27.00	100.00
		Trader	0.00	0.00	100.00
Do workers (including seasonal workers) have written or clearly agreed terms of work (e.g. share, tasks, rest days, payment schedule)?	No	Processor	6.00	5.30	5.30
		Producer	5.00	4.40	9.70
		Trader	32.00	28.10	37.80
	Yes	Processor	22.00	19.30	57.10
		Producer	26.00	22.80	79.90
		Trader	23.00	20.20	100.00
If there are any issues related to human rights, regulations, injuries, or other problems, is there an authority you can go to for assistance?	No	Processor	0.00	0.00	0.00
		Producer	0.00	0.00	0.00
		Trader	3.00	2.60	2.60
	Yes	Processor	28.00	24.60	27.20
		Producer	31.00	27.20	54.40
		Trader	52.00	45.60	100.00

The majority of workers across the Omena value chain rely on verbal agreements, particularly processors (78.57%) and producers (80.65%), while written agreements are extremely rare, with only one producer (3.23%) reporting a written contract (Table 5). Traders show the highest incidence of having no formal agreement (58.18%), which could expose them to disputes or exploitation (Jul-Larsen, 2003; Platteau and

Nugent, 1992). The Pearson χ^2 and likelihood ratio tests indicate a significant association between occupation and type of work agreement ($\chi^2 = 21.20$, $df = 4$, $p < 0.001$), confirming that the mode of agreement varies systematically across occupational categories. This finding aligns with studies highlighting the informal and often precarious nature of small-scale fisheries in East Africa (Abila *et al.*, 2009; Béné *et al.*, 2010).

Table 5. Terms of Work or Agreement in Lake Victoria Omena (*Rastrineobola argentea*) Fisheries, Kenya (N = 114).

Occupation	Verbal	Written	None	Total
Processor	22.00	0.00	6.00	28.00
Producer	25.00	1.00	5.00	31.00
Trader	23.00	0.00	32.00	55.00
Total	70.00	1.00	43.00	114.00
Association tests				
Test	Value	df	p-value	
Pearson χ^2	21.20	4.00	*p* < .001	
Likelihood ratio χ^2	21.90	4.00	*p* < .001	
Fisher's exact test			*p* < .001	
N	114.00			

The survey responses on authority recognition reveal a hierarchical perception of authority among Omena fishers, with BMUs and Market Masters as the primary nodes of control, reflecting both regulatory and economic influence in enterprise operations. The Beach Management Unit (BMU) emerges as the most frequently cited authority, with nearly all respondents acknowledging its role in governance and enforcement of fisheries regulations. This prominence reflects the critical role of BMUs in co-management and local oversight of Lake Victoria fisheries (Obiero *et al.*, 2015). Market Masters rank second in the frequency of recognition, highlighting their importance in regulating local fish trade and mediating between fishers and buyers, consistent with observations on middlemen as essential actors in small-scale fisheries value chains (Crona *et al.*, 2010). The Chief, Police, County Council, and County Department of Fisheries are cited less frequently, indicating that formal government authorities have limited day-to-day influence on Omena fishers compared to community-based or semi-formal governance structures (Etiegni, 2022). The disparity in recognition of authorities underscores the decen-

tralized and community-centered nature of governance in small-scale Lake Victoria fisheries, where local institutions often play a more immediate role in decision-making than state agencies (Njiru *et al.*, 2018). These findings align with broader evidence that successful small-scale fisheries management frequently relies on local, participatory structures rather than centralized enforcement alone (Chuenpagdee and Jentoft, 2019).

The survey responses regarding safety precautions reveal a distinct hierarchy in self-reported practices between on-shore processing enterprises and fishing boat operations (Figure 3). For processing enterprises, the reported precautions are limited to the use of personal protective equipment (PPE). Respondents indicated the use of face masks, gloves, aprons, and gum boots. This set of measures addresses direct occupational health hazards but represents the narrowest scope of safety implementation reported in the survey. In contrast, fishing boat enterprises report a more extensive and multi-layered approach to safety. The most frequently reported precautions form an essential core of maritime safety: life jackets, two paddles, an anchor, a first aid kit, and adherence to an avoid drugs policy. A secondary set of reported measures includes critical emergency and operational tools: a knife, a fire extinguisher, a safety hook, and a toolbox. The reporting of "patrol boats" indicates an awareness of external enforcement as a component of the safety environment, though this is not a precaution implemented by the enterprise itself. The data (Figure 3) shows that boat-based enterprises report a broader, more systematic integration of safety precautions compared to processing enterprises. The hierarchy suggests that immediate lifesaving measures and substance policy compliance are the most consistently reported priorities for fishers, while processors report a focus solely on basic personal protective gear.

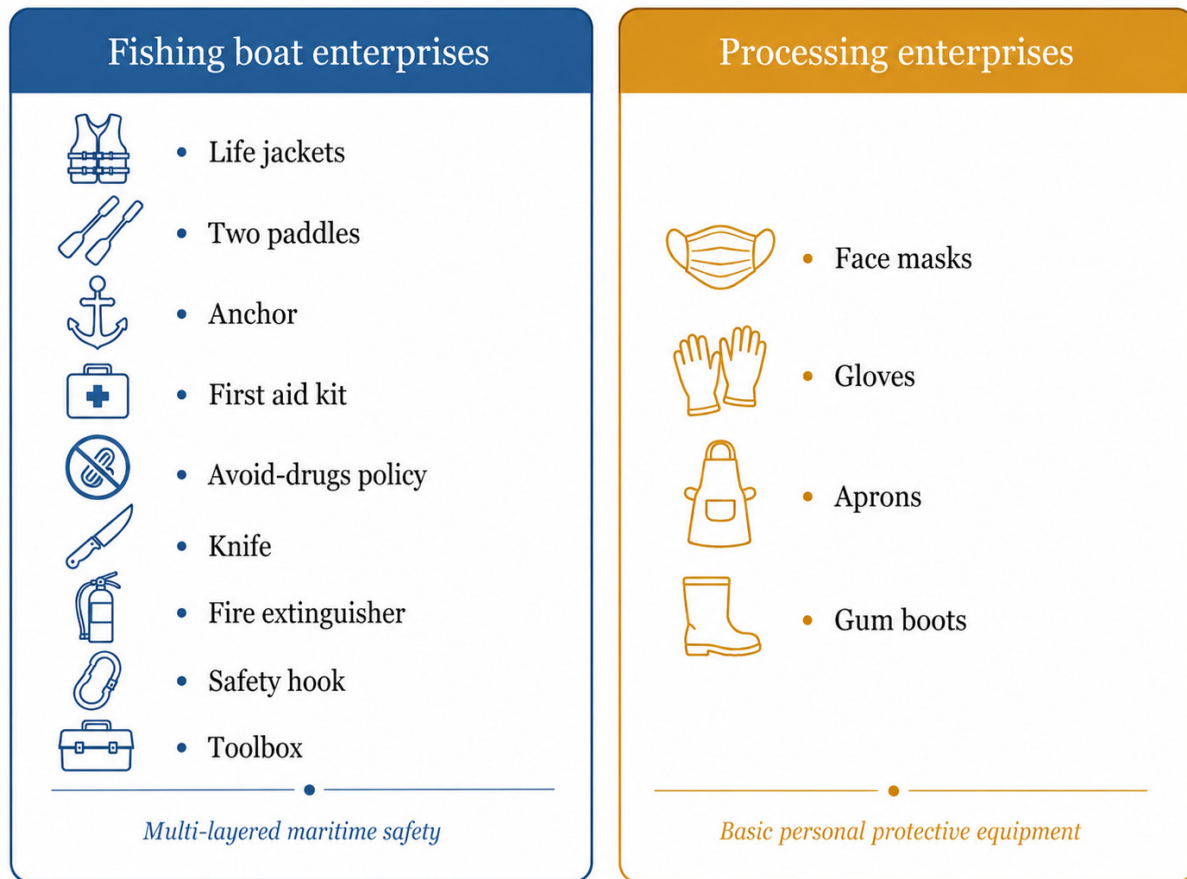


Figure 3. Self-reported safety precautions in Omena (*Rastrineobola argentea*) fishing and processing enterprises on Lake Victoria, Kenya.

The Likert-scale ranking based on Total Weighted Scores and Average Weighted Scores reveals clear patterns in the governance- and rights-related challenges faced by Omena fishing enterprises. Although all issues record Average Weighted Scores closer to the lower bound of the scale, none approach the minimum value of 1.00, indicating that these challenges occur with measurable regularity rather than being entirely absent. Harassment, threats, or violence from authorities ranks highest, with a Total Weighted Score of 168 and an Average Weighted Score of 1.47. Interactions with fisheries officers and police therefore emerge as the most frequently encountered governance-related challenge. Previous analyses of Lake Victoria fisheries highlight that enforcement practices are often experienced as coercive and inconsistently applied, particularly within informal and highly seasonal fisheries systems (Abila *et al.*, 2009). Such dynamics have also been shown to weaken fisher trust in regulatory institutions and co-manage-

ment arrangements (Nunan *et al.*, 2015). Forced payments, bribes, or unofficial fees rank second, with a Total Weighted Score of 163 and an Average Weighted Score of 1.43. The persistence of informal payments reflects structural weaknesses in accountability and monitoring within fisheries governance frameworks (Onyango and Luomba, 2017). Similar patterns have been documented in small-scale fisheries where informal payments disproportionately burden less powerful actors along the value chain, reinforcing livelihood vulnerability (Béné *et al.*, 2010).

Harassment or threats from other fishers or groups ranks third, with a Total Weighted Score of 157 and an Average Weighted Score of 1.38. This finding points to enduring social tensions within fishing communities, often driven by competition over access to fish, markets, and landing sites. Studies of Lake Victoria landing beaches emphasize that such conflicts are mediated through informal institutions and local power relations rather than formal regulatory processes (Crona *et al.*, 2010; Etie-

gni *et al.*, 2017). Restriction of access to traditional landing or fishing areas ranks lowest, with a Total Weighted Score of 152 and an Average Weighted Score of 1.33. While comparatively less frequent, access constraints remain a meaningful concern for a subset of enterprises. Research on inland fisheries governance shows that such restrictions often arise through localized gatekeeping and informal territorial control, rather than explicit stated exclusion (Jul-Larsen, 2003; Obiero *et al.*, 2015). The ranking indicates that governance-related pressures associated with enforcement practices and informal payments pose more immediate challenges than peer-level conflicts or spatial access restrictions. This pattern reinforces broader evidence that weaknesses in co-management implementation continue to shape everyday experiences of risk and vulnerability in small-scale fisheries systems (Chuenpagdee and Jentoft, 2019; Njiru *et al.*, 2018). This finding suggests that the current co-management model may be co-opted or operating in a way that perpetuates, rather than alleviates, power asymmetries and predatory behavior. For “inclusive governance” to move beyond rhetoric, reforms must directly address this accountability gap. This requires mechanisms to make BMUs more transparent, subject to community oversight, and accountable for equitable and respectful enforcement, ensuring they serve as protectors of fishers’ rights rather than instruments of their exploitation.

Income distribution and labour practices

The income patterns among different enterprise roles in Lake Victoria Omena fisheries show significant heterogeneity across roles and between seasons (Table 7). The very high standard deviations relative to the mean incomes, particularly for

boat owners, indicate a highly skewed distribution where a small number of high-earning enterprises pull the mean upwards, masking the typical earnings for most. Therefore, the median income provides a more accurate representation of central tendency for these roles. Boat owners consistently earn the highest monthly incomes, with a mean of KES 72,441.00 in the low season and KES 126,000.00 in the high season. This reflects their capital ownership, control over fishing operations, and direct access to catches, which allows them to capture most of the revenue from sales (Abila, Odongkara and Onyango, 2009). Fishers (crew, excluding the owner) earn substantially less than boat owners, averaging KES 10,176.00 during the low season and KES 24,623.00 in the high season. The increase during the high season highlights the strong influence of seasonality on earnings, likely driven by higher fish availability and market demand (Béné, Hersoug and Allison, 2010). Crew members are dependent on revenue-sharing arrangements, which limit their income compared to owners but still provide a crucial livelihood (Platteau and Nugent, 1992). Management personnel, who may oversee processing, storage, or trading activities, earn a mean of KES 7,277.00 in the low season and KES 22,154.00 in the high season. This role bridges labor and ownership, offering more stable income than seasonal laborers but lower earnings than fishers and owners during peak production. The higher variance in high-season earnings reflects differences in enterprise scale, operational responsibilities, and market linkages (Crona *et al.*, 2010). Seasonal laborers, often employed for auxiliary tasks such as carrying, packing, or guarding, earn the lowest mean incomes: KES 3,015.00 in the low season and KES 8,688.00 in the high season. Despite being critical for operational continuity, these workers are highly dependent on availability of seasonal work and have minimal bargaining power in income

Table 6. Likert-Scale Analysis of Harassment, Coercion, and Access Constraints in Lake Victoria Omena Omena (*Rastrineobola argentea*) Enterprises, Kenya (N = 114), Where the Total Weighted Score (TWS) Is Calculated as (1 × Never) + (2 × Sometimes) + (3 × Often), Using Likert Weights Never = 1, Sometimes = 2, Often = 3, and the Average Weighted Score (AWS) Is Calculated as (Weighted Score / N).

Issue	Never	Sometimes	Often	TWS	AWS	Rank
Harassment, threats or violence from authorities	73	28	13	168	1.47	1
Forced payments, bribes or unofficial fees	78	23	13	163	1.43	2
Harassment, threats or violence from other fishers or groups	76	33	5	157	1.38	3
Restriction of access to traditional landing or fishing areas	86	18	10	152	1.33	4

allocation. Their earnings fluctuate sharply with seasonality, reinforcing their vulnerability within the fisheries value chain (Béné *et al.*, 2016). The income distribution highlights a hierarchical structure in Omena fisheries: owners capture most revenue, fishers and management earn intermediate levels, and seasonal laborers occupy the lowest tier. Seasonality amplifies these differences, making high-season earnings pivotal for household livelihoods, particularly for lower-income groups (Njiru *et al.*, 2018). This pattern reflects broader dynamics in small-scale fisheries, where access to capital and control over production strongly influence income and socio-economic resilience (Cinner *et al.*, 2014). The comparison between median and mean incomes starkly illustrates the hierarchical and unequal structure of Omena fisheries. While mean figures are influenced by high outliers, the median reveals the more common, and considerably lower, economic reality for most participants. This pattern reinforces that access to capital (boat ownership) is the primary determinant of wealth capture, while labor (crew, management, seasonal workers) is compensated at levels that suggest high levels of economic precarity, particularly for non-owner roles.

The employment of additional workers for packing, guarding, or managing storage varies across enterprise types (Table 8). Processors and traders are more likely to hire extra labor, reflecting higher operational scale and post-harvest handling needs (Crona *et al.*, 2010). Producers rarely employ additional workers, suggesting these activities are largely managed at the household level (Bjorndal *et al.*, 2014). Among processors, 12 out of 28 respondents employed workers for these tasks, indicating that only some processing operations reach a scale justifying labor outsourcing. Traders, handling larger volumes and broader market networks, employed extra workers in 17 cases, highlighting the role of labor specialization in ensuring efficient market operations (Abila *et al.*, 2009). The data also reflect differences in operational complexity between enterprise types. Traders manage both the sale and movement of fish, often across multiple sites, which necessitates labor for storage and security, whereas producers focus primarily on harvesting and may lack the capital or market demand to hire additional workers (Béné *et al.*, 2016). This pattern aligns with small-scale fisheries elsewhere, where labor outsourcing is linked to enterprise scale, market integration, and post-harvest responsibilities (Njiru *et al.*, 2018).

Table 7. Monthly Earnings of Different Enterprise Roles in Lake Victoria Omena (*Rastrineobola argentea*) Fisheries Across Low and High Seasons (KES month⁻¹), Highlighting Income Heterogeneity and Role-Based Differences.

Enterprise Role	Low Season Earnings (KES month ⁻¹) (Mean ± SD)	High Season Earnings (KES month ⁻¹) (Mean ± SD)	Median Low Season	Median High Season
Boat owner	72441.00 ± 218014.00	126000.00 ± 224753.00	19,000	75,000
Fishers (crew, excluding owner)	10176.00 ± 15068.00	24623.00 ± 37451.00	5,000	15,000
Management	7277.00 ± 7808.00	22154.00 ± 23384.00	6,000	15,000
Laborers seasonal	3015.00 ± 3052.00	8688.00 ± 8705.00	2,280	6,360

Table 8. Employment of Additional Workers for Packing, Guarding, and Storage Across Lake Victoria Omena (*Rastrineobola argentea*) Fishery Enterprises, Highlighting Operational Scale, Outsourcing Practices, and Role-Specific Labor Requirements.

Characteristic	Category	Occupation	Counts	% of Total	Cumulative %
Do you employ workers specifically for packing, guarding or managing storage?	No	Processor	16	14.00	14.00
		Producer	31	27.20	41.20
		Trader	38	33.30	74.60
	Yes	Processor	12	10.50	85.10
		Producer	0	0.00	85.10
		Trader	17	14.90	100.00

Daily earnings data for carriers and packers complement these findings and reveal role-specific income patterns (Table 9). Among processors, carriers earned a mean of KES 131.00 per day, slightly higher than packers at KES 96.30, indicating a greater reliance on transport labor for moving fish from landing sites to processing facilities (Crona *et al.*, 2010). In trading enterprises, packers earned a mean of KES 132.00 per day, higher than carriers at KES 70.40, reflecting the labor-intensive nature of packaging and handling fish for market readiness (Abila *et al.*, 2009). Producers reported no income for either role, confirming that post-harvest tasks in small-scale household operations are often performed by family members or not separately remunerated (Bjorndal *et al.*, 2014). The variation in daily earnings, reflected by wide standard deviations and confidence intervals, highlights substantial heterogeneity in post-harvest labor compensation. Differences in catch volumes, enterprise size, and seasonal availability of fish contribute to these fluctuations (Njiru *et al.*, 2018). The data demonstrate that labor outsourcing and role-specific earnings are critical factors shaping the structure and efficiency of Omena fisheries, particularly in processing and trading enterprises where operational scale demands specialized labor contributions (Béné *et al.*, 2016).

Gender dynamics and participation

The data indicate that the majority of respondents reported that women and girls in their households did not experience specific risks at fishing or landing sites, with 68.40% of female and 28.10% of male respondents indicating “No” (Table 10). A small proportion, however, reported challenges such as harassment or safety concerns, reflecting the vulnerabilities women face in fishing communities, particularly around landing sites at night (Frangoudes and Gerrard, 2018). Regarding aquaculture participation, female involvement was low, with only 5 women (4.40%) and 4 men (3.50%) reporting engagement in aquaculture activities, while the majority had no participation (Table 10). This indicates that aquaculture remains a limited livelihood option for most households, and that gender disparities persist in access and engagement (Kleiber *et al.*, 2015). These findings highlight the importance of considering gender-specific risks and opportunities in fisheries and aquaculture planning. While most households report minimal direct safety issues for women, the presence of even a small number of affected individuals emphasizes the need for safety measures at landing sites. Low female participation in aquaculture underscores barriers to entry, including access to capital, training, and prevailing social norms (Odhon *et al.*, 2020; Lawless *et al.*, 2021).

Table 9. Daily Earnings of Carriers and Packers Across Lake Victoria Omena (*Rastrineobola argentea*) Fishery Enterprises, Highlighting Role-Specific Income Variation and Post-Harvest Labor Contributions (KES Day⁻¹).

Descriptive	Occupation	Carriers Income Day ⁻¹	Packers Income Day ⁻¹
N	Processor	17.00	8.00
	Producer	0.00	0.00
	Trader	23.00	26.00
(Mean ± SD)	Processor	131.00 ± 123.00	96.30 ± 50.40
	Producer	0.00 ± 0.00	0.00 ± 0.00
	Trader	70.40 ± 56.70	132.00 ± 115.00
95% CI mean lower bound	Processor	67.50	54.1.00
	Producer	0.00	0.00
	Trader	45.90	85.80
95% CI mean upper bound	Processor	194.0	138.00
	Producer	0.00	0.00
	Trader	94.90	179.00

Table 10. Gender-Specific Experiences and Participation in Fisheries and Aquaculture in Lake Victoria Communities, Highlighting Risks, Safety, and Involvement (N = 114)

Characteristic	Category	Gender	Counts	% of Total	Cumulative %
Have women or girls in your household faced any specific risks or problems related to fishing or landing sites (e.g. harassment, safety at night)?	No	Female	78	68.40	68.40
		Male	32	28.10	96.50
	Yes	Female	2	1.80	98.20
		Male	2	1.80	100.00
Do you practice aquaculture?	No	Female	75	65.80	65.80
		Male	30	26.30	92.10
	Yes	Female	5	4.40	96.50
		Male	4	3.50	100.00

Omena fishing enterprises, revealing pronounced gender specialization across the value chain. Overall, the results demonstrate very high gender concentration in most activities, underscoring deeply entrenched gendered divisions of labor in Lake Victoria fisheries. Fishing on the boat exhibits a very high male concentration (GCI = 0.89), with 108 responses indicating men and only 6 indicating women. This reflects longstanding norms that associate fishing operations particularly night fishing and physically demanding tasks with men, while women's participation in capture activities remains minimal (Béné *et al.*, 2009; Kleiber *et al.*, 2015). In contrast, post-harvest and market-related activities are overwhelmingly dominated by women. Fish processing (drying, sorting, and related tasks) and buying fresh fish both record a very high female concentration (GCI = 1.00), indicating exclusive or near-exclusive female participation. Similarly, fish trading and marketing show a very high female concentration (GCI = 0.85). These patterns are consistent with fisheries literature documenting women's central role in post-harvest handling, informal trading networks, and small-scale fish commerce across African inland fisheries (Harper *et al.*, 2013; Frangoudes *et al.*, 2019). Financial and decision-making roles display slightly lower but still substantial gender concentration. Managing money from fish sales (GCI = 0.67) and deciding how enterprise income is used (GCI = 0.51) both fall within the high female concentration category, suggesting that women play a dominant role in day-to-day financial management and household-level

allocation of fisheries income. This challenges simplistic narratives that equate men's control over fishing assets with full financial authority, instead highlighting women's significant influence over cash flows and expenditure decisions (Kleiber *et al.*, 2015; Lawless *et al.*, 2021). Borrowing money or accessing credit shows a moderate female concentration (GCI = 0.47), indicating comparatively more gender balance relative to other roles. This suggests that while women remain the primary actors in credit-related decisions often through informal savings groups and trader-financier relationships men also participate meaningfully in borrowing, particularly where larger capital investments are required (Odhon *et al.*, 2020). Taken together, the GCI results demonstrate that Omena fishing enterprises are characterized by gendered functional specialization rather than gender neutrality. Men dominate capture fisheries, while women control post-harvest, marketing, and several financial and decision-making roles. These findings have important policy implications: interventions targeting fisheries sustainability, credit access, or value chain upgrading must be gender-responsive and tailored to these differentiated roles to avoid reinforcing existing inequalities or overlooking women's central economic contributions. Interventions aiming for gender equity must therefore move beyond supporting women's existing roles to actively facilitating their access to capital and representation in formal governance, transforming their substantive economic role into formalized strategic power.

Table 11. Gender Concentration Index of Household Roles in Omena Fishing Enterprises, Lake Victoria, Kenya. For consistency with fisheries and gender literature, the Gender Concentration Index (GCI) is calculated as: $GCI = (M - W) / (M + W)$ Where: M = number of responses indicating Mainly men, W = number of responses indicating Mainly women.

Interpretation

0.00–0.24 → Low concentration (gender-balanced)

0.25–0.49 → Moderate concentration

0.50–0.74 → High concentration

≥ 0.75 → Very high concentration

Activity	Mainly Men (M)	Mainly Women (W)	GCI	Gender Concentration
Fishing on the boat	108	6	0.89	Very high male
Fish processing (drying, sorting, etc.)	0	102	1	Very high female
Buying fresh fish	0	106	1	Very high female
Fish trading / marketing	7	85	0.85	Very high female
Managing money from fish sales	14	72	0.67	High female
Borrowing money or credit	23	64	0.47	Moderate female
Deciding how enterprise income is used	19	59	0.51	High female

Conclusions and recommendations

This study has systematically elucidated the internal structure of Omena (*Rastrineobola argentea*) fishing enterprises on the Kenyan shores of Lake Victoria, focusing on labor, income distribution and gender dynamics. The findings reveal a fishery that is a vital economic engine but is fundamentally organized around informal, hierarchical and gendered principles that create significant equity and sustainability challenges. The Omena enterprise system is not a level playing field but a tiered socio-economic structure where benefits and risks are allocated based on one's position related to capital ownership, gender, and seasonality. Four primary conclusions emerge. First, the fishery exhibits a deeply entrenched gendered division of labor, quantified by high Gender Concentration Index (GCI) values. While men monopolize capture fishing, women are the unequivocal backbone of the post-harvest value chain, dominating processing, trading and daily financial management. This substantive economic control, however, exists in parallel with their systematic exclusion from strategic capital (boat ownership) and for-

mal governance forums like Beach Management Units (BMUs), creating a paradox of high responsibility with low formal power. Second, income distribution is profoundly unequal and skewed. The extreme disparity between mean and median incomes, especially for boat owners, reveals a reality where a small minority captures most of the wealth. The typical (median) seasonal laborer earns less than one-tenth of the typical boat owner during the high season, and this is drastically amplified during low-season closures. Third, the governance environment undermines the stated goals of co-management. BMUs, designed as community-led institutions, are the most recognized authority but are simultaneously implicated as a primary source of harassment and informal taxation "Harassment from authorities" ranked highest. This erodes the legitimacy and trust necessary for effective, inclusive resource management. Fourth, occupational safety reflects this tiered value system: boat crews adopt multiple maritime safety measures, while the predominantly female onshore processing sector reports only basic personal protective equipment, indicating a systemic undervaluation of health risks in post-harvest work.

Based on these conclusions, several recommendations follow for policymakers, researchers and development practitioners seeking to enhance the equity and sustainability of the Omena fishery. The most immediate priority is to reform co-management so that it earns legitimacy and becomes genuinely gender-inclusive: Beach Management Units should be made accountable through independent, accessible grievance mechanisms and mandatory financial transparency that curb harassment and rebuild fisher trust, while enforceable quotas for women—particularly processors and traders—on BMU committees, backed by targeted capacity-building, would ensure that management decisions reflect the realities of the entire value chain rather than the capture sector alone. Alongside governance reform, deliberate measures are needed to promote economic equity and reduce vulnerability. Model written benefit-sharing agreements should be developed, disseminated and promoted for crew members so that deductions are standardised and net shares clarified, reducing the exploitative practices that opaque share systems allow; targeted social protection, such as facilitated access to savings groups or conditional transfers, should be designed for highly vulnerable groups like seasonal labourers to cushion the severe impact of low seasons and fishing bans; and financial instruments such as group-guaranteed loans and leasing models, together with supporting programmes, should be created to enable women's collectives and entrepreneurs to acquire capital assets such as boats and improved processing technology, moving them up the value chain. The predominantly female post-harvest sector warrants particular attention: investment in improved processing (for example, hybrid dryers), storage and packaging technologies would reduce losses, raise product quality and value, and increase profitability, while comprehensive occupational-health standards that extend beyond basic personal protective equipment should be integrated into training and licensing for processing enterprises, recognising post-harvest work as formal, high-risk labour deserving of protection. Finally, future research should consolidate and extend these findings through longitudinal studies that track income stability and well-being across different enterprise roles over time, deeper qualitative investigation of the power dynamics embedded in informal credit and share systems, and comparative cross-border studies with Tanzania and Uganda to assess how differing policy environments shape these common socio-economic structures.

Acknowledgements

The authors thank the Kenya Marine and Fisheries Research Institute (KMFRRI) for the institutional, technical and logistical support that made this study possible, the Beach Management Unit officials who facilitated access to landing sites, and the enterprise owners and workers who participated in the survey.

Funding

This study was supported by the Kenya Marine and Fisheries Research Institute (KMFRRI).

References

- Abila RO, Odongkara KO, Onyango PO (2009) Macro-economic assessment of the Lake Victoria fishing industry in East Africa (Technical Report, pp. 1–8)
- Beaumont JF (2020) Are probability surveys bound to disappear for the production of official statistics? *Survey Methodology*, 46: 1–29
- Belhabib D, Sumaila UR, Pauly D (2015) Feeding the poor: Contribution of West African fisheries to employment and food security. *Ocean & Coastal Management*, 111: 72–81
- Bennett NJ, Cisneros-Montemayor AM, Blythe J, Silver JJ, Singh G, Andrews N, Calò A, Christie P, Di Franco A, Finkbeiner EM, Gelcich S (2019) Towards a sustainable and equitable blue economy. *Nature Sustainability*, 2: 991–993
- Béné C, Hersoug B, Allison EH (2010) Not by rent alone: Analysing the pro-poor functions of small-scale fisheries in developing countries. *Development Policy Review*, 28: 325–358
- Béné C, Arthur R, Norbury H, Allison EH, Beveridge M, Bush S, Campling L, Leschen W, Little D, Squires D, Thilsted SH (2016) Contribution of fisheries and aquaculture to food security and poverty reduction: Assessing the current evidence. *World Development*, 79: 177–196

- Bjorndal T, Child A, Lem A (2014) Value chain dynamics and the small-scale sector (FAO Fisheries and Aquaculture Technical Paper No. 581). Food and Agriculture Organization of the United Nations
- Braun V, Clarke V (2006) Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3: 77–101
- Bush S, Oosterveer P (2019) Governing sustainable seafood. Routledge
- Chuenpagdee R, Jentoft S (2019) Small-scale fisheries: Too important to fail. In *The future of ocean governance and capacity development* (pp. 153–154). Brill
- Cinner JE, Daw T, Huchery C, Thoya P, Wamukota A, Cedras M, Abunge C (2014) Winners and losers in marine conservation: Fishers' displacement and livelihood benefits from marine reserves. *Society & Natural Resources*, 27: 994–1005
- Cinner JE, Lau JD, Bauman AG, Feary DA, Januchowski-Hartley FA, Rojas CA, Barnes ML, Bergseth BJ, Shum E, Lahari R, Ben J (2019) Sixteen years of social and ecological dynamics reveal challenges and opportunities for adaptive management in sustaining the commons. *Proceedings of the National Academy of Sciences*, 116: 26474–26483
- Creswell JW, Plano Clark VL (2017) Designing and conducting mixed methods research. Sage Publications
- Crona B, Nyström M, Folke C, Jiddawi N (2010) Middlemen, a critical social-ecological link in coastal communities of Kenya and Zanzibar. *Marine Policy*, 34: 761–771 [<https://doi.org/10.1016/j.marpol.2010.01.023>]
- Crona BI, Basurto X, Squires D, Gelcich S, Daw TM, Khan A, Havice E, Chomo V, Troell M, Buchary EA, Allison EH (2016) Towards a typology of interactions between small-scale fisheries and global seafood trade. *Marine Policy*, 65: 1–10
- Etiegni CA, Irvine K, Kooy M (2017) Playing by whose rules? Community norms and fisheries rules in selected beaches with-in Lake Victoria (Kenya) co-management. *Environment, Development and Sustainability*, 19: 1557–1575
- Etiegni CA (2022) Fisher folk participation for sustainable fisheries: An illusion or reality for Lake Victoria (Kenya) co-management. Doctoral dissertation, Wageningen University and Research
- Food and Agriculture Organization of the United Nations (2018) The state of world fisheries and aquaculture 2018: Meeting the Sustainable Development Goals. FAO
- Frangoudes K, Gerrard S (2018) (En)gendering change in small-scale fisheries and fishing communities in a globalized world. *Maritime Studies*, 17: 117–124
- Harper S, Adshade M, Lam VW, Pauly D, Sumaila UR (2020) Valuing invisible catches: Estimating the global contribution by women to small-scale marine capture fisheries production. *PLoS ONE*, 15: e0228912
- Joshi A, Kale S, Chandel S, Pal DK (2015) Likert scale: Explored and explained. *British Journal of Applied Science and Technology*, 7: 396–403
- Jul-Larsen E (Ed.) (2003) Management, co-management or no management? Major dilemmas in southern African freshwater fisheries (FAO Fisheries Technical Paper No. 422). Food and Agriculture Organization of the United Nations
- Kittinger JN, Teh LCL, Allison EH, Bennett NJ, Crowder LB, Finkbeiner EM, Hicks C, Scarton CG, Nakamura K, Ota Y, Young J (2017) Committing to socially responsible seafood. *Science*, 356: 912–913
- Kleiber D, Harris LM, Vincent ACJ (2015) Gender and small-scale fisheries: A case for counting women and beyond. *Fish and Fisheries*, 16: 547–562

- Lawless S, Cohen PJ, Mangubhai S, Kleiber D, Morrison TH (2021) Gender equality is diluted in commitments made to small-scale fisheries. *World Development*, 140: 105348
- Manyala JO, Ojuok JE (2007) Survival of the Lake Victoria *Rastrineobola argentea* in a rapidly changing environment: Biotic and abiotic interactions. *Aquatic Ecosystem Health & Management*, 10: 407–415
- Njiru J, van der Knaap M, Kundu R, Nyamweya C (2018) Lake Victoria fisheries: Outlook and management. *Lakes & Reservoirs: Research and Management*, 23: 152–162
- Nunan F, Hara M, Onyango P (2015) Institutions and co-management in East African inland and Malawi fisheries: A critical perspective. *World Development*, 70: 203–214
- Obiero KO, Abila RO, Njiru MJ, Raburu PO, Achieng AO, Kundu R, Ogello EO, Munguti JM, Lawrence T (2015) The challenges of management: Recent experiences in implementing fisheries co-management in Lake Victoria, Kenya. *Lakes & Reservoirs: Research and Management*, 20: 139–154
- Odhon AO, Mahiri I, Onsongo F (2020) Assessing gender roles in the Omena fishery value chain among fishing communities on Lake Victoria: A case study of Lake Victoria beaches in Siaya County, Kenya. *International Journal of Current Aspects*, 4: 13–32
- Ojea E, Pearlman I, Gaines SD, Lester SE (2017) Fisheries regulatory regimes and resilience to climate change. *AMBIO*, 46: 399–412
- Ojwang WO, Ojuok JE, Nyamweya C, Agembe S, Owili M, Yongo E, Wakwabi EO (2014) The intriguing dynamics of the *Rastrineobola argentea* fishery in the Kenyan waters of Lake Victoria. *Aquatic Ecosystem Health & Management*, 17: 80–89
- Okeke-Ogbuafor N, Gray T, Stead SM (2020) Is there a ‘wicked problem’ of small-scale coastal fisheries in Sierra Leone? *Marine Policy*, 118: 103471
- Onyango P, Luomba J (2017) Report on the responsible governance of tenure in Lake Victoria fisheries. Food and Agriculture Organization of the United Nations
- Onyango PO (2017) Socio-economic characteristics of the Lake Victoria fisheries. In *Lake Victoria fisheries resources: Research and management in Tanzania* (pp. 161–184). Springer
- Platteau JP, Nugent J (1992) Share contracts and their rationale: Lessons from marine fishing. *Journal of Development Studies*, 28: 386–422
- Schumann S, Macinko S (2007) Subsistence in coastal fisheries policy: What’s in a word? *Marine Policy*, 31: 706–718
- Smith H, Basurto X (2019) Defining small-scale fisheries and examining the role of science in shaping perceptions of who and what counts: A systematic review. *Frontiers in Marine Science*, 6: 236
- Song AM, Cohen PJ, Hanich Q, Morrison TH, Andrew N (2019) Multi-scale policy diffusion and translation in Pacific Island coastal fisheries. *Ocean & Coastal Management*, 168: 139–149
- Taabu-Munyaho A, Marshall BE, Tomasson T, Marteinsdottir G (2016) Nile perch and the transformation of Lake Victoria. *African Journal of Aquatic Science*, 41: 127–142
- Troell M, Naylor RL, Metian M, Beveridge M, Tyedmers PH, Folke C, Arrow KJ, Barrett S, Crépin AS, Ehrlich PR, Gren Å (2014) Does aquaculture add resilience to the global food system? Proceedings of the National Academy of Sciences, 111: 13257–13263
- Tumwebaze R, Cowx I, Ridgway S, Getabu A, MacLennan DN (2007) Spatial and temporal changes in the distribution of *Rastrineobola argentea* in Lake Victoria. *Aquatic Ecosystem Health & Management*, 10: 398–406

Characterization of the mud crab (*Scylla serrata*) market chain in Kilifi County, Kenya: A reconnaissance survey

Edward Waiyaki^{1*}, Esther Fondo², Elisha Mrabu³, Hellen Ngoa¹, Faith Kimanga¹, Stephen Makupe¹ and Nicholas Karani¹

¹Kenya Marine and Fisheries Research Institute (KMFRI), Socio-economics Directorate, P.O. Box 81651 – 80100, Mombasa, Kenya

²KMFRI, Marine Fisheries Department, P.O. Box 81651 – 80100, Mombasa, Kenya

³KMFRI, Oceanography and Hydrography Department, P.O. Box 81651 – 80100, Mombasa

*Corresponding author E-mail: ewaiyaki@kmfri.go.ke

Abstract

The Kenyan government has significantly prioritized efforts to enhance national food security. Kenya's marine crab fisheries may have the potential to alleviate existing food deficits. This reconnaissance survey characterized aspects of the crab market chain in Kilifi County, Kenya, to provide baseline information for subsequent research. Data collection involved informal conversations/interviews with key stakeholders in the crab fisheries sub-sector, viz: Fishermen, Processing/Exporting firms, Traders, a retail outlet (restaurant). From the survey's results, the Crab fishery within Kilifi, though still in its infancy, appears to have the potential to generate socio-economic benefits for the local population. Demand for crabs was identified across multiple market segments, including crab processing firms in Malindi, tourist establishments, higher-income households, and an emerging domestic market along the Gede–Mida corridor. Inadequate inputs for local crab fishermen constituted the primary operational constraint. Further investigation into current and projected crab stocks, as well as community perceptions regarding crab culturing and consumption, is required to more conclusively assess the resource's potential contribution to food security.

Keywords: Crab fisheries, market chain, food security, reconnaissance survey, Kilifi county

Introduction

Crabs constitute an important source of dietary protein and income for coastal communities worldwide (Lunn and Dearden, 2006; Murugan and Anandhi, 2016). In the Western Indian Ocean (WIO) region, the mangrove mud crab *Scylla serrata* is the most commercially significant edible crab (Mirera, 2009). It is exploited almost entirely by artisanal fishers, who employ traditional capture methods including hooked sticks, pots, traps, hand-digging from burrows, and seine nets (Muthiga, 1986; Fondo, 2006; Ochiewo, 2006). Along the Kenyan coast, mud crab fishing is an established livelihood activity,

concentrated at Mtwapa Creek (Mtomondoni), Kilifi Creek (Kibokoni), Mida Creek (Watamu) and the Marereni–Gongoni–Fundisa area (Mirera *et al.*, 2013) – all within Kilifi County. Consequently, the *S. serrata* fishery is more developed, and reported on than all other edible crabs (Onyango, 2002; Fondo, 2006; Mirera and Mtile, 2009; Mirera, 2011). The fishery is currently the only crab species in Kenya which is cultured and harvested for export, principally to Asian markets (Fondo and Ogutu, 2021).

Despite its commercial importance, the wild stock supporting this fishery is increasingly recognized as vulnerable. Genetic evidence from

across the WIO indicates reduced nucleotide diversity in East African *S. serrata* populations relative to historical baselines, consistent with overexploitation or recent demographic bottlenecks, and underscores the need for sustainable harvesting and mangrove management to safeguard the resource (Rumisha *et al.*, 2017). Habitat loss compounds this pressure: mangrove deforestation has direct, measurable negative effects on mud crab abundance along the Kenyan coast (Fondo, 2006), linking the long-term viability of the fishery inextricably to the health of its mangrove habitat. These pressures coincide with persistent food insecurity in Kenya. Despite favourable rainfall in 2022 and part of 2023, many regions continue to experience drought and associated food deficits, driven by successive failed rainfall seasons, below-average crop yields, and insecurity arising from human-wildlife conflict and terrorism resulting in population displacement. Under the Integrated Food Security Phase Classification for February–June 2022, Kilifi County was categorized in the Crisis phase (GoK *et al.*, 2022). Food security features prominently in various local and international policy frameworks, including Kenya's Vision 2030, and the United Nations Sustainable Development Goal 2. While certain marine products finfish and octopus in particular have long underpinned coastal communities' subsistence and commerce, Kenya's crab resources have the potential to offer an additional, currently under-utilized contribution to coastal food security.

With the prominence given by the Kenyan government to addressing food insecurity, the country's crab fisheries could contribute food security. Determining this resource's potential requires assessment of its production capacity and the willingness of the local population to consume it. Critically, however, the basic information required to evaluate this potential is

largely absent. Little is known about the status of crab stocks in coastal Kenya, nor about local perceptions regarding crab consumption or the willingness to engage in commercial culturing of crabs. In the absence of such baseline data, the resource's capacity to contribute to food security cannot be reliably assessed. This reconnaissance study sought to gain baseline information on aspects of the crab fishery in Kilifi County specifically the Malindi and Watamu areas, within Malindi and Kilifi North constituencies respectively, to inform the development of a comprehensive research proposal on the crab fishery in the county.

Through structured interviews with key stakeholders in the crab fisheries sub-sector, *viz*: fishermen, processing/exporting firms, traders, a retail outlet (restaurant), this survey was able to generate preliminary findings. These results will help in facilitating the development of a comprehensive proposal to further investigate the sub-sector's potential in terms of contributing towards food security in Kenya. This study aimed to characterize aspects of the crab market chain within the Watamu and Malindi areas of Kilifi County.

Materials and methods

Study area

The reconnaissance survey was conducted at four locations within Kilifi County, on the north coast of Kenya: Mida (3°21'51.79" S, 39°57'59.68" E), Dabaso (3°20'44.44" S, 39°59'27.84" E), Watamu (3°21'07.35" S, 40°01'25.84" E) and Malindi (3°13'42.62" S, 40°07'38.91" E; 3°13'02.11" S, 40°07'27.84" E) (Fig. 1). These sites encompass the Mida Creek–Watamu mangrove system and the Malindi area, which together support the local artisanal crab fishery and its associated processing and retail enterprises.

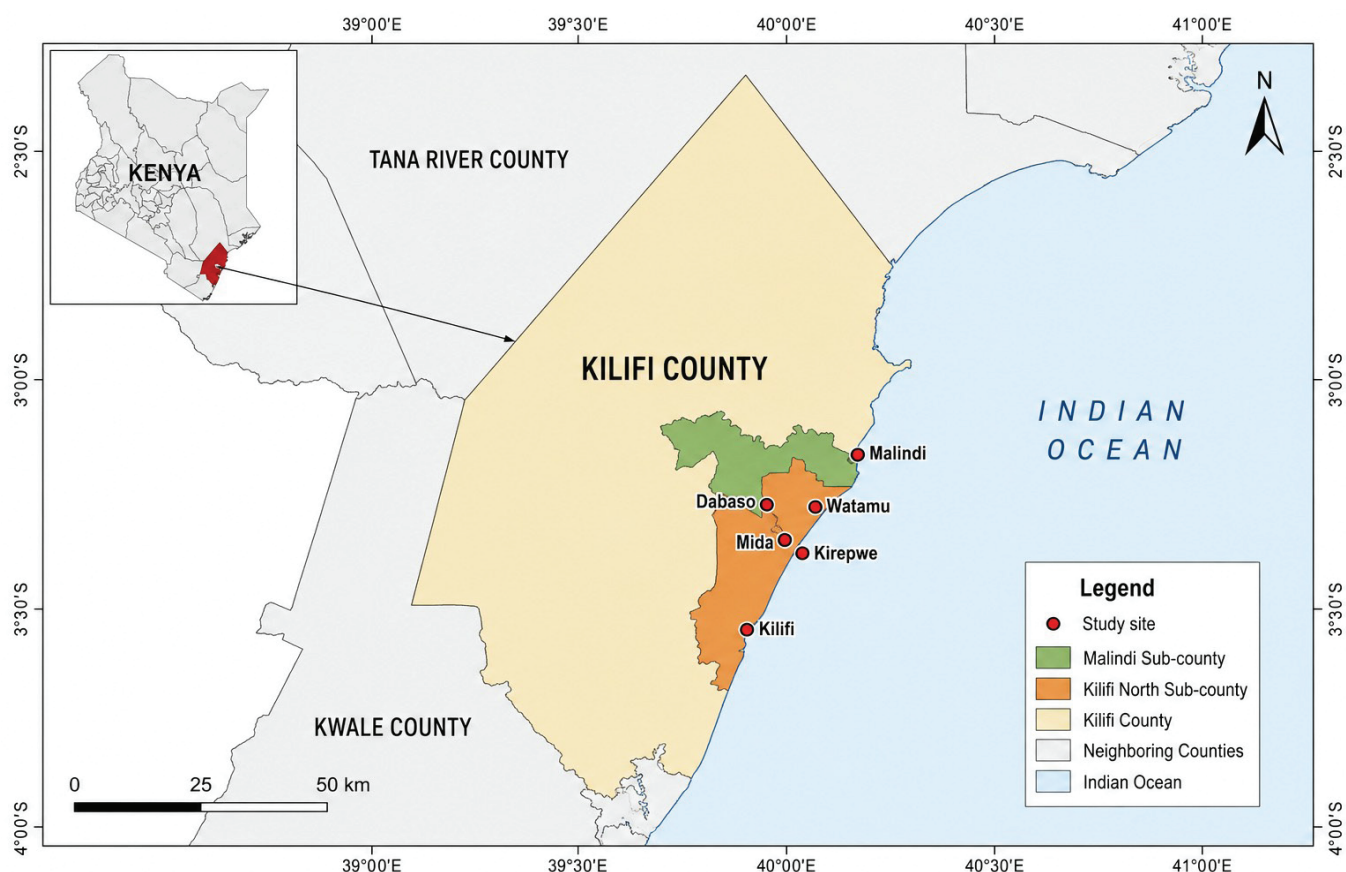


Figure 1. Study area (Source: AI).

Sampling design

The participants in this study were essentially key informants (Table 1). Key Informants are individuals whose experience and or knowledge, because of their position, can provide insight and information into the larger population (Malleret-King *et al.*, 2006). Given the varied locations from which the fishers sourced their crabs, this sample of fishermen was considered to provide an adequate degree of representativeness for the reconnaissance survey with respect to supply sources.

Table 1. List of respondents engaged in the reconnaissance survey.

Interviewee	Institution	Location
Respondent 1	Chairman, Watamu Beach Management Unit (BMU)	Watamu
Respondent 2	Crab fisherman	Kirepwe
Respondent 3	Crab fisherman	Kirepwe
Respondent 4	Crab fisherman	Mida
Respondent 5	Crab fisherman	Mida

Interviewee	Institution	Location
Respondent 6	Crab Trader (Crab Retailer)	Watamu
Respondent 7	Crab fisherman	Dabaso
Respondent 8	Firm 1 (Crab Processor)	Malindi
Respondent 9	Firm 2 (Crab Processor)	Malindi
Respondent 10	Crab serving restaurant (Crab Retailer)	Watamu

The selection of all participants in the survey was purposive, with the sole inclusion criteria being their involvement in either commercial crab fishing, processing or sale. The identification and recruitment of respondents was facilitated by the Watamu Fisheries Officer, whose long-standing interaction with local fishers enabled our meeting with the appropriate Key Informants – including the crab processing firms. In addition, the Operations manager of the Crab Shack restaurant was able refer us to two local crab fishers whom we interviewed. This data was collected intermittently between March 2021 and November 2022.

Data Collection

For the crab fishermen interviewed, an unstructured, conversational interviewing approach was employed. Informal interviewing is typically done as part of the process of observing a social setting of interest, and may best be used in the early stages of the development of an area of inquiry, where there is little literature describing the setting, experience, culture or issue of interest. Such interviews do not require pre-scheduled appointments with respondents and are conducive to open, uninhibited dialogue. These interviews are useful in understanding, gaining trust, establishing rapport and developing an empathetic, non-hierarchical relationship with the respondent (Cohen and Crabtree, 2006; Swain and Spire, 2020). For the Watamu Beach Management Unit (BMU) Chairman, crab processing firms, and the Crab Shack restaurant, a combination of unstructured interviewing and a short interview guide was employed for data collection. The guide contained suggested probes and prompts. Crab habitats within the mangrove environments were directly observed.

Data analysis

As an exploratory reconnaissance survey, the study prioritized discovery rather than inference. Because participants were selected purposively rather than at random, the data does not support statistical inference, and no a priori sample-size calculation was performed. Analysis was therefore predominantly descriptive: quali-

tative responses were organized into categories and broad themes, while quantitative responses – principally crab prices by grade – were tabulated and summarized using descriptive statistics. Qualitative data from the two processing firms were likewise summarized in tabular form. This approach was intended to provide a general but informative overview of the crab fisheries sub-sector in the Malindi and Watamu areas.

Ethical considerations

Participation was voluntary and based on verbal informed consent obtained after each respondent had been introduced to the research team and given an explanation of the study's purpose. Respondents are identified in this paper only by role and location (Table 1); no personal identifiers are reported. Fishers received a modest payment (KES 500) in recognition of the time given to the interviews.

Results and discussion

Overview of the crab fishery in Kilifi County

The survey identified a short, multi-actor market chain (Fig. 2). Crabs are harvested by artisanal fishers in the Watamu–Mida area and move along three principal channels: to local dealers and the Crab Shack restaurant for the domestic and tourist trade; to tourist hotels and higher-income households directly; and to Chinese-owned processing firms in Malindi, which export live mud crab (*Scylla serrata*) mainly to China, with secondary domestic supply to Nairobi.

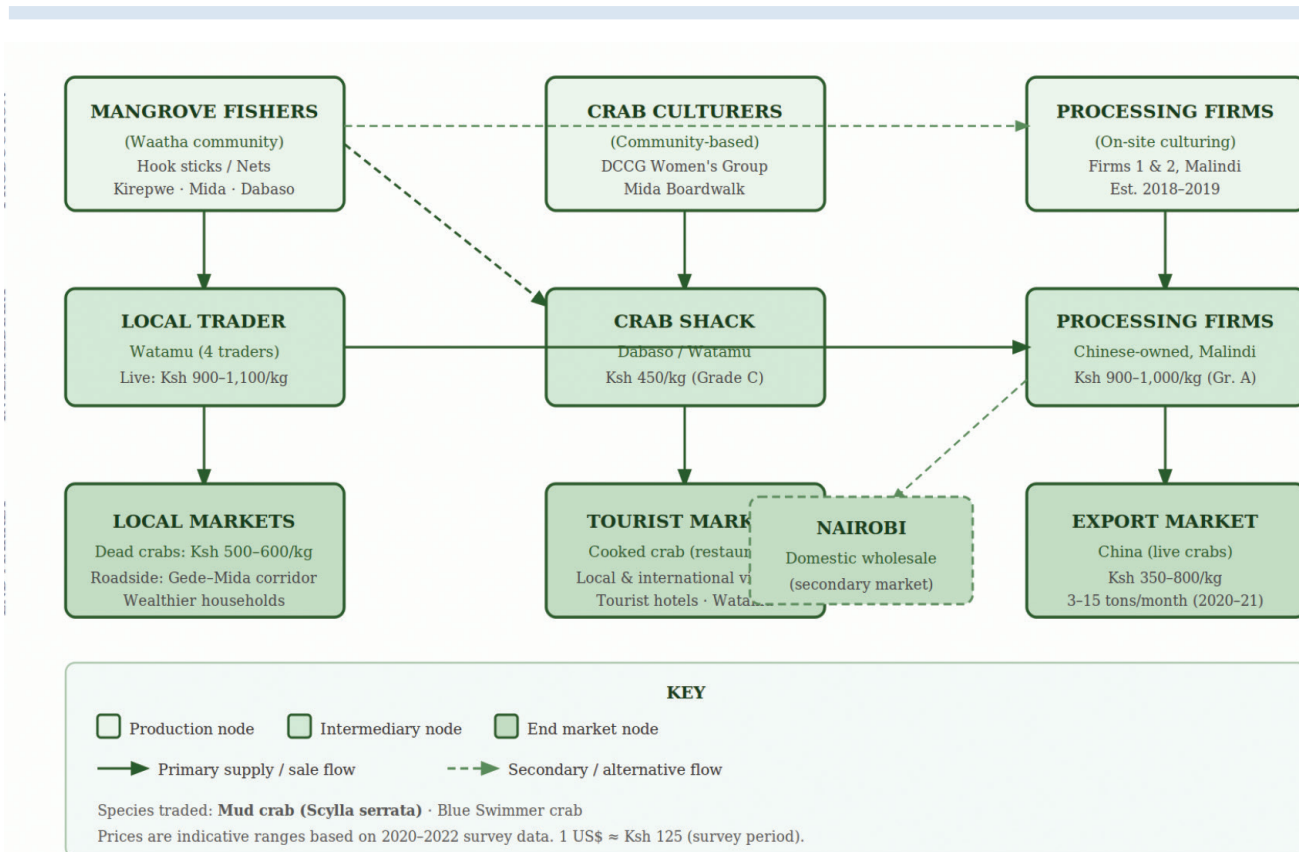


Figure 2. Crab market chain in Kilifi County, Kenya (Source: Authors).

The crab fishery in Watamu

Five crab fishers were interviewed – two from Kirepwe Island, two from Mida, and one from Dabaso – all of whom belonged to the Waatha community. Respondents used rudimentary gear comprising a hooked stick, a machete, and a foil-lined carton carry-bag. Capturing crabs by this method demands considerable manual dexterity, which respondents considered to be largely absent among non-Waatha coastal fishers. The two Kirepwe fishers additionally deployed thread (non-monofilament) nets of 7-inch mesh to capture mud crab and blue swimmer crab; monofilament nets were avoided as they are illegal, non-biodegradable, and implicated in ghost fishing.

Fishers harvest mud crab within the mangrove forest, where the crabs occupy burrows. Each fisher typically identifies and regularly monitors a set of burrows that he conceals from other harvesters. Harvesting is conducted either daily, over an average of four hours (range 2–6 h), or by setting

nets overnight. Respondents reported that supply peaks during the cooler south-east monsoon (April–July), when water levels are high and burrows remain submerged for longer periods.

The fishers' principal market was the Crab Shack restaurant, which paid KES 550 per kg (~US\$4.4) for mud crab and KES 250 per kg (~US\$2) for blue swimmer crab¹. Respondents identified additional demand from tourist hotels, higher-income households, and Chinese dealers in Malindi. Crabs are graded A–C with a residual "Reject" grade and priced accordingly (Table 2). Selling prices varied seasonally, being highest during the low-supply months (August–March) and lowest during the high-supply months (April–July) (Table 3); demand was reported to be lowest in November–December, the hottest period.

Following capture, crabs are held for approximately three days to accumulate a saleable quantity. Fishers identified several operational constraints: difficulty in obtaining fishing and transport licenses; high daily transport costs (up

¹ At the time of the study, US\$1 ≈ KES 125.

to KES 500 per day by motorbike) for those living far from harvesting grounds; and a lack of protective footwear, suitable vessels, and life jackets for working the mangrove terrain and higher tides.

Despite being the commercially preferred species, mud crab is seldom consumed locally. Respondents attributed this to its high price relative to alternative proteins – a single crab costs KES 500–1,000 (US\$4–8) depending on season, exceeding the cost of beef or fish – and to the labour-intensive preparation it requires relative to a standard meal.

Table 2. Market classification of crabs (weight and price).

Grade	Minimum weight (g)	Price (KES per kg)
A (processing firms)	700+	900–1,000 (US\$7.2–8)
B (processing firms)	500–600	700 (US\$5.6)
C (processing firms)	≤500	450 (US\$3.6)
Crab Shack	500	450 (US\$3.6)
Reject	Small	250 (US\$2)

A Watamu fisheries-products dealer with 15 years' experience in the crab trade was interviewed; at the time of the survey, only four crab traders operated in Watamu. The respondent dealt exclusively in mud crab, sourced primarily from local fishers who also supplied the Crab Shack restaurant. When local supply was insufficient, crabs were procured from as far as Lamu at KES 300 per kg. Supply peaked at the onset of the south-east monsoon (March–April), when Grade A crabs (700–900 g) were bought at KES 900 per kg (US\$7.2) and sold at KES 1,000–1,100 per kg (US\$8–8.8). Chinese processors in Malindi constituted the primary market, supplied with live crabs, while dead crabs were sold locally at KES 500–600/kg (US\$4–4.8).

Monthly income from the trade ranged from KES 9,000 to KES 20,000 (US\$72–160), the upper figure reflecting periods of Lamu sourcing. The principal constraint identified was limited local supply, attributed to the preferential prices offered by Chinese processing firms, which had substantially redirected available supply away from other buyers – although the respondent acknowledged the firms' role in maintaining a consistent market for fishers and traders alike.

During the interview with the (late) Watamu BMU Chairman, fisheries in the area were described as generally productive, with crabs abundant in the local mangroves; black- and red-coloured crab species were reported as the most prevalent. The Chairman noted that only a few crab dealers operated in Watamu and drew attention to a community-based women's group at the Mida Boardwalk engaged in crab culturing. He identified two principal constraints affecting the sub-sector: limited access to capital for crab culturing, and difficulty in accessing markets.

Crab supply dynamics: the Malindi processing firms

Two Chinese-owned crab processing and exporting firms (Firms 1 and 2) operating in Malindi were visited; these represented the most recent development in the local market chain. Both firms sourced crabs from local fishers and traders, processed them, and exported them – principally live mud crab to China, with secondary domestic supply to Nairobi – and each had begun culturing crabs on its premises. Firm-level data are summarized in Table 4, and the decline in their supplier base between 2019 and 2020 is shown in Figure 3. Notably, during the height of the Covid-19 pandemic in the latter half of 2020, the firms sustained local fishers' livelihoods by continuing to purchase locally supplied crabs.

Table 4. Data from the two crab processing firms in Malindi.

Variable	Firm 1	Firm 2
Start of crab processing in Kenya	2018	2019
Employees	10	8
Source of crabs (coastal Kenya)	Marereni; Lamu; Shekiko; Kinyaole	Marereni; Lamu
Species handled (now / last year)	Mud crab; same	Mud crab
Buying specification	≥500 g	≥500 g
No. of crab suppliers – 2020	3	6
No. of crab suppliers – 2019	10	>10
Market – local	Kenya (Nairobi)	Kenya (Nairobi)
Market – export	China	China
Seasonality of supply	High during rains	High during rains
Export price/kg – 2019	KES 500 (US\$4)	–
Export price/kg – 2020	KES 350 (US\$2.8)	KES 800 (US\$6.4); 10–15 t/month
Export price/kg – 2021	KES 500 (US\$4)	KES 800 (US\$6.4); 3 t/month
Impact of Covid-19	Lack of transport halted operations	Competition was very low
Current export challenges	Limited market due to high mortality Pre-export preservation is difficult	Stick capture injures crabs (unacceptable quality) Crab culturing is difficult Govt. restrictions on undersized crabs
Vision for the future	Expand markets	Buy berried (egg-bearing) crabs and culture them to support local fishers Introduce modern cage crab farming
Recommendations	Engage and equip more crab fishers to enhance supply	Identify and recruit more crab suppliers

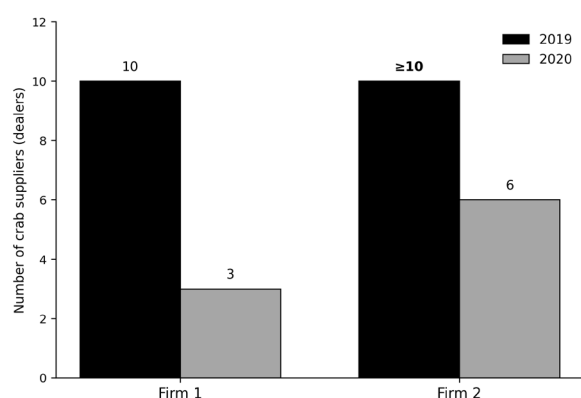


Figure 3. Number of crab suppliers (dealers) reporting to the two Malindi processing firms in 2019 and 2020. Firm 2's 2019 figure was reported as "more than ten" and is shown as ≥ 10.

Crab retailing: the crab shack restaurant

The Crab Shack restaurant, situated at Mida Creek in Dabaso village, is a low-impact wooden structure at the edge of the mangrove forest, accessed via a 200-m boardwalk and overlooking the Creek and Kirepwe Island (Fig. 4). It is among the leading Kenyan establishments serving cooked crab to local and international visitors. The restaurant is managed by the Dabaso Creek Conservation Group (DCCG), established in 2001 to conserve the local environment through sustainable mangrove use, controlled harvesting, and the elimination of destructive fishing. With initial institutional support from KMFRI, the group established its first crab-culturing site, and formal culturing commenced in 2014. The Crab Shack itself began as a roadside stall selling crab samosas and expanded in response to visitor demand.



Figure 4. The Crab Shack restaurant, Watamu – Kenya (Source: Crab Shack restaurant).

Seven fishers supply the restaurant daily, rising to as many as fifteen during periods of peak demand. Both mature and immature crabs are sourced: mature crabs are cooked and sold immediately, while immature crabs are fattened prior to sale. Management identified two principal constraints: unmet excess demand, requiring capacity expansion; and the impact of the COVID-19 pandemic, during which visitor numbers fell to zero, sharply reducing revenue while incurring boardwalk maintenance costs arising from prolonged disuse. Recognizing the dependence of its crab supply on mangrove health, the restaurant is actively engaged in community-based mangrove replanting within Mida Creek (Fig. 5).



Figure 5. Mangrove seedlings at Mida Creek set up by the Crab Shack management. The restaurant is engaged in community-based mangrove restoration initiatives in the area (Source: Edward Waiyaki).

This reconnaissance survey provides baseline evidence that the crab fishery in Kilifi County, although artisanal and largely informal, constitutes a functioning market chain with demonstrable socio-economic relevance. The findings corroborate comparable surveys elsewhere in sub-Saharan Africa (Gnan-sounou *et al.*, 2022; Nyangoko *et al.*, 2022), in which crab and mangrove-associated resources serve dual roles as livelihood assets and contributors to local food security. The implications of the survey are considered below under

five themes: coastal livelihoods, the Blue Economy, artisanal fisheries governance, food security, and mangrove conservation.

Coastal livelihoods and the crab fishery

The survey identifies the crab fishery as a meaningful, if constrained, source of income for a small number of coastal households in Kilifi. The exclusive involvement of the Waatha community in manual harvesting reflects ethnically specific ecological knowledge, consistent with Mirera *et al.* (2013), who documented the role of hereditary knowledge in shaping artisanal mud crab (*Scylla serrata*) fishing along the Kenyan coast. The reported scarcity of capture dexterity among non-Waatha fishers reinforces the specialized nature of this livelihood and underscores the importance of recognizing and protecting such indigenous technical knowledge within fisheries management frameworks.

Despite this income, fishers face significant structural constraints — high daily transport costs, the absence of protective gear and suitable vessels, and difficulties in obtaining licenses — that erode net returns and elevate occupational risk. Their stated preference for supplying the Crab Shack restaurant over Chinese dealers offering comparable or higher cash prices suggests that fishers value market stability

and durable buyer relationships over immediate price maximization. This is consistent with risk-averse livelihood strategies documented among small-scale fishers in developing coastal economies (Lunn and Dearden, 2006), and implies that strengthening domestic buyer relationships may yield more durable livelihood benefits than optimizing for export-driven price signals alone.

The crab fishery and Kenya's blue economy

Kenya's Blue Economy agenda recognizes marine and coastal resources as strategic assets for sustainable economic development. The entry of Chinese-owned processing and exporting firms into Malindi from 2018 represents a significant, externally driven market development that has integrated the local fishery into international value chains. Both firms export live mud crab primarily to China, with secondary supply to Nairobi, generating employment for fishers, traders, and processing workers. Fondo and Ogutu (2021) similarly identified the mud crab fishery's potential contribution to the Blue Economy, while cautioning that its sustainability depends on preventing overexploitation of wild stocks.

The findings point to a tension inherent in Blue Economy development at the artisanal scale: while export-oriented firms stimulate demand and provide ready cash markets, they simultaneously concentrate market power, compress domestic supply, and may incentivize overharvesting. The sharp decline in the number of suppliers to both firms between 2019 and 2020 – from ten to as few as three for Firm 1 (Fig. 3) – illustrates the fragility of supply chains built on unregulated wild-stock extraction. For the Blue Economy to deliver equitable and sustainable outcomes locally, crab mariculture must be scaled up alongside wild-capture regulation, with investment directed toward community-based culturing initiatives such as those already piloted by the Dabaso Creak Conservation Group (DCCG).

Artisanal fisheries governance

The governance landscape of the Kilifi crab fishery is characterized by institutional gaps at multiple levels. Few crab traders operate in

Watamu, and formal registration of market participants with Beach Management Units appears incomplete. The BMU Chairman's identification of capital access and market linkages as primary constraints reflects broader deficits in county-level institutional support for small-scale fisheries, consistent with comparable East African contexts (Malleret-King *et al.*, 2006).

The use of sticks to capture crabs flagged by a processor as a significant quality problem owing to the physical injury caused, points to the absence of enforced harvest standards and inadequate fisher training. Similarly, the illegal use of monofilament nets, though uncommon in the sample, represents a governance failure with long-term ecological consequences. Effective governance requires multi-stakeholder engagement led by the County Fisheries office, encompassing fisher registration, standardization of gear and harvest practices, and minimum-size regulations aligned with existing government restrictions on undersized crabs.

Food security and the nutritional potential of crabs

Kenya continues to face significant food insecurity, with the Government of Kenya (2022) reporting that multiple counties remain in crisis or stressed phases of the Integrated Food Security Phase Classification. Against this backdrop, the nutritional potential of the crab fishery warrants policy attention. Mud crab is a protein-dense resource currently exported in preference to domestic consumption, partly because of its cost relative to other proteins (KES 500–1,000 per crab) and partly because of cultural unfamiliarity among non-coastal communities.

Comparable surveys in West Africa (Gnansounou *et al.*, 2022) and Tanzania (Nyangoko *et al.*, 2022) have shown that mangrove crab resources can contribute meaningfully to community-level food security when appropriately managed and promoted. Realizing this potential in Kenya would require a sustained sensitization campaign to shift dietary attitudes among non-traditional consumers, alongside participatory assessment of the trade-offs between domestic supply and export. Food security pol-

icy should consider incentivizing domestic crab consumption, particularly in coastal counties, as part of a broader strategy to diversify accessible and affordable protein sources.

Mangrove conservation and fishery sustainability

The mud crab's ecological dependence on mangrove habitats creates an inextricable link between fishery productivity and ecosystem health. Fondo (2006) demonstrated that mangrove deforestation has direct negative effects on mud crab abundance along the Kenyan coast, underscoring the ecological risk of treating the fishery and its habitat as independent management concerns. The Crab Shack's active engagement in mangrove replanting within Mida Creek reflects a community-level recognition of this interdependence and represents a model of conservation-aligned enterprise that merits broader institutional support.

The sustainability of the fishery is therefore contingent on mangrove health. Any expansion of harvesting or culturing must be underpinned by robust habitat monitoring and conservation. Community-based mangrove management, as practised by the DCCG, should be formalized and supported through county and national environmental-governance structures. The integration of mangrove conservation into fisheries-management plans for Kilifi County is an operational necessity, not merely an environmental aspiration.

Limitations

This study is subject to several limitations. The reconnaissance design, while appropriate for baseline characterization, precludes statistical inference from the findings (Morgan *et al.*, 2006). The small sample of fishers, one dealer, and two processing firms limits representativeness. The inability to interview roadside crab retailers near Mida village is a specific gap, as this segment constitutes an important – and here unquantified – domestic supply channel. Finally, data collected during and immediately after the Covid-19 pandemic may not fully represent normal market conditions, given the documented disruptions to both supply and demand.

Conclusion and recommendations

This reconnaissance survey found that the Kilifi crab fishery generates measurable income for local fishers, traders, and processors, and shows potential to contribute to household food security, despite remaining underdeveloped relative to the county's finfish sector. Realizing this potential will require structured follow-up research into stock status, market capacity, and community perceptions of crab consumption and culturing, with particular attention to the sustainability of the mud crab's mangrove habitat. Engagement of stakeholders at all levels of the market chain will be essential. County fisheries authorities should prioritize coordinated investment in the sub-sector, including fisher registration, targeted capacity-building, and a participatory assessment of crab mariculture viability – to translate the fishery's demonstrated potential into tangible and sustainable socio-economic outcomes.

Based on these findings, several actions are recommended on the basis of these findings. Most fundamentally, a comprehensive, multi-stakeholder crab stock assessment and market study should be conducted to generate the quantitative evidence base required for informed management. Building on this, the County Fisheries office should establish a structured registration and capacity-building programme for crab fishers, traders, and processors that addresses gear standardization, licensing, and occupational safety. Community-based crab-culturing initiatives – particularly those already operating at Mida Creek – should be formally supported and, where viable, scaled through targeted financing, while a public sensitization campaign is designed and implemented to promote domestic crab consumption within food-security objectives. Finally, mangrove conservation should be embedded within any future management framework for the fishery, with community-managed conservation schemes accorded formal recognition and technical support.

Acknowledgements

We are grateful to all community members at the study sites for their cooperation and commitment throughout the fieldwork. We also thank the Watamu Fisheries Office for its coordinating role during data collection.

The authors thank KMFRI for the financial and logistical support that made this research possible. We are grateful to all community members at the study sites for their cooperation and commitment throughout the fieldwork, without which this work could not have been completed.

Declaration of use of AI

AI tools were used in the preparation of this manuscript solely for editorial and analytical assistance, including language refinement, structural editing, and figure generation. AI assistance was applied only to aggregated data at the level of the market chain and sub-sector; no individual participant data, including personal identifiers, or raw interview transcripts were processed through any AI system.

References

- Bunce L, Townsley P, Pollnac RB (2000) Socio-economic manual for coral reef management. Australian Institute of Marine Science, Townsville, Australia
- Cohen D, Crabtree B (2006) Qualitative research guidelines project. Robert Wood Johnson Foundation, Princeton
- Fondo EN (2006) Effects of mangrove deforestation on mangrove crab fishery. Final Report WIOMSA MARG I, p. 52
- Fondo EN, Ogutu B (2021) Sustainable crab fishery for Blue Economy in Kenya. *Aquatic Ecosystem Health and Management*, 24(1): 21–26 [https://doi:10.14321/aeahm.024.01.05]
- Fox N (2009) Using interviews in a research project. NIHR Research Design Service for the East Midlands/YorkESire and the Humber, 26
- Franzel S, Crawford EW (1987) Comparing formal and informal survey techniques for farming systems research: A case study from Kenya. *Agricultural Administration*, 25(1): 13–23 [https://doi:10.1016/0269-7475(87)90007-9]
- Gnansounou SC, Salako KV, Sagoe AA, Mattah PAD, Aheto DW, Glèlè Kakai R (2022) Mangrove ecosystem services, associated threats and implications for wellbeing in the Mono transboundary biosphere reserve (Togo–Benin), *West Africa. Sustainability*, 14(4): 2438 [https://doi:10.3390/su14042438]
- Government of Kenya, FAO, FEWS NET, UNICEF, Action Against Hunger, Food for the Hungry, NDMA, Save the Children, WFP, World Vision (2022) Integrated Food Security Phase Classification: Kenya – IPC Food Security Snapshot, February–June 2022. IPC Technical Working Group, Nairobi
- Lunn KE, Dearden P (2006) Monitoring small-scale marine fisheries: An example from Thailand's Ko Chang archipelago. *Fisheries Research*, 77(1): 60–71 [https://doi:10.1016/j.fishres.2005.08.009]
- Malleret-King D, Glass A, Wanyonyi I, Bunce L, Pomeroy B (2006) Socio-economic monitoring guidelines for coastal managers of the Western Indian Ocean (SocMon WIO). CORDIO East Africa Publication, Mombasa
- Mirera DO, Ochiewo J, Munyi F, Muriuki T (2013) Fishing tactics and dynamics of artisanal mangrove crab (*Scylla serrata*) fishery. *Ocean and Coastal Management*, 84: 119–129 [https://doi:10.1016/j.ocecoaman.2013.08.002]
- Mirera OD (2011) Trends in exploitation, development and management of artisanal mud crab (*Scylla serrata* Forsskal, 1775) fishery and small-scale culture in Kenya: An overview. *Ocean and Coastal Management*, 54(11): 844–855 [https://doi:10.1016/j.ocecoaman.2011.08.001]

- Mirera DO, Mtile A (2009) A preliminary study on the response of mangrove mud crab (*Scylla serrata*) to different feed types under drive-in cage culture system. *Journal of Ecology and Natural Environment*, 1(1): 7–14
- Morgan D, Sanz C, Onononga J, Strindberg S (2006) Ape abundance and habitat use in the Goulougo Triangle, Republic of Congo. *International Journal of Primatology*, 27(1): 147–179
- Murugan S, Anandhi DU (2016) An overview of crustacean diversity in mangrove ecosystem. In: *Arthropod Diversity and Conservation in the Tropics and Sub-tropics*, pp. 81–99. Springer, Singapore
- Muthiga NA (1986) Edible crabs of Kenya. *Kenya Aquatica Bulletin*, 3: 61–65. Kenya Marine and Fisheries Research Institute, Mombasa
- Nyangoko B, Shalli M, Mangora M, Gullström M, Berg H (2022) Socioeconomic determinants of mangrove exploitation and management in the Pangani River Estuary, Tanzania. *Ecology and Society*, 27(2): 32
- Ochiewo J (2006) Harvesting and sustainability of marine fisheries in Malindi–Ungwana Bay, northern Kenya coast (Report No: WIOMSA/MARG-I/2006–03). Kenya Marine and Fisheries Research Institute
- Onyango DS (2002) The breeding cycle of *Scylla serrata* (Forsskal, 1755) at Ramisi River estuary, Kenya. *Wetlands Ecology and Management*, 10(4): 257–263
- Pido MD, Pomeroy RS, Carlos MB, Garces LR (1996) A handbook for rapid appraisal of fisheries management systems (Version 1). International Center for Living Aquatic Resources Management (ICLARM), Manila
- Rumisha C, Huyghe F, Rapanoel D, Mascaux N, Kochzius M (2017) Genetic diversity and connectivity in the East African giant mud crab *Scylla serrata*: Implications for fisheries management. *PLoS ONE*, 12(10): e0186817 [<https://doi.org/10.1371/journal.pone.0186817>]
- Swain J, Spire Z (2020) The role of informal conversations in generating data, and the ethical and methodological issues they raise. *Forum: Qualitative Social Research*, 23(1): Article 2
- Wilson C (2014) Semi-structured interviews – phone interviews. In: *Interview Techniques for UX Practitioners*, Chapter 2 and 4. Morgan Kaufmann, Waltham, MA

Optimizing salinity for enhanced reproductive performance of the Kenyan *Artemia franciscana* population

Derick Gitari^{1,4}, Morine Mukami², Sheban Hinzano¹, David Midumbi^{1,4}, Anthony Nzioka¹, Mary Opiyo³, Cosmas Munga⁴, Miriam Wainaina² and Betty Nyonje²

¹Kenya Marine and Fisheries Research Institute, Aquaculture Directorate, Shimoni Mariculture Center, P.O Box 2001–80400, Ukunda

²Kenya Marine and Fisheries Research Institute, Aquaculture Directorate, Mombasa Center, P.O Box 81561–80100, Mombasa

³Kenya Marine and Fisheries Research Institute, Aquaculture Directorate, Sagana Center, P.O Box 81561–80100, Mombasa

⁴Technical University of Mombasa, Department of Chemistry and Biological Sciences, P.O Box 90420–80100, Mombasa

Abstract

Salinity is a key factor regulating *Artemia* survival, reproduction and life-history strategies, making strain- and location-specific studies essential. This study evaluated effects of salinity (35, 80, 100, 120, 140 gL⁻¹) on survival and reproductive performance of a Kenyan *Artemia* population. Decapsulated cysts were hatched and nauplii reared on *Chaetoceros* spp at each treatment. At maturity, 50 mating pairs (10 replicates per treatment) were isolated in Falcon tubes and monitored daily for nauplii and cyst production using Lugol staining and microscopy.

Moderate salinities (35–100 gL⁻¹) supported optimal survival, with complete survival at 80 gL⁻¹, while hypersaline conditions (120–140 gL⁻¹) significantly increased mortality. Brood numbers stayed stable, but brood intervals decreased at higher salinities, indicating stress-induced reproductive acceleration. A clear shift in reproductive mode emerged: lower salinities favoured ovoviviparity with high nauplii output, while higher salinities reduced nauplii production and increased cyst production, reflecting a transition to oviparity under stress.

These findings demonstrate salinity-driven reproductive plasticity in *Artemia* and its relevance to aquaculture, where salinity manipulation can optimize nauplii or cyst output. Future studies should examine effects on cyst quality, hatching efficiency, nauplii nutrition, and interactions with other environmental factors.

Keywords: *Artemia*, salinity gradient, reproductive strategy, nauplii, cyst production

Introduction

Brine shrimp of the genus *Artemia* are halophilic Anostraca crustaceans widely distributed in hypersaline lakes, coastal lagoons and solar salt-works globally. Their tolerance to elevated salinities, broad temperature ranges and variable environmental conditions has positioned them

as valuable model organisms for investigating osmoregulation, stress physiology and diapause mechanisms (Abatzopoulos *et al.*, 2002). Critically, *Artemia* remains the predominant live feed in global aquaculture, particularly for larviculture of marine fish and crustaceans, owing to the nauplii's appropriate size, high digestibility, favorable nutritional composition and the

unique attributes of their cysts, which enable long-term storage, international transport and on-demand hatching (Dhont & Sorgeloos, 2002; Lavens & Sorgeloos, 1996).

In Kenya, *Artemia* populations are primarily confined to the coastal salt belt, where hypersaline conditions characterize solar saltworks and associated evaporation ponds. These populations derive from introductions of *Artemia franciscana* Kellogg, 1906, during the mid-1980s, using broodstock originating from San Francisco Bay, USA (Rasowo, 1986; Ngarari *et al.*, 2024). Following inoculation, the species has successfully established persistent, self-sustaining populations across multiple salt production sites (Mremi, 2011). Although the initial introductions aimed to enhance salt crystallization processes and explore aquaculture potential, growing demand for high-quality live feeds in regional marine and freshwater hatcheries has since elevated interest in local *Artemia* production. Consequently, elucidating the environmental regulators of reproduction in Kenyan *Artemia* populations carries important implications for both ecological dynamics and sustainable aquaculture development.

A hallmark of *Artemia* biology is its pronounced reproductive plasticity. Females exhibit dual reproductive modes: ovoviviparity, yielding free-swimming nauplii or oviparity, resulting in diapause-encysted embryos (cysts). This flexibility confers adaptive advantages in temporally unstable habitats and underpins the species' commercial utility (Drinkwater & Crowe, 1991). The relative allocation to nauplii versus cyst production is modulated by key environmental cues, including salinity, temperature, photoperiod, dissolved oxygen concentration and nutritional availability (Browne & Wanigasekera, 2000). Salinity exerts particularly strong control, as it governs osmotic homeostasis, metabolic energy expenditure, and resource partitioning toward reproduction (Abatzopoulos *et al.*, 2003).

At moderate salinities, osmoregulatory costs remain comparatively low, facilitating enhanced somatic growth and ovoviviparous reproduction, which typically maximizes nauplii output. Conversely, elevated salinities induce osmotic stress, often promoting a shift toward oviparous reproduction and cyst formation as a protective strategy (Browne & Wanigasekera, 2000; Drinkwater & Crowe, 1991). Extreme salinity, however, can compromise survival, fecundity and overall reproductive output through excessive metabolic demands and diminished feeding efficiency (Agh *et al.*, 2008; Baxeavanis *et al.*, 2004). Reproductive performance thus tends to be optimized within a strain-specific salinity window that balances physiological tolerance with reproductive yield (Ngarari *et al.*, 2024; Triantaphyllidis *et al.*, 1995).

In Kenya's coastal saltworks, salinity regimes fluctuate markedly in response to seasonal evaporation, precipitation patterns and operational salt-harvesting practices. Such variability likely influences in situ reproductive mode allocation, cyst biomass and nauplii production. From an applied perspective, strategic salinity manipulation represents a feasible intervention for optimizing output: reduced salinities may favor nauplii production to meet immediate hatchery needs, while elevated salinities can enhance cyst yields for storage, distribution and commercialization (Ngarari *et al.*, 2024; Van Stappen, 1996). Defining salinity optima for the Kenyan *Artemia franciscana* population is therefore essential to boost production efficiency, diminish dependence on imported cysts and fortify domestic aquaculture supply chains.

Although *Artemia* has been the subject of extensive international research, local populations frequently display divergent physiological thresholds and reproductive responses attributable to site-specific environmental selective pressures and genetic adaptation (Baxeavanis *et al.*, 2004; Ngarari *et al.*, 2024). Strain and location-specific investigations are thus indispensable for generating actionable, context-

ally relevant data. Examination of salinity effects on reproductive success in the Kenyan *Artemia* population therefore provides valuable insights into both fundamental ecological processes and the advancement of sustainable, regionally adapted *Artemia* production protocols.

Materials and methods

Experimental design

The experiment was conducted at the *Artemia* Laboratory of the Kenya Marine and Fisheries Research Institute (KMFRI), Mombasa, Kenya. The cysts of *Artemia franciscana* used in this study were collected from artisanal salt ponds in Kaduhoni Village, Kilifi County, Kenya (2°58'54" S, 40°08'37" E). After collection, cysts were taken to the KMFRI *Artemia* Laboratory for processing and preparation for hatching under controlled laboratory conditions.

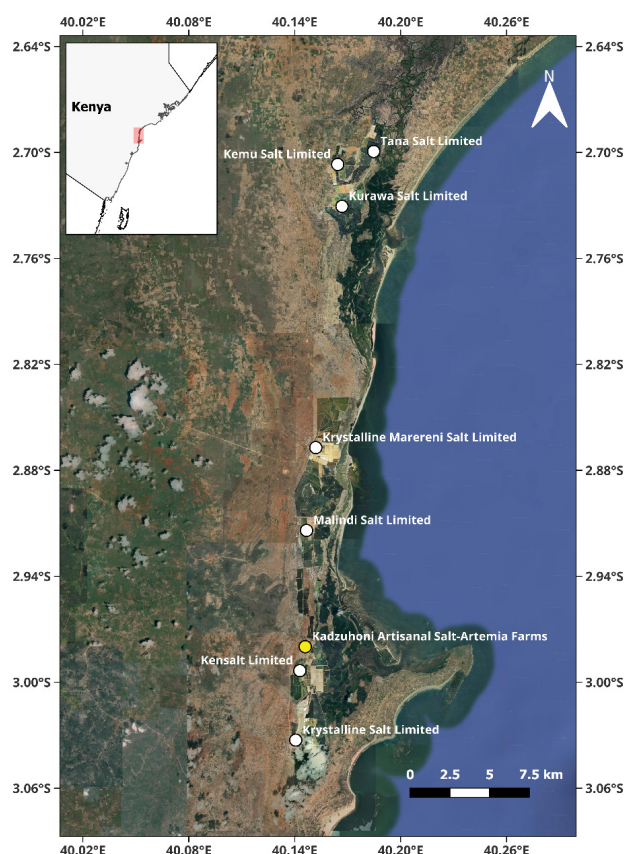


Figure 1. Showing the study area.

Cyst decapsulation, hatching and culture conditions

The processed *Artemia franciscana* cysts were decapsulated prior to hatching following the pro-

cedure of (Lavens & Sorgeloos, 1996). The decapsulated cysts were then incubated in cartridge filtered and autoclaved natural sea water (21°C, 1 atm, 15 min) under continuous illumination and aeration for 18 h at 26±0.5°C. Newly hatched instar I nauplii were harvested using a 100 µm mesh net and rinsed thoroughly with filtered seawater for 5 min. Cleaned *Artemia nauplii* were stocked in glass bottles containing 600 mL saline water of different experimental salinities (35, 80, 100, 120 and 140 g L⁻¹) in duplicate. Stocking rate was adjusted to 1 nauplii mL⁻¹ to minimize growth suppression due to space limitations (Mejía *et al.*, 2013; Ngarari *et al.*, 2024). Experimental salinities of 35 (control), 80, 100, 120 and 140 g L⁻¹ were created by enriching filtered natural seawater with crude salt granules sourced from Kurawa Salt Works, a commercial salt producer located in Malindi, Kenya. Salinity was kept constant throughout culturing by replacing evaporated water with distilled water (Triantaphyllidis *et al.*, 1995) and was checked daily with a hand-held refractometer (AO 0 – 300-Extech Instruments, Nashua, NH, USA). Cultures experienced a 12-hour light and 12-hour photoperiod. Organisms were fed daily with the microalga *Chaetoceros* spp., following established husbandry methods (Naegel 1999). Monitoring and routine feeding ensured stable conditions and supported consistent culture development.

Reproductive assessment

Upon reaching sexual maturity, indicated by male clasping behavior, 50 pairs of coupling *Artemia* (corresponding to 10 replicates per salinity treatment) were randomly selected from the glass bottles and transferred into 50 mL Falcon tubes containing 30 mL of culture medium at a 1:1 male-to-female ratio per Falcon tube to study their life cycle characteristics. The Falcon tubes were checked every day for the production of nauplii or cysts, which were counted and recorded against each treatment. All dead males were immediately replaced with actively swimming males from the corresponding salinity level during the experiment according to (Agh *et al.*, 2008). In case of death of a female, counting was suspended on the affected replicate. During counting, the contents of each Falcon

tube were poured on to a petri plate, stained using 1 drop of 1% Lugol solution and the number of cysts and nauplii quantified under a dissecting microscope (Abatzopoulos *et al.*, 2006; Guermazi *et al.*, 2009). After counting the couples were returned into their respective Falcon tubes pre-filled with water of the same salinity.

Data analysis and statistical test

The collected data was cleaned and subjected to the Shapiro–Wilk test of normality. Summary statistics of the treatment groups were computed using Microsoft Excel (MS Excel Ver. 2019). Equality of variance among treatment groups was assessed using Levene's test. Since the data was normally distributed and confirmed equality of variance, a One-Way Analysis of Variance (ANOVA) was used to compare mean reproductive indices of the Kenyan *Artemia* population among the salinity treatment groups. Tukey's HSD post-hoc test was used to determine where significant differences occurred between treatment groups. All statistical tests were performed using R-statistical software (R program Ver. 4.5.2 for Windows) and were considered significant at 95% confidence interval. The relationship between cysts and nauplii produced by *Artemia* against a salinity gradient was assessed using a regression analysis on Microsoft Excel (MS Excel Ver. 2019). The results were presented using graphical and tabular illustrations.

Results

Reproductive parameters

Salinity had a pronounced effect on both survival and reproductive strategy of *Artemia* (Table 1). Mortality remained low at 35–100 gL⁻¹ ($\leq 4.55\%$), with complete survival observed at 80 g/L, indicating optimal environmental conditions within this range. However, mortality increased sharply at higher salinities, reaching 31.82% at 120 gL⁻¹ and 59.09% at 140 gL⁻¹, suggesting physiological stress under hypersaline conditions. The number of broods per female was relatively stable across treatments, though a slight increase was observed at 120 gL⁻¹. Interestingly, brood intervals decreased with increasing salinity, indicating a faster reproductive cycle under stress conditions. This may reflect a compensatory response to unfavorable environments.

A clear shift in reproductive mode was observed with increasing salinity. At lower salinities (35–80 gL⁻¹), *Artemia* predominantly produced nauplii, with the highest number recorded at 35 gL⁻¹ (36.75 ± 3.13 nauplii/brood). However, as salinity increased, nauplii production declined drastically, dropping to negligible levels at 120 and 140 gL⁻¹. Conversely, cyst production increased significantly with salinity, from 4.96 ± 1.40 cysts/brood at 35 gL⁻¹ to 41.91 ± 1.75 at 140 gL⁻¹. Similarly, total cyst output per female rose markedly at higher salinities. This indicates a shift from ovoviviparous reproduction (nauplii release) to oviparous reproduction (cyst production), a well-known adaptive strategy in *Artemia* to withstand harsh environmental conditions.

Table 1. Reproductive parameters of the Kenyan *Artemia* population under different salinity treatments. Data is presented as mean $\pm$ standard deviation. Similar superscripts in the same row indicate that values are not significantly different.

Parameters	35 gL ⁻¹	80 gL ⁻¹	100 gL ⁻¹	120 gL ⁻¹	140 gL ⁻¹
Proportion of total mortality (%)	4.55 ^a	0.00 ^b	4.55 ^a	31.82 ^c	59.09 ^d
Number of broods/females	4.00 $\pm$ 0.41 ^a	4.00 $\pm$ 0.41 ^a	4.00 $\pm$ 0.71 ^a	5.50 $\pm$ 1.19 ^a	4.75 $\pm$ 1.31 ^a
Intervals between broods (days)	1.64 $\pm$ 0.20 ^a	1.63 $\pm$ 0.22 ^a	1.77 $\pm$ 0.20 ^a	1.36 $\pm$ 0.20 ^a	1.31 $\pm$ 0.36 ^a
Number of cysts/broods	4.96 $\pm$ 1.40 ^a	2.14 $\pm$ 0.57 ^a	11.08 $\pm$ 1.44 ^a	25.45 $\pm$ 2.48 ^b	41.91 $\pm$ 1.75 ^b
Number of nauplii/brood	36.75 $\pm$ 3.13 ^a	21.81 $\pm$ 1.86 ^b	19.03 $\pm$ 5.11 ^b	1.80 $\pm$ 0.78 ^c	1.58 $\pm$ 1.38 ^c
Number of nauplii/female	147 $\pm$ 12.53 ^a	87.25 $\pm$ 7.44 ^a	67.50 $\pm$ 15.46 ^c	10.75 $\pm$ 5.88 ^d	10.75 $\pm$ 9.76 ^d
Number of cysts/females	20.50 $\pm$ 6.76 ^{ab}	9.25 $\pm$ 3.09 ^a	46.50 $\pm$ 11.21 ^b	137.75 $\pm$ 3.68 ^c	148.75 $\pm$ 4.38 ^d

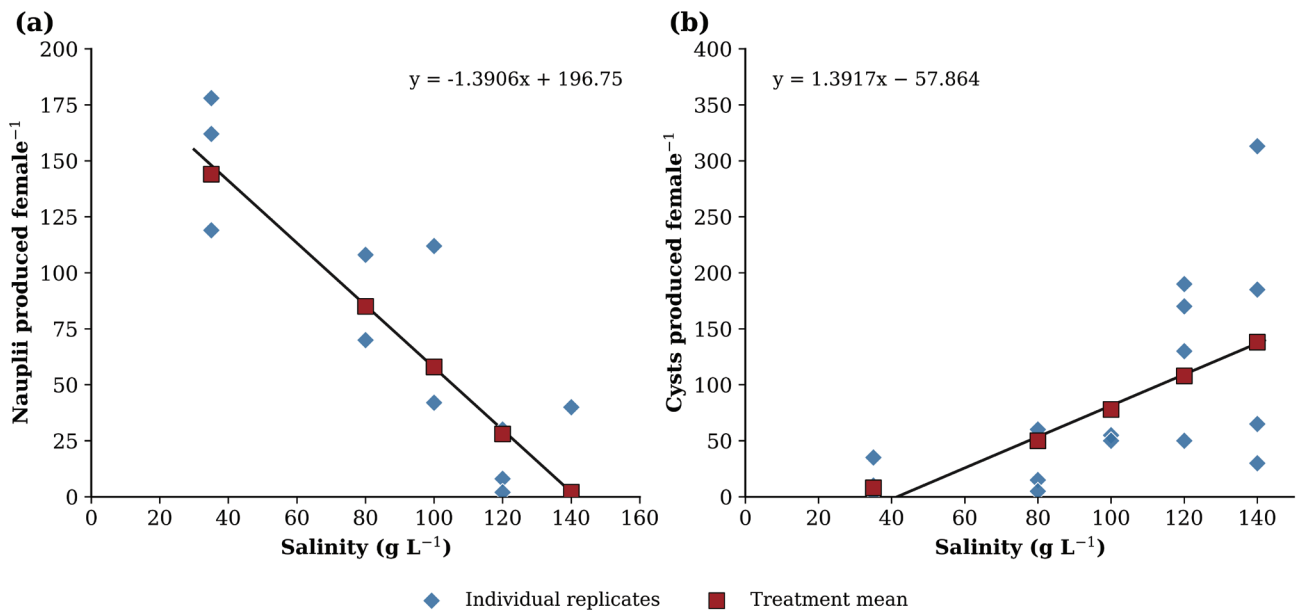


Figure 2. A regression analysis between counts of nauplii (a) and cysts (b) produced during the experimental period. The negative slope (a) indicates a decreasing number of nauplii with increasing salinity. The positive slope (b) indicates an increasing number of cysts with increasing salinity. The red marks are the predicted y values while the blue are the actual y variables.

Relationship between salinity and *Artemia* reproductive parameters

The number of nauplii produced per female significantly decreased with increasing salinity ($F = 98.96$, $p\text{-value} = 0.00$) suggesting that nauplii production is inversely proportional to salinity. Cysts produced per female significantly increased with increasing salinity ($F = 11.36$, $p\text{-value} = 0.00$) suggesting that cysts production is directly proportional to salinity level. The results indicate a shift in reproduction strategy from live bearing in salinities below 100 ppt to encysts embryos that can withstand extreme salinities (>100 ppt).

Discussion

The present study demonstrates that salinity is a key environmental regulator influencing survival, reproductive output and reproductive mode in *Artemia*. The observed patterns reveal a clear trade-off between nauplii production and cyst formation across the salinity gradient, highlighting the species' remarkable phenotypic plasticity in response to environmental stress. These findings are consistent with a broad body of literature describing salinity as one of the most critical drivers of *Artemia* biology and life-history

strategies (Wang *et al.*, 2024; Guo *et al.*, 2024) they must obtain these compounds from their diet to meet the physiological and adaptive requirements needed in specific aquaculture stages and conditions. Carotenoid supplementation in *Artemia* represents a promising strategy to enhance pigmentation, health, and growth in aquaculture species, particularly in larvae and other early developmental stages. Methods: In this study, a β -carotene enrichment process was applied to *Artemia* metanauplii to investigate the biological fate and potential effects of β -carotene. Results: The results indicated significant β -carotene uptake by *Artemia*, with peak levels observed at 12 h. Alongside β -carotene, two xanthophylls—canthaxanthin and echinenone—were detected in *Artemia*, each exhibiting distinct patterns during the enrichment and subsequent depletion phases. The transcriptome analysis identified 2705 differentially expressed genes (DEGs).

Survival results indicate that moderate salinities (35–100 g L⁻¹) provide favourable conditions for *Artemia* culture. Mortality remained minimal within this range, with complete survival at 80 g/L, suggesting that this salinity approximates optimal osmotic conditions for physiological functioning. Similar findings have been reported

by Sorgeloos *et al.* (2001), who noted that *Artemia* thrives best in intermediate salinity ranges where osmotic stress is minimized and metabolic energy can be allocated efficiently to growth and reproduction. Recent studies further support this, showing that optimal survival and physiological performance occur under moderate salinity regimes (Nguyen, 2022; Ngari *et al.*, 2024; Rahman *et al.*, 2025). In contrast, the sharp increase in mortality at 120 and 140 gL⁻¹ reflects the onset of hypersaline stress, which likely imposes high energetic demands for osmoregulation. Under such conditions, energy is diverted from growth and reproduction toward maintenance, leading to reduced fitness and increased mortality (Browne *et al.*, 1984; Castro-Mejía *et al.*, 2011; Rahman *et al.*, 2025).

Interestingly, the number of broods per female did not decline significantly with increasing salinity and even peaked at 120 gL⁻¹. This suggests that brood frequency may be less sensitive to salinity stress compared to other reproductive parameters. However, the observed reduction in intervals between broods at higher salinities indicates an accelerated reproductive cycle. Such a response can be interpreted as a stress-induced reproductive strategy, whereby organisms reproduce more rapidly in anticipation of reduced survival prospects. This phenomenon has been described as “terminal investment” or stress-induced reproduction in crustaceans (Lavens & Sorgeloos, 1996). Recent findings by Yang & Sun (2023) also confirm that environmental stressors, including salinity, can significantly alter reproductive timing without necessarily affecting brood number.

One of the most striking findings of this study is the shift in reproductive mode from ovoviviparity (nauplii release) at lower salinities to oviparity (cyst production) at higher salinities. At 35 gL⁻¹, females produced the highest number of nauplii per brood and per individual, indicating that favourable environmental conditions promote live offspring production. This is consistent with previous studies showing that under optimal conditions, *Artemia* prioritizes rapid population expansion through nauplii release (Triantaphyllidis *et al.*, 1998; Nguyen, 2022). Nauplii production

is advantageous in stable environments because it allows immediate recruitment into the population without the delay associated with cyst hatching.

However, as salinity increased beyond 100 gL⁻¹, nauplii production declined sharply, becoming almost negligible at 120 and 140 gL⁻¹. Concurrently, cyst production increased dramatically, both per brood and per female. This shift reflects a classic adaptive response to environmental stress. Cysts are highly resistant dormant stages capable of withstanding extreme conditions, including desiccation, high salinity and temperature fluctuations. The production of cysts under adverse conditions ensures long-term survival of the species by creating a “bank” of viable embryos that can hatch when favourable conditions return (Clegg & Trotman, 2002; Li *et al.*, 2024).

The increase in cyst output at higher salinities observed in this study aligns with findings by Browne & Wanigasekera, (2000), who reported that environmental stressors such as high salinity, low food availability and extreme temperatures promote oviparous reproduction in *Artemia*. Recent studies further demonstrate that salinity is a primary trigger for cyst formation, with molecular mechanisms involving stress-response proteins and metabolic adjustments (Li *et al.*, 2024). Although energetically costly, this strategy provides a survival advantage under harsh conditions.

The inverse relationship between nauplii and cyst production observed in this study highlights a fundamental life-history trade-off. At lower salinities, energy is invested in producing large numbers of nauplii, maximizing short-term reproductive success. In contrast, at higher salinities, energy is redirected toward producing fewer but more resilient offspring in the form of cysts. This trade-off is consistent with life-history theory, which predicts that organisms allocate resources differently depending on environmental conditions to optimize fitness (Stearns, 2000). In *Artemia*, this flexibility allows populations to persist across highly variable and often extreme habitats, as also emphasized in recent ecological studies (Guo *et al.*, 2024).

The decline in nauplii per female at elevated salinities has important implications for aquaculture. Nauplii are widely used as live feed in the larviculture of fish and crustaceans due to their high nutritional value and appropriate size. The results suggest that maintaining salinity within the range of 35–80 gL⁻¹ is optimal for maximizing nauplii production. This is in agreement with aquaculture practices recommended by recent studies highlighting improved growth and nutritional quality under moderate salinities (Rahman *et al.*, 2023). Conversely, the enhanced cyst production at higher salinities may be advantageous for commercial cyst production systems. However, recent work indicates that extreme salinity may negatively affect physiological quality, including hatching efficiency and biochemical composition (Nevárez-Prado *et al.*, 2022; Rahman *et al.*, 2023). This highlights the need for a balance between inducing stress for cyst production and maintaining broodstock viability.

Conclusion and recommendations

The findings of this study confirm that salinity is a critical determinant of survival and reproductive strategy in *Artemia*. Moderate salinity levels (35–80 gL⁻¹) supported optimal survival and maximized nauplii production, making them suitable for live feed generation in aquaculture. In contrast, hypersaline conditions (≥ 120 gL⁻¹) significantly increased mortality and triggered a shift from ovoviviparous reproduction (nauplii release) to oviparous reproduction (cyst production), reflecting an adaptive response to environmental stress. The observed trade-off between nauplii and cyst production highlights the species' reproductive plasticity, enabling rapid population growth under favourable conditions and long-term survival through resistant cyst formation under stress. These results reinforce the importance of salinity as a key driver of *Artemia* life-history strategies and provide practical insights for aquaculture production systems for the Kenyan *Artemia* population. Future studies should evaluate

the effect of salinity on cyst quality, hatching efficiency and nutritional composition of nauplii to better inform aquaculture applications. Future research should build on these findings by investigating how salinity not only affects the quantity but also the quality of *Artemia* outputs, particularly cyst viability, hatching efficiency and the nutritional composition of nauplii under different salinity regimes.

References

- Abatzopoulos TJ, Baxevas AD, Triantaphyllidis GV, Criel G, Pador EL, Van Stappen G, Sorgeloos P (2006) Quality evaluation of *Artemia urmiana* Günther (Urmia Lake, Iran) with special emphasis on its particular cyst characteristics (International Study on *Artemia* LXIX). *Aquaculture*, 254(1–4): 442–454
- Abatzopoulos TJ, Kappas I, Bossier P, Sorgeloos P, Beardmore JA (2002) Genetic characterization of *Artemia tibetiana* (Crustacea: Anostraca). *Biological Journal of the Linnean Society*, 75(3): 333–344
- Abatzopoulos TJ, Triantaphyllidis GV, Roedaki N, Baxevas AD, Triantaphyllidis A, Sorgeloos P (2003) Elevated salinities may enhance the recovery of hydrated heat-shocked *Artemia franciscana* cysts (International Study on *Artemia*. LXV). *Belgian Journal of Zoology*, 2
- Agh N, VanStappen G, Bossier P, Mohammadyari A, Rahimian H, Sorgeloos P (2008) Life cycle characteristics of six *Artemia* populations from Iran. In: Characterization of *Artemia* Populations from Iran. *Pakistan Journal of Biological Sciences*, p. 65
- Baxevas AD, El-Bermawi N, Abatzopoulos TJ, Sorgeloos P (2004) Salinity effects on maturation, reproductive and life span characteristics of four Egyptian *Artemia* populations (International Study on *Artemia*. LXVIII). *Hydrobiologia*, 513(1): 87–100

- Browne RA, Sallee SE, Grosch DS, Segreti WO, Purser SM (1984) Partitioning genetic and environmental components of reproduction and lifespan in *Artemia*. *Ecology*, 65(3): 949–960
- Browne RA, Wanigasekera G (2000) Combined effects of salinity and temperature on survival and reproduction of five species of *Artemia*. *Journal of Experimental Marine Biology and Ecology*, 244(1): 29–44
- Castro-Mejía J, Castro-Barrera T, Hernández-Hernández LH, Arredondo-Figueroa JL, Castro-Mejía G, de Lara-Andrade R (2011) Effects of salinity on growth and survival in five *Artemia franciscana* (Anostraca: Artemiidae) populations from Mexico Pacific Coast. *Revista de Biología Tropical*, 59(1): 199–206
- Clegg JS, Trotman CNA (2002) Physiological and biochemical aspects of *Artemia* ecology. In *Artemia: Basic and Applied Biology*, pp. 129–170. Springer Netherlands
- Dhont J, Sorgeloos P (2002) Applications of *Artemia*. In *Artemia: Basic and Applied Biology*, pp. 251–277. Springer Netherlands
- Drinkwater LE, Crowe JH (1991) Hydration state, metabolism, and hatching of Mono Lake *Artemia* cysts. *The Biological Bulletin*, 180(3): 432–439
- Guo XM, Gao W, Chen X, Wang HL, Zhao RH, Xie GS, Huang J (2024) Is *Artemia* susceptible to the microsporidium *Ecytonucleospora hepatopenaei* (EHP) infection? *Aquaculture*, 590: 741014
- Guermazi W, Ayadi H, Aleya L (2009) Correspondence of the seasonal patterns of the brine shrimp, *Artemia salina* (LEACH, 1819) (Anostraca) with several environmental factors in an arid solar saltern (Sfax, Southern Tunisia). *Crustaceana*, 82: 327–348
- Lavens P, Sorgeloos P (1996) Manual on the production and use of live food for aquaculture (1st ed.)
- Li K, Wang Y, Du G, Yao X, Bao H, Han X, Sui L (2024) Effects of temperature and particle size on the filter-feeding rate of brine shrimp *Artemia franciscana* at different growth stages and stocking densities. *Aquaculture International*, 32(6): 7355–67
- Mejía JC, Mejía GC, Bridi R, Costa DO (2013) Salinity effects on the reproductive patterns of five coastal Pacific *Artemia franciscana* strains from Mexico. *International Journal of Science and Knowledge*, 2(1): 26–33
- Mremi PA (2011) Pond production of *Artemia* in a solar salt work in Kenya. Faculty of Bioscience Engineering, Ghent University, Ghent, Belgium
- Naegel LCA (1999) Controlled production of *Artemia* biomass using an inert commercial diet, compared with the microalgae *Chaetoceros*. *Aquacultural Engineering*, 21(1): 49–59
- Nevárez-Prado LO, Amaya-Olivas N, Sustaita-Rodríguez A, Rodríguez-Zapién J, Zúñiga-Rodríguez E, Cordova-Lozoya M, García-Triana A, Sandoval-Salas F, Hernández-Ochoa L (2022) Chemical composition and toxicity of extracts of *Fouquieria splendens* against *Artemia salina*. *AIMS Agriculture and Food*, 7(2)
- Ngarari MM, Hinzano SM, Opiyo MA, Rugendo DG, Midumbi DO, Okalo FA, Nyonje BM, Ngugi CC, Gatune CW (2024) Salinity tolerance, growth and survival of three *Artemia franciscana* (Kellogg, 1906) populations under laboratory conditions. *Aquaculture, Fish and Fisheries*, 4(2): e166
- Nguyen VH (2022) Use of *Artemia* cysts in crustacean hatcheries in the Mekong Delta, Vietnam

- Rahman MM, Sorgeloos P (2023) Brine shrimp *Artemia* pond culture in Cox's Bazar, Bangladesh. *World Aquaculture*, 54(2), June 2023. World Aquaculture Society
- Rahman MH, Roy TK, Alam MW, Islam MS, Hossen MS, AlBakky A, Begum N, Islam MS, Ismail Z, Idris AM (2025) Enhancement of *Artemia* biomass and cyst production using supplementary feeds: A preliminary study. *Scientific Reports*, 15(1): 41148
- Rasowo J, Radull J (1986) Inoculation of the brine shrimp *Artemia salina* in Kenya: Expected impact on aquaculture development. In Aquaculture research in the Africa Region. Proc. Afr. seminar on aquaculture. International Foundation for Science (IFS) Stockholm Sweden. Pudoc Wageningen, Netherlands 1986 pp. 54–59
- Sorgeloos P, Dhert P, Candreva P (2001) Use of the brine shrimp, *Artemia* spp., in marine fish larviculture. *Aquaculture*, 200(1–2): 147–159
- Stearns SC (2000) Life history evolution: Successes, limitations, and prospects. *Naturwissenschaften*, 87(11): 476–486
- Triantaphyllidis G, Abatzopoulos T, Sorgeloos P (1998) Review of the biogeography of the genus *Artemia* (Crustacea, Anostraca). *Journal of Biogeography*, 25(2): 213–226
- Triantaphyllidis GV, Pouloupoulou K, Abatzopoulos TJ, Pérez CA, Sorgeloos P (1995) International study on *Artemia* XLIX. Salinity effects on survival, maturity, growth, biometrics, reproductive and lifespan characteristics of a bisexual and a parthenogenetic population of *Artemia*. *Hydrobiologia*, 302(3): 215–227
- Van Stappen G (1996) Introduction, biology and ecology of *Artemia*. In Manual on the production and use of live food for aquaculture. FAO 361, 9–106
- Wang W, Ma Z, Li W, Xue Y, Moss AS, Wu M (2024) Impact of β -Carotene enrichment on carotenoid composition and gene expression in *Artemia metanauplii*. *Metabolites*, 14(12): 676
- Yang JY, Sun SC (2023) Combined effects of temperature, photoperiod, and salinity on reproduction of the brine shrimp *Artemia sinica* (Crustacea: Anostraca). *PeerJ*, 11: e15945

Socio-economic determinants and user perceptions of solar cooling and drying (SolCoolDry) technology for fish preservation in Kwale County, Kenya

Josephine Marigu^{1*}, Morine M. Ngarari¹, James Mwaluma¹, Peter Oduor–Odote¹, Raymond Ruwa¹, Winnie Jefwa¹, Derrick Gitari¹, Immaculate Kinyua¹, Maureen Kinyua¹, Rael Achieng¹, Linus Kosambo², Huxley Makonde³

¹ Kenya Marine and Fisheries Research Institute (KMFRI), P.O. Box 81651–80100, Mombasa.

² Kenya Industrial Research and Development Institute (KIRDI), P.O. Box 30650–00100, Nairobi, Kenya

³ Technical University of Mombasa (TUM), P.O. Box 30650–00100, Mombasa, Kenya

*Corresponding author E-mail: jmarigu@kmfri.go.ke

Abstract

Globally, food loss and waste (FLW) in fish value chains is estimated at 35% of total production and remains a major constraint, particularly in developing countries with inadequate modern preservation technologies. The Solar Cooling and Drying (SolCoolDry) system, a renewable-energy-based fish preservation technology that combines solar-powered ice-flake production and improved drying, was developed to reduce post-harvest fish losses (PHFLs). This study profiled the socio-economic status of direct SolCoolDry technology recipients and assessed their perceptions on fish preservation technologies in selected areas within Kwale County. Data were collected using semi-structured questionnaires administered to fishermen, fish farmers, fish traders and fish processors across four landing sites. Findings indicate that fisheries-related activities remain the primary livelihood for most respondents, whose education levels are generally low. Traditional fish preservation practices such as sun drying and smoking were dominant, exposing fish to contamination and spoilage. Respondents expressed positive perceptions toward the SolCoolDry system, particularly on its potential to improve fish preservation and reduce PHFLs. However, insufficient ice production capacity and limited drying space during peak landing periods were reported. The results highlight the importance of improving post-harvest infrastructure and promoting climate-smart preservation technologies to reduce FLW, improve fish quality and enhance coastal fisheries communities' livelihoods.

Keywords: Post-harvest fish losses (PHFLs), fish value chain, food loss and waste (FLW), SolCoolDry, fish preservation, socioeconomics

Introduction

The global population continues to grow rapidly, placing increasing pressure on food production systems. The world's population was estimated at 7.8 billion in 2020 and is projected to exceed 8.5 billion by 2030 (UN DESA, 2019). It is estimated that nearly 98% of this population growth will occur in developing countries, particularly in Africa and Asia (Ryskov and Shlyakhtin, 2023). The

increasing population in developing countries such as Kenya, where food insecurity remains a major concern (United Nations, 2019) is expected to significantly increase the demand for affordable and accessible nutritious sources of animal protein (Omukoto *et al.*, 2024). These developing countries continue to grapple with constraints in agricultural productivity due to declining soil fertility, climate change and limited technological advancement (Farah *et al.*, 2025).

In this context, aquatic foods have become increasingly important for food and nutrition security. Fish provides high-quality protein, essential fatty acids, vitamins and micronutrients; and is often more affordable than other animal proteins in tropical countries (Mohanty *et al.*, 2017; Pradeepkiran, 2019). According to FAO (2024), fish provide nearly 20% of the average per capita intake of animal protein for over 3.2 billion people worldwide. Fisheries and aquaculture also contribute significantly to employment, income generation and livelihoods for millions of people, particularly in coastal and rural communities in developing countries (Béné *et al.*, 2015; Martuscelli, 2022; FAO, 2024).

Despite its high nutritional and economic value, fish is highly perishable due to its high moisture content, near-neutral pH, enzymatic activity and spoilage microorganisms that accelerate spoilage immediately after harvest (Huss, 1995; Tavares *et al.*, 2021; Nie *et al.*, 2022). In 2011, FAO estimated that about 35% of aquatic foods are lost or wasted globally, one of the highest rates among major food groups (FAO, 2011; Kruijsen *et al.*, 2020b; Love *et al.*, 2023). More recent studies approximate post-harvest fish losses at 20–75%, often higher in low- and middle-income countries. This is mainly attributable to poor handling, inefficient preservation technologies and inadequate cold chain infrastructure (Keerthana, 2022; Abelti and Teka, 2024).

Post-harvest fish losses (PHFLs) occur at various stages along the fisheries value chain, from fishing and landing to transport, processing, and marketing, and are particularly pronounced in small-scale fisheries in sub-Saharan Africa. Regional studies estimate that PHFLs in Africa can reach about one-third of total production, with quality losses often exceeding physical losses in some supply chains (Tesfay and Teferi, 2017; Kaminski *et al.*, 2020; Abelti and Teka, 2024). These losses stem from high ambient temperatures in this tropical region, long fishing and hauling times, poor handling, limited use of ice for preservation and severe inadequacies in fish storage, processing and transport infrastructure (Mramba and Mkude, 2022; Abelti and Teka, 2024). As a result, most fish that reaches local

markets in sub-Saharan Africa is of low quality and thus fetches lower prices—compromising food safety and imposing significant income losses on fishing communities and national food systems (Gyan *et al.*, 2020; Kaminski *et al.*, 2020; Torell *et al.*, 2020).

The Kenyan coast is rich in valuable marine fishery resources, which provide an essential source of income and employment while enhancing food and nutritional security for up to 80% of local communities (Fondo *et al.*, 2016; Aloo *et al.*, 2014). This is particularly significant given the region's high ambient temperatures, seasonal rainfall variability, and limited agricultural productivity, which collectively heighten dependence on marine resources as a primary source of income. In Kwale County, coastal fisheries generate an estimated KES 182 million (≈US\$2.2 million) annually, but their sustainability is threatened by climate variability, habitat degradation and high fishing pressure (Ahmed *et al.*, 2022).

Traditionally, capture fisheries have been the primary source of fish supply. However, declining fish stocks, increased fishing pressure and environmental or climatic changes have reduced catches in recent decades, prompting the development of aquaculture and mariculture initiatives to help bridge the growing gap between fish demand and supply (Onyango and Munguti, 2016). Despite these efforts, substantial post-harvest losses continue to occur along fish value chains in coastal Kenya, significantly reducing the quantity and quality of fish available for consumption and sale (Owaga *et al.*, 2011). These losses are largely attributed to inadequate fish preservation facilities and poor handling techniques such as drying fish on the ground, which expose fish to contamination, insect infestation, and rapid spoilage (Odoli *et al.*, 2019).

To address these challenges, innovative and sustainable climate-smart fish preservation technologies are increasingly being promoted within small-scale fisheries in Kenya (Odoli *et al.*, 2019; Manyise *et al.*, 2023). Solar-powered fish preservation systems, in particular, have gained attention as environmentally friendly and cost-effective solutions capable of en-

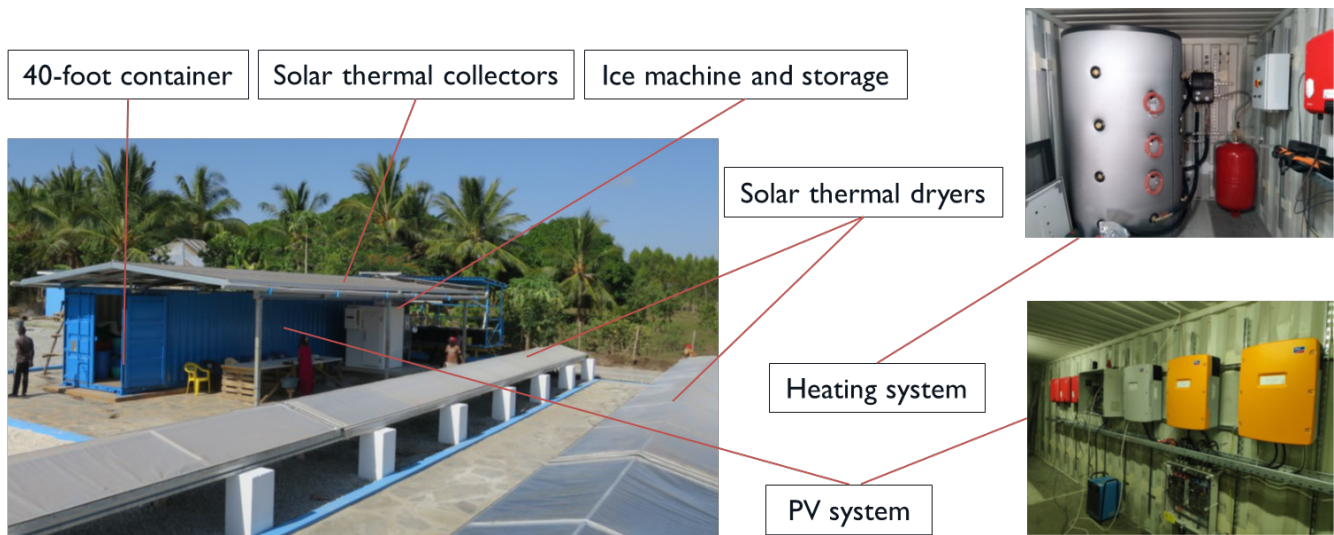


Figure 1. The Solar Cooling and Drying (SolCoolDry) system installed at Mwazaro, Kwale County (Source: Authors).

hancing product quality while simultaneously reducing post-harvest losses (Puri *et al.*, 2023). Compared to traditional sun drying of fish on the ground, improved solar drying technologies offer enclosed drying environments that shield the product from contaminants and adverse weather conditions while achieving shorter drying times, higher drying efficiency, and superior organoleptic quality in the final product (Bala and Mondol, 2001; Mustapha *et al.*, 2014). Similarly, reliable access to ice for preservation plays a critical role in maintaining fish quality by enabling prompt lowering of fish temperature, thereby retarding microbial proliferation and suppressing the enzymatic and autolytic reactions that drive early-stage spoilage (Huss, 1995; Gram and Huss, 1996).

The climate-smart SolCoolDry system

The SolCoolDry system (Fig. 1), situated in Mwazaro, Kwale County, was developed through a collaborative research initiative between three Kenyan institutions—Kenya Marine and Fisheries Research Institute (KMFRI), Kenya Industrial Research and Development Institute (KIRDI) and Technical University of Mombasa (TUM)—and two German partners, Fraunhofer Institute for Solar Energy Systems and Innotech Ingenieursgesellschaft mbH (Morgenstern & Pfanner, 2024). The system represents an integrated renewable-energy-based solution aimed at reducing fish post-harvest losses through the

production of clean ice flakes for fish preservation while simultaneously providing improved drying facilities for fish and other agricultural products. It combines the use of solar-powered cooling and drying technologies, providing a 100% solar-powered off-grid solution (Morgenstern *et al.*, 2023).

The technology consists of solar tunnel dryers and a solar thermal heating system (Fig. 1) which enables drying to continue during night hours, thereby reducing drying time and preventing rewetting or spoilage of partially dried products. The system seeks to enhance fish preservation, extend shelf life and improve the overall quality of fish products for local and regional markets. The SolCoolDry system has the potential to increase economic returns for fishers, traders and processors while strengthening food security and livelihood resilience among coastal communities.

Following its installation, the SolCoolDry system was formally transferred to community members in Mwazaro, who now operate it semi-autonomously with remote technical support from the implementing partners, and has since been running as designed (Morgenstern and Pfanner, 2024). This transition to community-based operation underscores the importance of understanding the socio-economic dynamics of the value chain actors who interact with the system. Characterizing these actors and understanding

their experiences is essential for evaluating the effectiveness and sustainability of new preservation technologies and identifying opportunities for improvement. It also provides valuable insights into the technology recipients' livelihood strategies, capacity to adopt innovations and the potential impacts of technological interventions on fisheries value chains.

The present study therefore aimed to assess the socio-economic characteristics of direct users of the SolCoolDry technology, including fishermen, fish farmers, fish traders and fish processors in selected areas of Kwale County, Kenya. The study further evaluated users' perceptions and experiences with the SolCoolDry fish preservation system and assessed the production potential of raw fisheries resources available to technology users in the study area. The findings provide insights into the adoption and effective-

ness of the SolCoolDry system and its potential to reduce post-harvest losses and strengthen the fisheries value chain in coastal Kenya.

Materials and Methods

Study area

The study was conducted at selected sites located in Kwale County at the South Coast of Kenya i.e. Mwazaro, Shimoni, Gazi, Kibuyuni (Fig. 2). The coastal region in Kenya is situated in a hot tropical zone, with its climatic regime being largely influenced by the North East and South East monsoon seasons (GoK, 2017). Site selection was dependent on the predominant activities conducted at the respective site (Table 1) and proximity to the Mwazaro BMU site where the SolCoolDry Research, Innovation and Business hub is located.

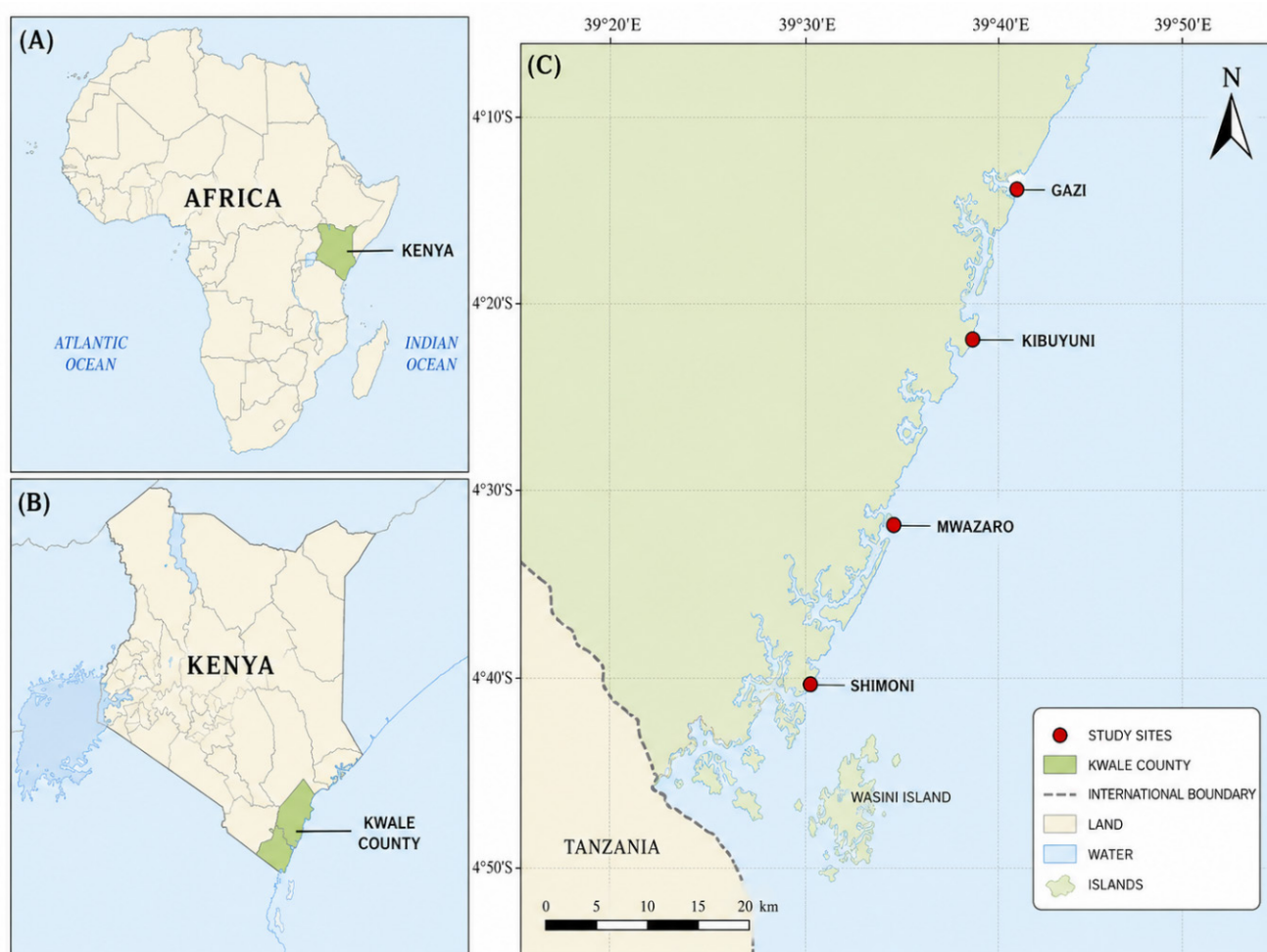


Figure 2. The study area located in Kwale County at the South Coast of Kenya i.e., Mwazaro, Shimoni, Gazi, Kibuyuni.

Table 1. Predominant activities for site selection and proximity to the Mwazaro BMU site where the SolCoolDry Research, Innovation and Business hub is located.

Site	Predominant activities
Mwazaro	Seaweed farming, Pond culture; Capture fisheries; Fish and seaweed processing
Shimoni	Capture fisheries; Fish processing
Gazi	Capture fisheries; Seaweed farming; Pond culture; Fish and seaweed processing
Kibuyuni	Cage culture; Seaweed farming and processing; Fish processing

Study design and data collection

Multi-stage random sampling procedure was used to select respondents for the study as guided by Hamed (2016). In the first stage, purposive sampling was used to select Kwale County because that is where the SolCoolDry facility is located. The second stage involved the selection of the four study sites based on their predominant activities. Lastly, the third stage involved the random selection of thirty (30) value chain actors from each site, repre-

senting each node of the value chain, making a total of one hundred and twenty (120) respondents targeted in this study.

Primary data was collected using a semi-structured questionnaire designed and administered through interviewing the respondents. The questionnaire was divided into two sections. The first section covered the socio-economic characterization of the SolCoolDry technology recipients, while the second section covered the respondents' daily activities in fish value chains and the significance of the SolCoolDry facility in those activities. The respondents represented key value chain actors in the fisheries sector including fishermen, fish farmers, seaweed farmers, processors and traders who were actively involved in these activities and were able to provide sufficient information on their respective areas of engagement. After a detailed briefing of the respondents on the objective of the survey to ensure provision of accurate and relevant information, the questionnaires were then administered individually (Fig. 3) using the local language. Confidentiality of the respondents' information was maintained throughout the study, and the data were anonymized during analysis to protect their privacy.

Data analysis

Data from the completed questionnaires were entered into Microsoft Excel for cleaning and subsequent analysis. Open-ended questions were coded before analysis. Descriptive statistics such as frequencies, percentages, means, and standard deviations were computed to profile the technology recipients.



Figure 3. KMFRI researchers administering the questionnaires to value chain actors at Mwazaro during the survey (Source: Authors).

Results and discussion

Demographic characteristics of respondents

The result of this study as shown in Figure 4a showed a relatively balanced gender representation among the respondents, with women accounting for 51% and men 49%. This finding highlights the important role played by women in fisheries value chains, particularly in fish post-harvest activities such as processing, drying and marketing. Similar patterns have been observed in small-scale fisheries across Africa where women dominate post-harvest activities while men are more involved in harvesting activities (Allison and Ellis, 2001; FAO, 2020). The active participation of women in the fisheries sector underscores the importance of inclusive technological interventions such as the Sol-CoolDry system that can improve productivity and livelihoods of both men and women.

The age distribution of respondents (Fig. 4b) indicated that most participants (63%) were within the economically active age group of 30 to 49 years. However, a smaller proportion of respondents (11%) were below the age of 30 years while about 30 (26%) were above 49 years. This demographic structure suggests that fisheries-related activities in the study area are largely undertaken by individuals in their productive years, which may positively influence the adoption and sustainability of improved fish preservation technologies. According to Rogers (2013), younger and middle-aged individuals are gen-

erally more receptive to technological innovations compared to older populations. Therefore, the demographic structure of the respondents may provide favorable conditions for the adoption of improved fish preservation technologies such as SolCoolDry.

Household sizes among respondents (Fig. 5a) were relatively large, with most households consisting of six to ten members. Approximately 36 respondents reported supporting between one and five dependents, while about 10 respondents had between 11 and 20 dependents. This implies that many people depend on the fisheries sector in the region. Large household sizes are common in rural coastal communities where livelihoods often depend on natural resource-based activities such as fishing and small-scale aquaculture. However, large household sizes may also increase pressure on fisheries resources and household incomes, thereby underscoring the importance of reducing post-harvest losses and improving the profitability of fisheries activities (Allison and Ellis, 2001).

The level of education among respondents was relatively low. More than half (52%) had only primary school education while about 25% had no formal education. Respondents with secondary education accounted for 20% while only 2% had attained tertiary education. Low levels of formal education have been widely reported in artisanal fisheries and may influence the adoption of improved technologies and best practices within the fisheries sector (Ogello *et al.*, 2018).

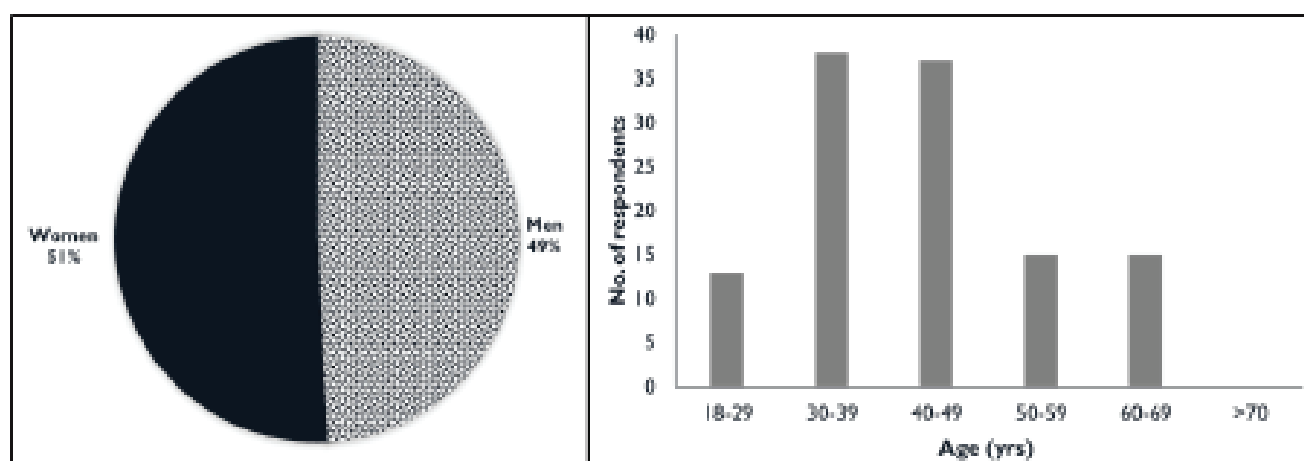


Figure 4. Demographic representation of value chain actors engaged by gender (a) and age (b).

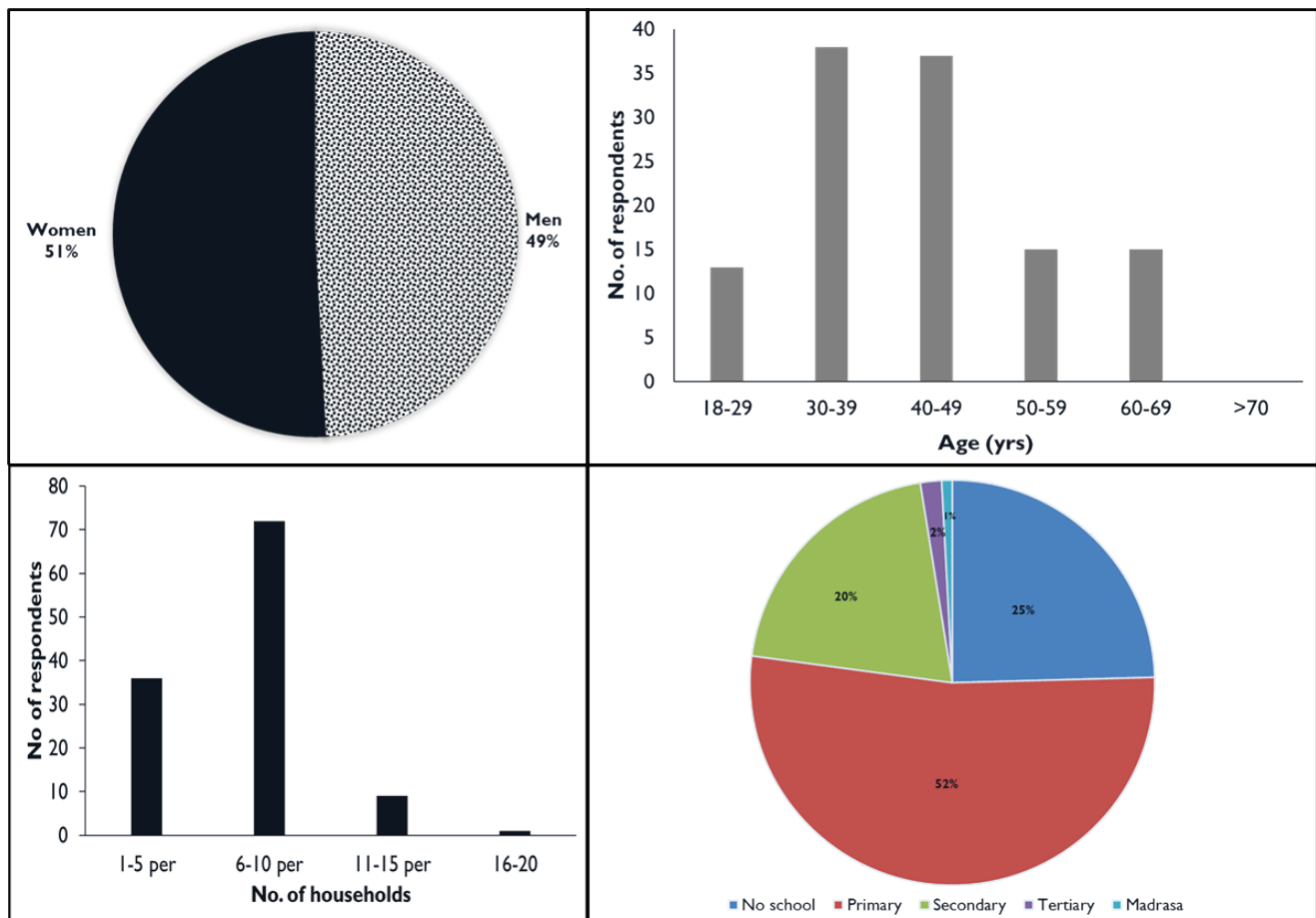


Figure 5. Demographic information showing the household sizes (a) and level of education (b) of the interviewed respondents.

Limited formal education may restrict access to technical knowledge, financial resources and training opportunities that are a requirement for adopting improved fish preservation technologies. These findings highlight the need for targeted training and awareness programs to support the effective adoption and utilization of innovations such as the SolCoolDry system.

Occupational structure of technology recipients

The occupational distribution of respondents showed that fishermen constituted the largest group (31%), followed by fish farmers (29%), while fish traders and processors each accounted for 20% (Fig. 6a). This distribution reflects the diversity of actors involved in the fisheries value chain within the study area, ranging from production, processing and marketing activities. Similar patterns have been observed in many small-scale fisheries systems where multiple stakeholders depend on fisheries resources for income and food security (FAO, 2020).

The majority of the respondents (75%) reported having relatively less than ten years of experience in their primary occupations (Figure 6b). This suggests that many individuals have recently entered the fisheries sector. This trend could be associated with declining agricultural productivity and limited employment opportunities in rural coastal areas, prompting households to diversify their livelihoods by engaging in fisheries-related activities. Livelihood diversification is a common strategy among many coastal communities seeking to reduce vulnerability to economic and environmental uncertainties (Béné, 2006).

Additionally, 65% of the respondents reported engaging in alternative economic activities (Fig. 6c) such as crop farming (21), casual labor (13) and small businesses (28). This diversification of livelihoods is common among small-scale fishing communities as it enhances their economic resilience to seasonal variability in fish catches and income fluctuations (Béné, 2006). However,

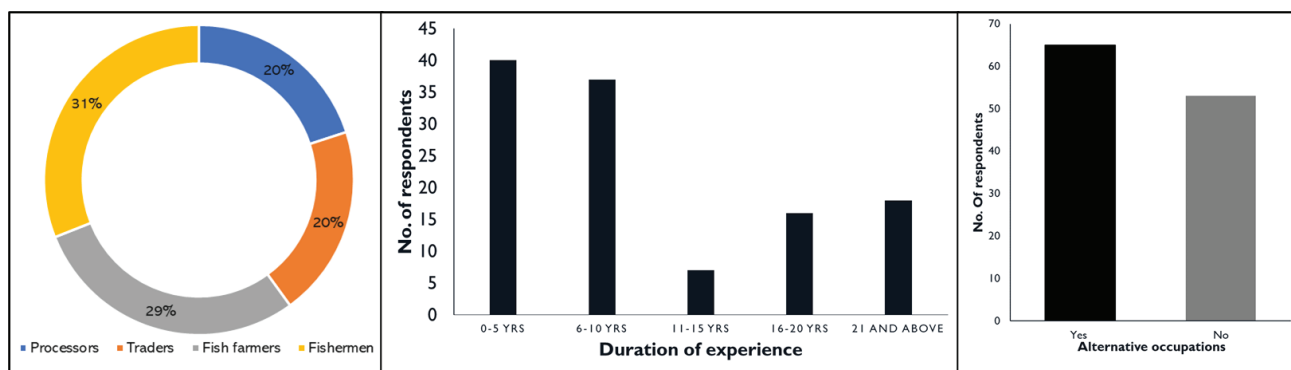


Figure 6. Distribution of respondents by roles played in the value chain (a), duration of experience in the fisheries activities (b) and alternative livelihoods (c).

er, engaging in multiple livelihood activities may also limit the amount of time and resources available for an individual to invest in adopting and effectively utilizing improved fish preservation technologies.

Household energy sources

The household energy sources used by respondents are presented in Figure 7. Woodfuel was the most commonly reported energy source (37%), followed by electricity (28%) and solar energy (21%), with kerosene (11%), LPG (2%) and other sources (1%) accounting for the remain-

der. These findings reveal that nearly half of respondents (48%) rely on biomass-based or conventional fossil fuel energy sources, reflecting the limited access to cleaner energy alternatives that is characteristic of rural coastal communities in Kenya (Karekezi *et al.*, 2012). The continued dependence on wood-fuel in particular has well-documented implications for deforestation, carbon emissions and indoor air pollution, underscoring the low level of transition toward climate-smart energy solutions among a substantial proportion of the study population (IEA, 2023).

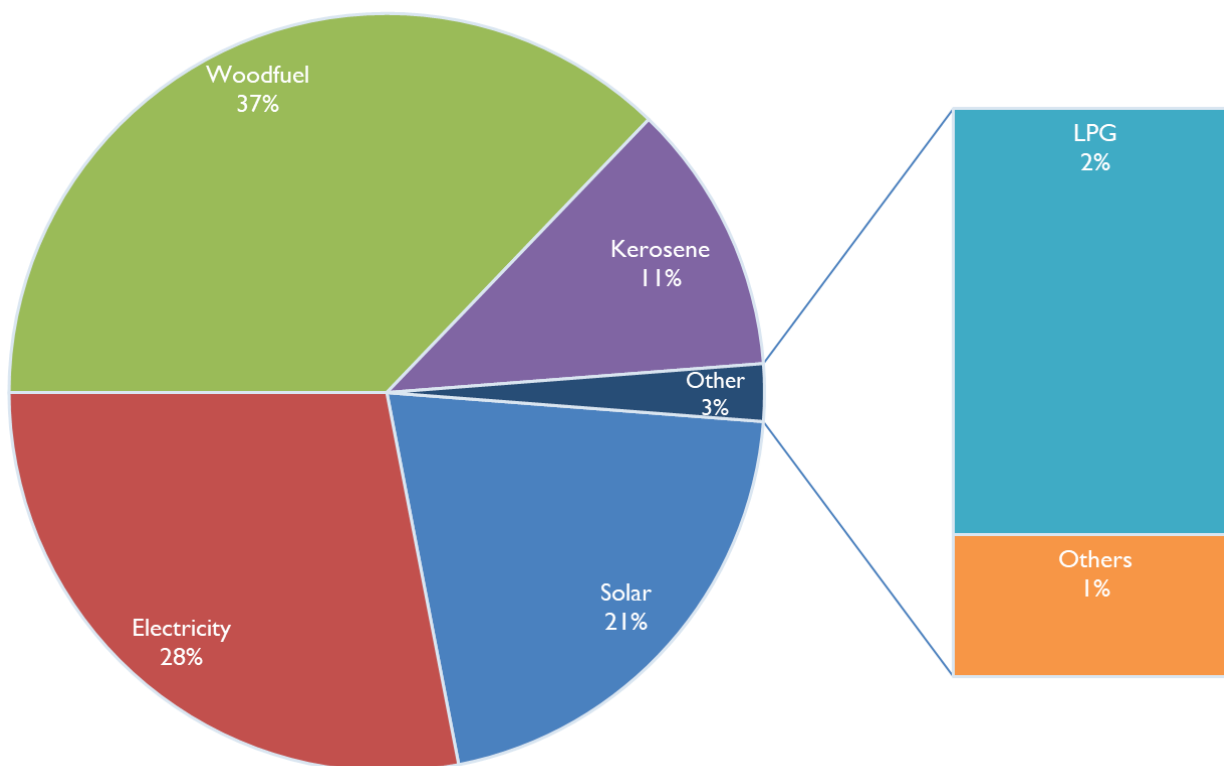


Figure 7. Energy sources used in households of survey respondents.

Nonetheless, the 21% of respondents already using solar energy at the household level indicates prior exposure to and acceptance of solar-based technologies within the community. This existing familiarity may lower practical and psychological barriers to adopting the SolCool-Dry system and early solar adopters could serve as important change agents in promoting wider uptake among their peers (Rogers, 2013). More broadly, transitioning fish preservation activities from conventional energy-dependent methods to solar-powered solutions such as SolCoolDry would not only reduce post-harvest losses but also contribute to decarbonizing the fisheries value chain and alleviating pressure on forest resources (FAO, 2022; Puri *et al.*, 2023). These findings highlight the need for targeted awareness programmes that sensitize value chain actors to the environmental and economic benefits of renewable energy, thereby creating a more enabling environment for the sustained utilization of climate-smart technologies.

Aggregation of direct technology recipients

The direct technology recipients were mainly organized into Beach Management Units (BMUs), which play an important role in coordinating fisheries-related activities and resource sharing among local communities. The groups interviewed that were within the BMUs included Bati Seaweed Farmers, Kibuyuni Seaweed Farmers Cooperative, Baraka Conservation Group, Imani Seaweed Farmers and Mwazaro Fish Farmers. BMUs in the coastal region of Kenya facilitate collective access to shared resources such as fishing grounds, drying racks, office space, processing areas and storage facilities at landing sites. Approximately 62.5% of the respondents reported using community-owned land or fishing grounds for their activities. Community-based resource management institutions such as BMUs have been widely recognized for their role in promoting sustainable fisheries management and improving the livelihoods of small-scale fishing communities (FAO, 2020).

The organisation of recipients within established BMU structures presents notable advantages for the adoption and sustainability of the SolCool-

Dry system as a community-owned innovation. Collective governance can facilitate equitable access, distribute operational and maintenance responsibilities among members, and foster the shared sense of ownership that is critical for sustaining community-based interventions beyond the initial implementation phase (Ostrom, 1990; Béné, 2006). However, community-based technology management also carries inherent risks. Unequal power dynamics, varying member commitment and potential conflicts over benefit-sharing could undermine effective utilization of the system if not proactively managed (Pomeroy and Berkes, 1997). The low levels of formal education recorded among respondents may further limit the technical capacity of community members to independently operate and maintain the system without sustained external support. These considerations highlight the importance of embedding transparent governance frameworks, structured capacity building and long-term technical backstopping arrangements into the operational model of the SolCool-Dry system to safeguard its continued functionality and community benefit.

Seaweed farming and fisheries and production capacity

Seaweed farming constituted an important livelihood activity in the study area. About 60% of the seaweed farmers cultivated only *Eucheuma spinosum*, while 37% cultured both *E. spinosum* and *Kappaphycus cottonii*. However, *E. spinosum* remained the dominant species, accounting for approximately 80–90% of production. In Kibuyuni, the average seaweed harvest was approximately 1,000 kg per farmer per season, whereas Mwazaro and Gazi recorded lower average harvests of about 500 kg per farmer per season (Fig. 6a).

Fishers across the study sites targeted different fish species and recorded varying catch volumes (Fig. 6b). In Gazi, the main catch consisted of sardines together with other mixed fish species, while fishers in Kibuyuni, Shimoni and Mwazaro mostly caught mixed fish species. Fishing activities were conducted both inshore and offshore. Catch volumes varied considerably between sites, with Gazi recording the highest average catch of approxi-

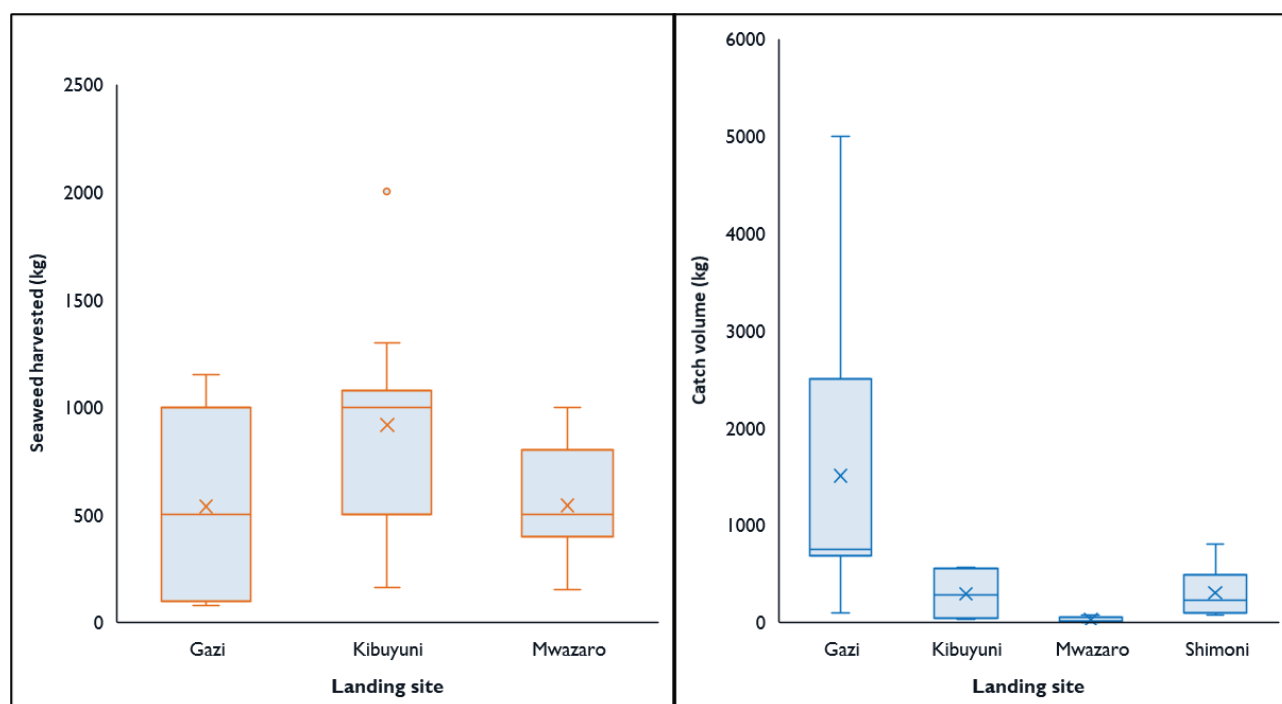


Figure 8. Production volumes of seaweeds (a) and fish (b) at the selected landing sites

mately 1,500 kg, followed by Shimoni (300 kg) and Kibuyuni (290 kg). Mwazaro recorded the lowest average catch at approximately 25 kg. Variations in catch volumes among sites may be attributed to differences in fishing effort, fishing gears, access to fishing grounds and environmental conditions. Similar spatial variations in fisheries productivity have been reported in many coastal fisheries systems (FAO, 2020) and illustrate the need for effective post-harvest technologies to mitigate against post-harvest losses, particularly during bumper-harvest seasons.

Post-harvest handling practices varied among the different fisheries value chain actors (Fig. 7). For seaweed farmers, post-harvest handling begins immediately after harvesting and involves sorting the seaweed by species and quality, followed by solar drying on raised perforated wooden racks before packaging for sale. Some farmers also process seaweed into value-added products such as seaweed salads, soaps, lotions, shampoos and powders in order to obtain higher market prices compared to raw dried seaweed.

For capture fisheries, post-harvest handling begins at sea, where fish are often gutted and cleaned before landing. After landing, fish may be sold directly to commercial traders, middle-

men or small-scale traders. Commercial traders usually clean, chill or freeze the fish before distribution. Small-scale processors, commonly known locally as “*Mama Karanga*,” typically gut, descale and fry fish before selling them to consumers. Sardines undergo a slightly different post-harvest process that involves cleaning, blanching and drying. Women play a key roles in the fish value chain, particularly in post-harvest processing activities.

Post-harvest losses encountered

The proportion of respondents reporting experience of post-harvest losses varied across value chain actor groups (Figure 8). Fish traders recorded the lowest incidence of post-harvest losses, with only 13% reporting having experienced losses in their activities, followed by fish processors at 21%. In contrast, a markedly higher proportion of fishers (59%) and seaweed farmers (55%) reported having experienced post-harvest losses, highlighting the greater vulnerability of primary producers to post-harvest loss events. High post-harvest losses are a common challenge in small-scale fisheries, particularly in tropical regions where high temperatures accelerate spoilage and preservation infrastructure is limited (Diei-Ouadi and Mgawe, 2011). The



Figure 9. Value chain activities undertaken by different actor groups for fish and seaweed in the study area. Steps highlighted in red practices actively employed by respondents to reduce post-harvest losses. (Source: Authors).

proportion of respondents reporting experience of post-harvest losses varied across value chain actor groups (Figure X). Fish traders recorded the lowest incidence of post-harvest losses, with only 13% reporting having experienced losses in their activities, followed by fish processors at 21%. In contrast, a markedly higher proportion of fishers (59%) and seaweed farmers (55%) reported having experienced post-harvest losses, highlighting the greater vulnerability of primary producers to post-harvest loss events. High post-harvest losses are a common challenge in small-scale fisheries, particularly in tropical regions where high ambient temperatures accelerate spoilage and preservation infrastructure is limited (Diei-Ouadi and Mgawe, 2011; FAO, 2020).

The higher incidence of losses among fishers is consistent with the well-documented practice of artisanal fishermen rarely using ice during fishing operations, resulting in fish being exposed to ambient temperatures for extended periods between capture and landing, thereby accelerating microbial spoilage and quality deteriora-

tion (Huss, 1995; Gram and Huss, 1996; Akande and Diei-Ouadi, 2010). Fish traders, by contrast, tend to experience fewer losses as they typically have better access to ice and cooler boxes and are motivated to maintain fish quality to guarantee better prices for their fish (Diei-Ouadi and Mgawe, 2011). The high proportion of fishers and seaweed farmers reporting post-harvest losses underscores the importance of improved accessibility to ice and drying infrastructure for preservation across all nodes in the value chain.

Across all four sampling sites, the majority of respondents reported having experienced post-harvest losses (Figure 10a), with Gazi recording the highest number of actors reporting losses (29), followed by Mwazaro (25), Kibuyuni (13) and Shimoni (9). This confirms that post-harvest losses are a pervasive challenge throughout the study area, irrespective of location. The higher incidence reported at Gazi may be attributable to the diversity of value chain activities undertaken there, including seaweed farming and sardine processing, which are par-

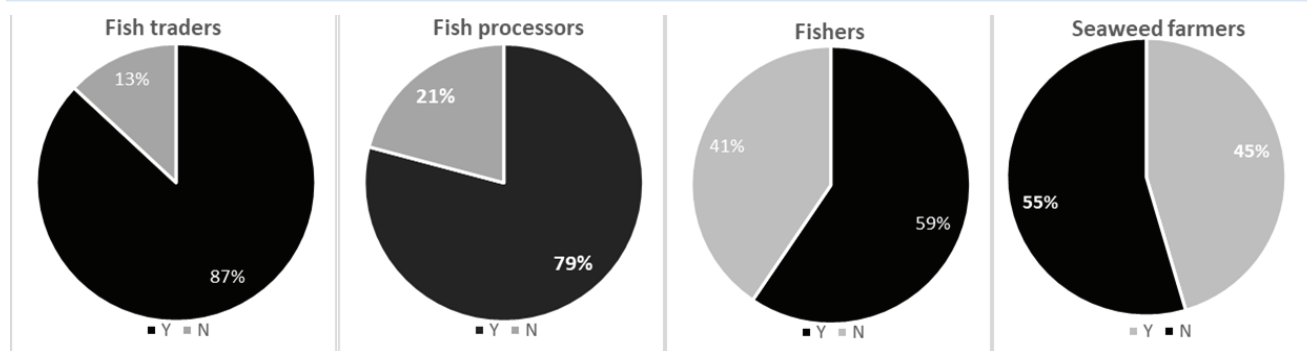


Figure 10. Proportion of value chain actors reporting experience of post-harvest losses in their fisheries activities in the study area. Y = Yes (reported experiencing losses); N = No (reported not experiencing losses).

ticularly susceptible to quality deterioration under ambient tropical conditions (Akande and Diei-Ouadi, 2010; Diei-Ouadi and Mgawe, 2011).

In terms of the magnitude of losses reported (Fig. 10b), the majority of respondents who experienced post-harvest losses indicated that these were relatively modest in scale, with the largest group (27) reporting losses of less than 5%, followed by 22 respondents reporting losses in the range of 6–10%. Fewer respondents reported losses in the higher ranges, with approximately 11 reporting losses exceeding 50%, and 10 reporting losses of 21–50%. The predominance of low-level losses is consistent with findings from other small-scale fisheries contexts in sub-Saharan Africa, where incremental quality losses – rather than total product loss – are more commonly reported, yet cumulatively represent significant economic and nutrition-

al losses across the value chain (Akande and Diei-Ouadi, 2010; FAO, 2020). However, the proportion of respondents reporting losses exceeding 50% is of particular concern, as such levels of loss can severely undermine the livelihoods and food security of affected households (Huss, 1995; Diei-Ouadi and Mgawe, 2011).

Existing fish preservation practices and their challenges

The results of the study revealed that fish preservation in the study area relies heavily on the use of ice, with 78% of fresh fish traders using ice blocks, flakes or freezers. Ice is widely recognized as one of the most effective methods for preserving fresh fish because it rapidly reduces the temperature of the fish and slows microbial growth and enzymatic spoilage processes (Huss, 1995; Gram and Huss, 1996). Traders reported obtaining ice from various sources including private ice dealers, the

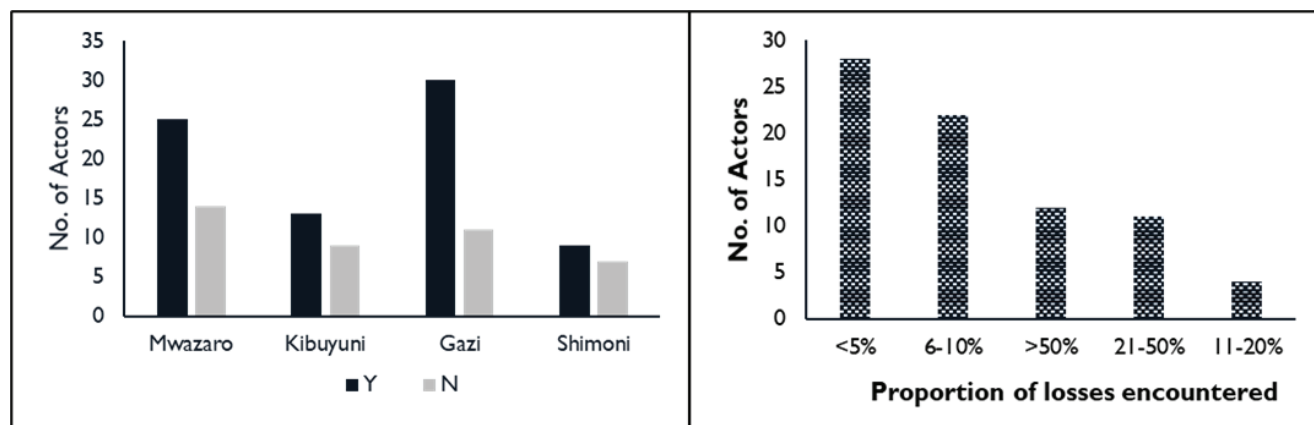


Figure 10. Post-harvest loss experience among value chain actors in the study area based on (a) the proportion of respondents at each sampling site who reported having experienced post-harvest losses (Y = yes; N = no) and (b) magnitude of losses reported by affected respondents.

Shimoni ice flake machine, rented freezer space and recently, the SolCooDry system at Mwazaro. The limited availability of ice and cold storage infrastructure was identified as a significant challenge by actors who handle fresh fish (Figure 11a). All fishers (100%) reported the absence of fishing vessels equipped with cold storage as a major constraint, while 95% cited inadequate local ice production, 89% reported a lack of cooler boxes and 83% of traders highlighted the high cost of hiring freezer space. These findings are consistent with broader evidence from small-scale fisheries in sub-Saharan Africa, where inadequate cold chain infrastructure is consistently identified as a primary driver of post-harvest losses (Akande and Diei-Ouadi, 2010; Diei-Ouadi and Mgawe, 2011). In tropical environments such as the Kenyan coast, where ambient temperatures are consistently high, the absence of reliable chilling infrastructure compounds the risk of rapid spoilage and

economic loss, underscoring the urgency of improving access to affordable and decentralised ice production and cold storage solutions (Huss, 1995; Puri *et al.*, 2023).

Fish drying was also identified as an important preservation method within the study area, particularly for sardines and seaweeds. However, significant infrastructure challenges were reported in the dried value chain (Figure 11b), with all processors (100%) citing inadequate shaded drying racks and 93% reporting the lack of reliable all-season drying systems as key constraints. Traditional open-air drying methods are highly dependent on favorable weather conditions and may expose fish products to contamination by dust, insects and microbial pathogens (Bala and Mondol, 2001; Mustapha *et al.*, 2014; Al-Ismaïli, 2021). The seasonal variability in drying conditions is also a particular

Key infrastructure and equipment challenges affecting post-harvest loss reduction across fresh and dried fisheries value chains in the study area

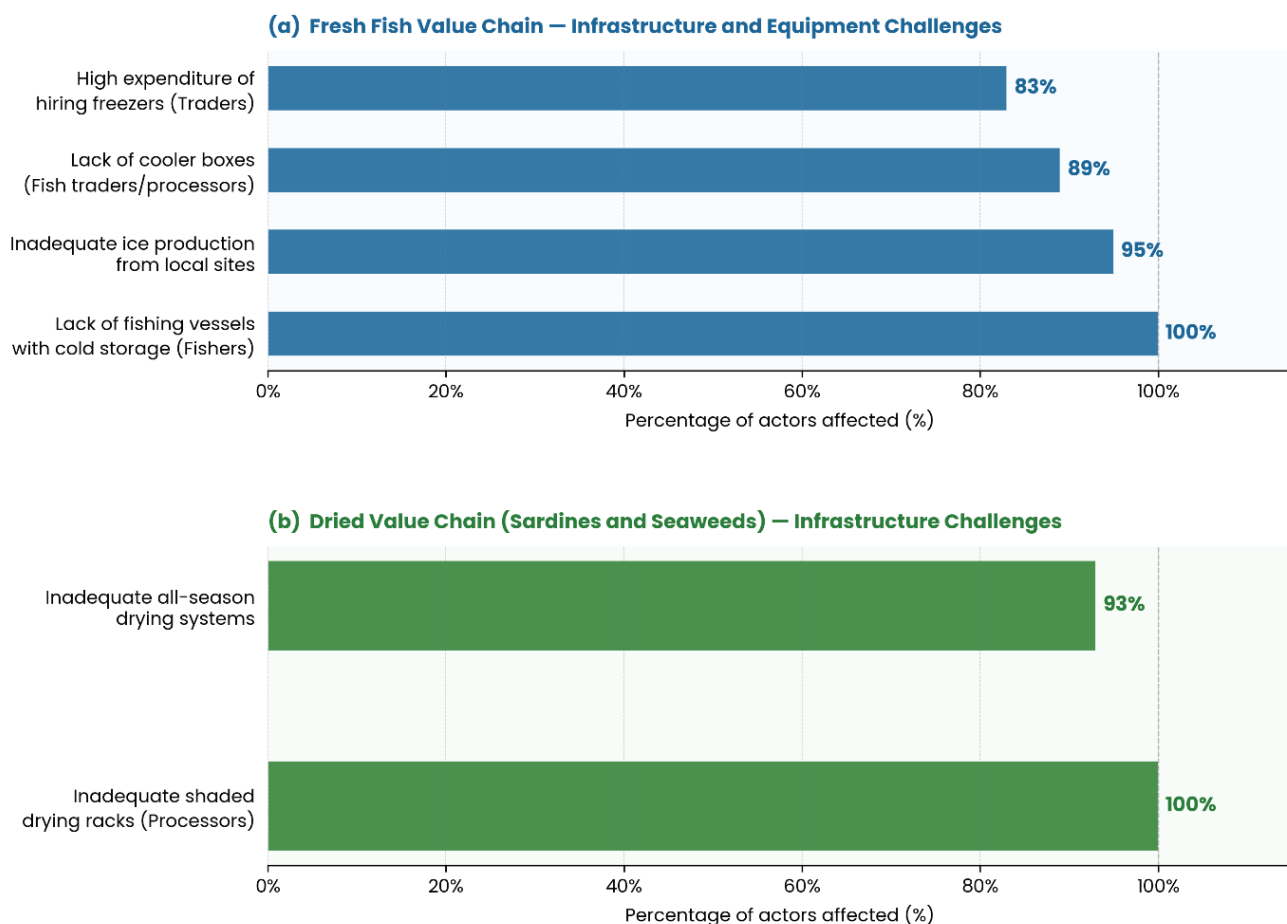


Figure 12. Challenges encountered by value chain actors during preservation to reduce post-harvest losses in fresh (a) and dried (b) fish and seaweed value chains.

concern in the coastal region, where rainfall and humidity can interrupt drying processes and lead to rewetting and spoilage of partially dried products. Improved solar drying technologies, such as the SolCoolDry system, directly address these limitations by providing enclosed, hygienic and weather-independent drying environments with extended drying capacity through solar thermal heating during night hours (Morgenstern *et al.*, 2023).

Awareness and utilization of the SolCoolDry system

Although the awareness of the SolCoolDry was relatively high among respondents (80%), only a small proportion (18%) reported using the facility (Fig. 12). Out of those that reported that they use the system, the majority (77%) obtained ice from the system while 23% used the drying section of the system. This gap between awareness and actual utilization were attributed to several factors including perceptions regarding the quality of ice produced by the system, its melting rate and the cost of accessing the service. Rogers

(2003) reported that technology adoption in rural communities is often influenced by perceived benefits, cost considerations and the compatibility of the technology with existing practices.

Perceptions of value chain actors on the SolCoolDry system

The perceptions of value chain actors towards the SolCoolDry system were broadly mixed, encompassing both positive attributes and areas of concern (Figure 13). On the positive side, respondents acknowledged the applicability of the system in reducing post-harvest losses, its ease of accessibility due to its location next to the road and the improved availability of ice provided by the system. These positive perceptions are consistent with the broader literature on community-based technology adoption, which identifies perceived usefulness and ease of access as key determinants of technology uptake in small-scale fisheries contexts (Rogers, 2013; Ostrom, 1990).

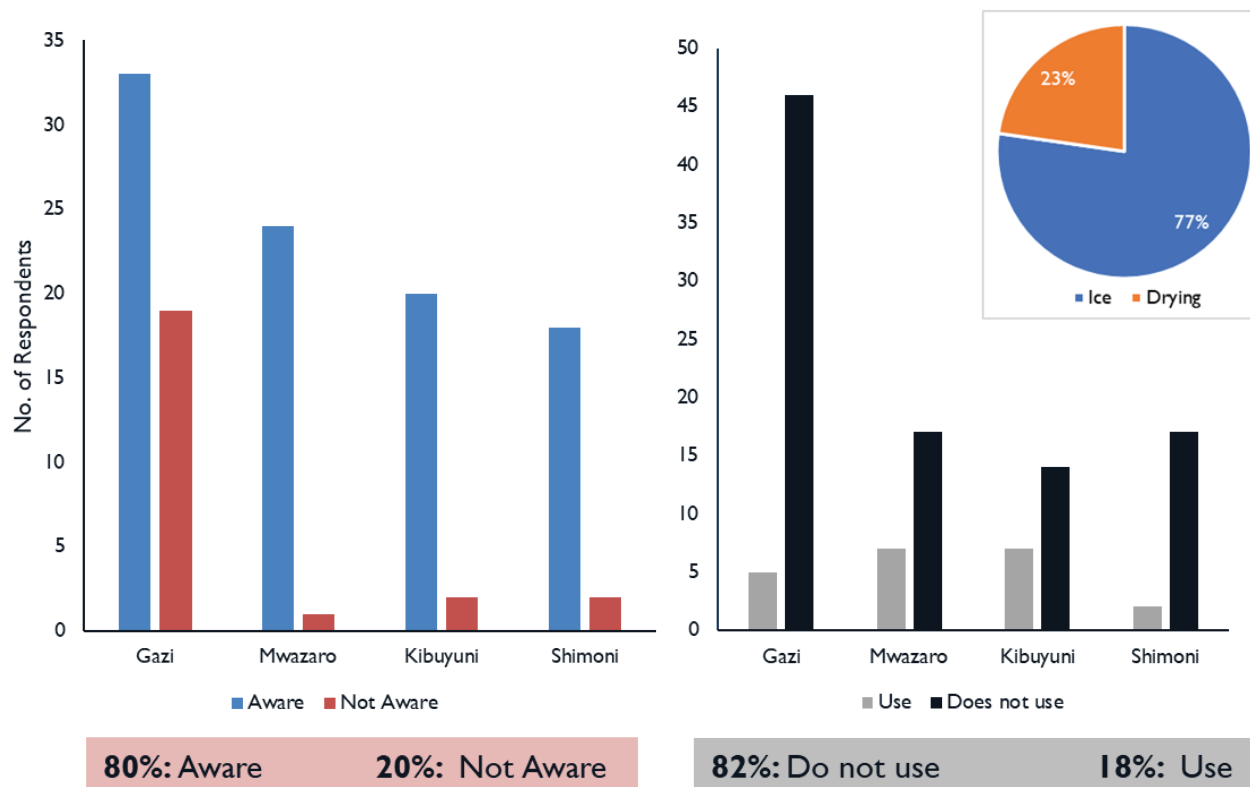
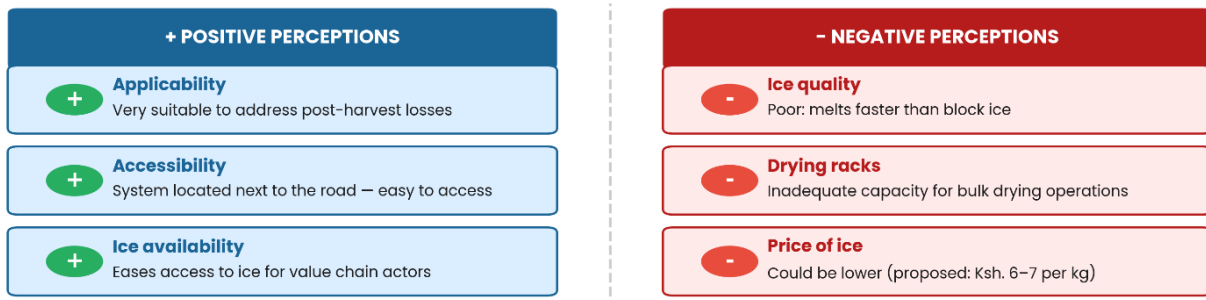


Figure 12. Awareness (a) and utilization (b) of the SolCoolDry system among value chain actors in the study area.

Community Perceptions of the SolCoolDry System

Positive and negative perceptions reported by value chain actors in the study area



Perceptions gathered from fishers, fish traders, processors and seaweed farmers engaged with the SolCoolDry system across Mwazaro, Kibuyuni, Gazi and Shimoni, Kwale County, Kenya.

Figure 14. Perceptions of value chain actors in the study area on the SolCoolDry system.

Despite these positive feedback perceptions, respondents raised several concerns that may be limiting wider utilization of the system. Users reported that flake ice produced by the SolCoolDry system melts faster than conventional block ice, suggesting a need for targeted training and demonstration on the well-documented advantages of flake ice, including its larger surface area that enables more rapid and uniform chilling of fish (Huss, 1995; FAO, 2020). The capacity of the drying racks was also considered inadequate for drying during peak seasons, and the current price of ice (Ksh. 10 per kg) was perceived as too high, with users proposing a rate of Ksh. 6–7 per kg as a more affordable alternative. Increasing the production capacity of the facility could improve accessibility and reduce costs, thereby encouraging greater adoption among fisheries stakeholders.

Conclusion and recommendations

The findings of this study highlight the critical importance of strengthening fish preservation infrastructure within coastal fisheries value chains. Inadequate access to ice, cold storage facilities and improved drying technologies continues to constrain the ability of fisheries stakeholders to maintain fish quality, reduce spoilage and maximize economic returns. These limitations contribute significantly to post-harvest losses, which remain a major challenge in many small-scale fisheries in developing countries. The introduction of innovative technologies such as the Sol-

CoolDry system offers a promising solution to these challenges. By integrating solar-powered cooling and drying technologies, the system provides a sustainable and environmentally friendly approach to fish preservation, particularly in off-grid coastal areas of Kenya where conventional energy sources are limited. The technology has the potential to significantly reduce post-harvest losses, extend product shelf life and improve the quality and market value of fish and other perishable products. In addition to technological improvements, the success and sustainability of such interventions depend on strong institutional support, effective stakeholder engagement and adequate capacity development among users. Enhancing collaboration between fisheries stakeholders, local governments, research institutions and development partners can facilitate the successful scaling and long-term adoption of renewable-energy-based preservation technologies. Overall, investments in integrated preservation technologies such as the SolCoolDry system can contribute not only to improved fish quality and market access but also to broader development goals, including enhanced food security, increased income opportunities, poverty reduction and the promotion of sustainable fisheries management in coastal communities. Based on the findings of this study, several strategic recommendations are proposed to enhance the effectiveness, sustainability and wider adoption of the SolCoolDry technology within coastal fisheries value chains.

First, there is a need to increase the daily ice production capacity of the system beyond the current 500 kg per day. The demand for ice among fishers, traders and processors often exceeds the available supply, particularly during periods of high fish landings. Expanding the ice production capacity would enable more users to preserve their fish immediately after landing, thereby maintaining product quality and reducing post-harvest losses. Previous studies have shown that adequate access to ice is one of the most effective methods of preserving fish quality during handling, transportation, and marketing (FAO, 2022; Huss, 1995).

Second, improvements in the quality and durability of the ice produced by the system are recommended. Enhancing ice density and reducing melting rates would extend its preservation potential during storage and transportation. High-quality ice that melts slowly helps maintain low temperatures for longer periods, thereby slowing microbial growth and enzymatic spoilage in fish (Gram and Dalgaard, 2002).

Third, the drying capacity of the SolCoolDry system should be expanded through the addition of more drying racks. During peak harvesting periods, especially when large quantities of sardines are landed or seaweed is harvested, the current drying space may not be sufficient to accommodate the volume of raw materials. Increasing drying capacity would allow fish processors and seaweed farmers to handle larger quantities of produce, improve processing efficiency and reduce the risk of spoilage associated with delays in drying.

Fourth, county governments and marine spatial planners should be actively involved during the site selection process when scaling up the SolCoolDry system. Early engagement with local authorities and planning institutions can help ensure that the technology is installed in strategically suitable locations with adequate infrastructure, accessibility and proximity to fishing communities. Such collaboration would also facilitate integration of the technology into broader coastal resource management and development plans.

Fifth, awareness creation initiatives should be strengthened to promote knowledge of the SolCoolDry system and its benefits among fisheries stakeholders. Many potential users may not be fully aware of the availability, functionality or advantages of the technology. Outreach programs, demonstration activities and community engagement initiatives can help increase adoption rates and encourage more fishers, traders and processors to utilize the system effectively.

Finally, capacity-building programs for direct technology recipients should be enhanced. Training in areas such as fish handling, hygienic processing, equipment maintenance and business management can improve the long-term sustainability of the technology. Strengthening the technical and managerial skills of users will ensure that the system is properly operated and maintained while maximizing its economic and social benefits.

References

- Abbas H, Zhao L, Gong X, Jiang M, Faiz T (2024) Environmental and economic influences of postharvest losses across the fish-food products supply chain in developing regions. *Environment, Development and Sustainability*, 26(11): 28335–28366 [https://doi.org/10.1007/s10668-023-03814-9]
- Abelti AL, Tekka TA (2024) Intervening fish post-harvest losses to narrow the gap between demand and supply: A review on magnitude of fish post-harvest losses in some Sub-Saharan African countries. *Aquaculture, Fish and Fisheries*, 4(2): e168 [https://doi.org/10.1002/aff.2.168]
- Ahmed H, Mwaura F, Thenya T, Kairo J (2022) Coastal and mangrove economic valuation associated fisheries and problems in Kwale County, Kenya. *Indo Pacific Journal of Ocean Life* [https://doi.org/10.13057/oceanlife/o060103]

- Ainomujuni S, Tinkasimire A (2025) Design and construction of a solar powered sil-ver-fish dryer for enhancing food security and economic livelihoods of fishing communities in East Africa. *East African Journal of Engineering*, 8(1): 179–189 [<https://doi.org/10.37284/eaje.8.1.2954>]
- Akinola A, Akinyemi A, Bolaji B (2006) Evaluation of traditional and solar fish drying systems towards enhancing fish storage and preservation in Nigeria
- Al-Ismaili A (2021) A review on solar drying of fish. *Journal of Agricultural and Marine Sciences*, 26(2): 1–12 [<https://doi.org/10.24200/jams.vol26iss2pp1-12>]
- Allegretti A, Omukoto J, Hicks C (2025) Food, power and agency: Revealing local post-harvest fisheries practices to improve food access from small-scale fisheries in coastal Kenya. *Maritime Studies*, 24 [<https://doi.org/10.1007/s40152-025-00402-7>]
- Allison EH, Ellis F (2001) The livelihoods approach and management of small-scale fisheries. *Marine Policy*, 25(5): 377–388 [[https://doi.org/10.1016/S0308-597X\(01\)00023-9](https://doi.org/10.1016/S0308-597X(01)00023-9)]
- Aloo P, Munga C, Kimani E, Ndegwa S (2014) A review of the status and potential of the coastal and marine fisheries resources in Kenya. *The International Journal of Marine Science*, 4
- Awuah GB, Ramaswamy HS, Economides A (2007) Thermal processing and quality: Principles and overview. *Chemical Engineering and Processing*, 46(6): 584–602
- Bala BK, Mondol MRA (2001) Experimental investigation on solar drying of fish using solar tunnel dryer. *Drying Technology*, 19(2): 427–436 [<https://doi.org/10.1081/DRT-100103936>]
- Béné C (2006) Small-scale fisheries: Assessing their contribution to rural livelihoods in developing countries (FAO Fisheries Circular No. 1008). Food and Agriculture Organization
- Béné C, Arthur R, Norbury H, Allison EH, Beveridge M, Bush S, Campling L, Leschen W, Little D, Squires D, Thilsted SH, Troell M, Williams M (2015) Contribution of fisheries and aquaculture to food security and poverty reduction: Assessing the current evidence. *World Development*, 79: 177–196 [<https://doi.org/10.1016/j.worlddev.2015.11.007>]
- Boretti A, Rosa L (2019) Reassessing the projections of the World Water Development Report. *NPJ Clean Water*, 2: Article 15
- Chen Q, Qian J, Yang H, Wu W (2022) Sustainable food cold chain logistics: From microenvironmental monitoring to global impact. *Comprehensive Reviews in Food Science and Food Safety*, 22(1) [<https://doi.org/10.1111/1541-4337.13014>]
- Deka D, Annapure U, Shirkole S, Thorat B (2022) Techno economics of solar assisted drying of small freshwater fish to ensure global nutritional security. *Drying Technology*
- Diei-Ouadi Y, Mgawe YI (2011) Post-harvest fish loss assessment in small-scale fisheries (FAO Fisheries and Aquaculture Technical Paper No. 559). Food and Agriculture Organization
- Dzoga M, Simatele D, Munga C, Yonge S (2020) Application of the DPSIR framework to coastal and marine fisheries management in Kenya. *Ocean Science Journal*, 55: 193–201 [<https://doi.org/10.1007/s12601-020-0013-y>]
- Food and Agriculture Organization (2011) Global food losses and food waste: Extent, causes and prevention. FAO
- Food and Agriculture Organization (2020a) Fishing for equality: How gender shapes fisheries and aquaculture. FAO
- Food and Agriculture Organization (2020b) The

- state of world fisheries and aquaculture 2020: Sustainability in action. FAO [https://doi.org/10.4060/ca9229en]
- Food and Agriculture Organization (2022a) The state of world fisheries and aquaculture 2022: Towards blue transformation. FAO [https://doi.org/10.4060/cc0461en]
- Food and Agriculture Organization (2022b) Renewable energy and reducing food loss and waste in fish value chains. FAO
- Food and Agriculture Organization (2024) The state of world fisheries and aquaculture 2024: Blue transformation in action. FAO [https://doi.org/10.4060/cd0683en]
- Farah AA, Mohamed MA, Musse OSH, Nor BA (2025) The multifaceted impact of climate change on agricultural productivity: A systematic literature review of SCOPUS-indexed studies (2015–2024). *Discover Sustainability*, 6(1): Article 150 [https://doi.org/10.1007/s43621-025-01229-2]
- Fondo E, Bitoun R, Kimani E, Munga C, Wambiji N, Ishmael N, Mwandikwa D, Busolo B, Okeri M, Abas S, Maina G, Devillers R (2025) The contributions of coastal small-scale fisheries toward the sustainable development goals: A Kenyan case study. *npj Ocean Sustainability*, 4: Article 17 [https://doi.org/10.1038/s44183-025-00117-6]
- Fondo E, Kimani E, Munga C, Aura C, Agembe S (2016) A review on Kenyan fisheries research: 1970–2009
- Ghaly AE, Dave D, Budge S, Brooks MS (2010) Fish spoilage mechanisms and preservation techniques: Review. *American Journal of Applied Sciences*, 7(7): 859–877 [https://doi.org/10.3844/ajassp.2010.859.877]
- Government of Kenya (2017) State of the coast report II: Enhancing integrated management of coastal and marine resources in Kenya. National Environment Management Authority
- Gram L, Huss HH (1996) Microbiological spoilage of fish and fish products. *International Journal of Food Microbiology*, 33(1): 121–137 [https://doi.org/10.1016/0168-1605(96)01134-8]
- Gyan W, Alhassan E, Asase A, Akongyuure D, Qi-Hui Y (2020) Assessment of post-harvest fish losses: The case study of Albert Bosomtwi–Sam fishing harbour, Western Region, Ghana. *Marine Policy*, 120: 104120 [https://doi.org/10.1016/j.marpol.2020.104120]
- Huss HH (1995) Quality and changes in fresh fish (FAO Fisheries Technical Paper No. 348). Food and Agriculture Organization
- International Energy Agency (2023) Africa energy outlook 2023. IEA
- Kaminski A, Cole S, Haddad R, Kefi A, Chilala A, Chisule G, Mukuka K, Longley C, Teoh S, Ward A (2020) Fish losses for whom? A gendered assessment of post-harvest losses in the Barotse Floodplain fishery, Zambia. *Sustainability*, 12(23): 10091 [https://doi.org/10.3390/su122310091]
- Karekezi S, McDade S, Boardman B, Kimani J (2012) Energy, poverty and development. In *Global energy assessment: Toward a sustainable future* (pp. 151–190). Cambridge University Press
- Kruijssen F, Tedesco I, Ward A, Pincus L, Love D, Thorne-Lyman AL (2020) Loss and waste in fish value chains: A review of the evidence from low and middle-income countries. *Global Food Security*, 26: 100434 [https://doi.org/10.1016/j.gfs.2020.100434]
- Love DC, Asche F, Fry J, Nguyen L, Gephardt J, Garlock TM, Jenkins LD, Anderson JL, Brown M, Viglia S, Nussbaumer EM, Neff R (2023) Aquatic food loss and waste rate in the United States is half of earlier estimates. *Nature Food*, 4(12): 1058–1069 [https://doi.org/10.1038/s43016-023-00881-z]

- Mercier S, Villeneuve S, Mondor M, Uysal I (2017) Time-temperature management along the food cold chain: A review of recent developments. *Comprehensive Reviews in Food Science and Food Safety*, 16(4): 647–667 [https://doi.org/10.1111/1541-4337.12269]
- Mohanty BP, Mahanty A, Ganguly S, Mitra T, Karunakaran D, Anandan R (2019) Nutritional composition of food fishes and their importance in providing food and nutritional security. *Food Chemistry*, 293: 561–570 [https://doi.org/10.1016/j.foodchem.2017.11.039]
- Nie X, Zhang R, Cheng L, Zhu W, Li S, Chen X (2022) Mechanisms underlying the deterioration of fish quality after harvest and methods of preservation. *Food Control*, 135: 108805 [https://doi.org/10.1016/j.foodcont.2021.108805]
- Odoli C, Owiti H, Kobingi N, Obiero M, Ogari Z, Mugo J, Nyamweya C, Aura C (2019) Post-harvest interventions in small-scale fisheries: A boon or bane to food and nutritional security in Kenya? *Food Security*, 11(4): 855–868 [https://doi.org/10.1007/s12571-019-00950-x]
- Ogello EO, Outa NO, Obiero KO, Kyule DN, Munguti JM (2018) The prospects of aquaculture development in Kenya: A review. *Scientific African*, 1: e00001 [https://doi.org/10.1016/j.sciaf.2018.e00001]
- Omukoto JO, Graham NAJ, Hicks CC (2024) Fish contributions toward nutritional security in Kenya. *Food Security*, 16(4): 951–971 [https://doi.org/10.1007/s12571-024-01459-8]
- Ostrom E (1990) *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press
- Pomeroy RS, Berkes F (1997) Two to tango: The role of government in fisheries co-management. *Marine Policy*, 21(5): 465–480 [https://doi.org/10.1016/S0308-597X(97)00017-1]
- Pradeepkiran JA (2019) Aquaculture role in global food security with nutritional value: A review. *Translational Animal Science*, 3(2): 903–910 [https://doi.org/10.1093/tas/txz012]
- Rogers EM (2013) *Diffusion of innovations* (5th ed.). Free Press
- Taherdoost H (2016) Sampling methods in research methodology: How to choose a sampling technique for research. *International Journal of Academic Research in Management*, 5(2): 18–27 [https://doi.org/10.2139/ssrn.3205035]
- Tavares J, Martins A, Fidalgo LG, Lima V, Amaral RA, Pinto CA, Silva AM, Saraiva JA (2021) Fresh fish degradation and advances in preservation using physical emerging technologies. *Foods*, 10(4): 780 [https://doi.org/10.3390/foods10040780]
- Tesfay S, Teferi M (2017) Assessment of fish post-harvest losses in Tekeze Dam and Lake Hashenge fishery associations: Northern Ethiopia. *Agriculture & Food Security*, 6: 4 [https://doi.org/10.1186/s40066-016-0081-5]
- Torell E, Jamu D, Kanyerere G, Chiwaula L, Nagoli J, Kambewa P, Brooks A, Freeman P (2020) Assessing the economic impacts of post-harvest fisheries losses in Malawi. *World Development Perspectives*, 19: 100224 [https://doi.org/10.1016/j.wdp.2020.100224]
- United Nations (2019) *World population prospects 2019: Highlights*. United Nations
- United Nations, Department of Economic and Social Affairs, Population Division (2019) *World population prospects 2019: Highlights* (ST/ESA/SER.A/423). United Nations
- Weeratunge N, Snyder KA, Sze CP (2010) Gleaner, fisher, trader, processor: Understanding gendered employment in fisheries and aquaculture. *Fish and Fisheries*, 11(4): 405–420 [https://doi.org/10.1111/j.1467-2979.2010.00368.x]

Authors' Instructions – The Kenya Aquatica

Editorial Policy

The Kenya Aquatica is the research publication of the Kenya Marine and Fisheries Research Institute (KMFRI). It publishes original research papers or other relevant information in all aspects of Kenya's marine and freshwater fisheries, aquaculture, environmental and ecological studies, and marine research including chemical and physical oceanography.

All manuscripts submitted to the Kenya Aquatica are accepted for consideration on the understanding that they are original and their content has not been published elsewhere and not under consideration by any other journal.

Manuscripts and all illustrations should be prepared according to the instructions provided below and submitted in electronic format as attachments via e-mail. Submissions will be subject to a pre-review by the Editorial Board and those that fall within the remit of the journal, make a substantial contribution to the field of research, and are in the correct style and format will be sent for review. Manuscripts that do not meet these criteria will be rejected. Every manuscript will be reviewed by at least two referees competent in the field of interest. The choice of reviewers is made by the Chief Editor or the Editorial Board.

The Manuscript

1. The manuscript is your own original work, and does not duplicate any other previously published work, including your own previously published work.
2. The manuscript has been submitted only to the Kenya Aquatica and it is not under consideration or peer review or accepted for publication or in press or published elsewhere.
3. By submitting your manuscript, you are agreeing to any necessary originality checks it may undergo during the peer-review and production process.
4. Contributions must be written in English. Any consistent spelling and publication styles may be used. Please use single quotation marks, except where 'a quote is "within" a quotation'. Long quotations of 40 words or more should be indented without quotation marks. If English is not your first language we suggest that an English-speaker edits the text, before submission.
5. All persons who have a reasonable claim to authorship must be named in the manuscript as co-authors; the corresponding author must be authorized by all co-authors to act as an agent on their behalf in all matters pertaining to publication of the manuscript, and the order of names should be agreed by all authors.
6. The manuscript must be typed in a normal type font (e.g. Times Roman, font size 12) and at least with 1.5 line spacing. The total number of pages should not exceed

20 manuscript pages (excluding figures and tables), both for Original Articles and Review Articles. Short Communications must not exceed 8 manuscript pages. A separate sheet should be used for each table and figure.

7. Species names must be in italics; the genus is written in full at the first mention in the Abstract, again in the main text and the figure and table legends, and abbreviated thereafter.
8. Illustrations (figures, tables) should be placed separately at the end of the manuscript. Originals of all figures should be in black and white (graphs) but colour is acknowledged for figures such as maps and diagrams, and complex graphs where black and white does not allow good separation of patterns; the lettering should be of a size readable after reduction for the final layout.

Figure legends (captions) should be written on a separate page. Table legends must incorporate all the information needed and placed on the same page as the table. Authors are requested to indicate the recommended position of figures and tables in the left-hand margin of the text.
9. The international system of units (SI Units) must be used throughout; abbreviations and acronyms should be defined where they first appear; mathematical symbols and formulae should be used only when absolutely necessary and should be clearly explained and defined in the text.
10. A complete Original Article manuscript must include the following: title page, abstract, keywords, introduction, materials and methods, results, discussion, acknowledgements, references, tables and figures (with figure legends) in that order.

11.

- a. Title Page: This should contain a concise title and the names of authors followed by affiliations and their complete postal addresses, phone numbers, and email addresses. The corresponding author and email address must be indicated.
- b. Abstract: The abstract should not exceed 200 words, and should be on a separate page. It should briefly describe the main points of the manuscript, i.e. the topic, the main findings and the conclusions.
- c. Keywords: four to six Keywords are required for indexing purposes.
- d. Introduction: A brief survey of relevant literature and objectives of the work should be given in this section. Thus, the introduction should largely be limited to the scope, purpose and rationale of the study.

- e. **Materials and Methods:** In this section, the methodology used should be clearly explained, including relevant references, such that anyone else can repeat the procedures. It should provide the framework to gain answers to the questions or problems identified. Sampling methods must be elaborated as well as analytical frameworks and model specifications.
- f. **Results:** Make the text as objective and descriptive as possible. Only material pertinent to the subject should be included. Presentation of the same information in both graphical and tabular form should be avoided.
- g. **Discussion:** This section could be combined with the above to present “Results and Discussion”. It should interpret the results in view of the problems identified in the introduction, as well as in relation to other published work. The final paragraph of this section could include concluding remarks and recommendations for future work. “Discussion and Conclusion” or “Conclusion and Recommendations” could also be combined to form separate sections or presented individually.
- h. **Citations:** Authors should be cited using their surnames, followed by the year of publication. Two authors should be separated by ‘and’. If there are more than two authors, only the first author, followed by “*et al.*”, should be given. This and other Latin or foreign terms should be italicized.
- i. **Acknowledgement/s:** This section should be brief. Authors are advised to limit acknowledgements to substantial contributions to the scientific and technical aspects of the paper, financial support or improvements in the quality of the manuscript.
- j. **References:** The reference section must contain an alphabetical list of all references mentioned in the text of the manuscript. Limit punctuation and special fonts as indicated and give all journal names in full. Examples for citations from periodicals, books and composite works are given below:
- **Periodicals.** Here the following should be sequentially listed: author's name/s, initials, year of publication, full title of paper, periodical (in full), volume, first and last page numbers. Example: Edmonton K, Randall J, Allistair J (1984) Adaptation of unicellular algae to irradiance: An analysis of strategies. *The New Scientist* 94: 168–183
 - **Books.** The following should be listed: author's or editor's name, initials, year of publication, full title, publisher, place of publication, total pages. Example: Klan OJP (1980) Light and photosynthesis in aquatic ecosystems. Cambridge University Press, Cambridge. 204 pp
 - **Composite works or serials.** The sequence should be as above, but also should include full title of paper followed by In: editor(s) if any, full title of publication, publisher, etc., and the first and last page numbers. Example: Nathwani P, Slatter J (1995a) Satellite analysis of benthic secondary production. In: Zhu MPC, Vanini WX (eds) Determination of secondary production from the molecular to the global Scale. ICES Marine Science Symposia, Vol. 95, Copenhagen. pp 337–432
 - **Articles with a Digital Object Identifier (DOI).** Example: Gooseff MN, McKnight DM, Lyons HJ, Blum RJ (2002) Weathering reactions and hyporheic exchange controls on stream water chemistry in a glacial meltwater stream in the McMurdo Dry Valleys. *Water Resources Bulletin* 38 [doi: 10.1029/2001WR000834]
- k. **Tables and illustrations:** Each figure/table/photograph should be numbered consecutively, accompanied by a complete caption, and must be cited in the text. Figures should be of high quality to allow reproduction and reduction without loss of information. When accepted for publication the original figure files may be requested from authors in order to ensure eventual standardization and graphical improvement. Photographs should be of excellent quality to maximise contrast and detail during printing (15cm longest edge @300 dpi), be focused and well composed.
- l. **Supplementary material:** In case it is found relevant, authors may submit appendices with relevant information of major interest for the interpretation of the manuscript results. This is not applicable for the raw data of normal research. The editors will decide its eventual inclusion as appendices.
12. A complete Review Article manuscript must include the following: title page, abstract, keywords, introduction, main body text (the central sections vary with specific divisions according to the theme), acknowledgements, references, tables and figures (with figure legends) in that order.
13. A complete Short Communication manuscript must include the same structure as an Original Article in a shorter format.

Volume 10, Issue No.01

KENYA *Aquatica*



A Scientific Journal of Kenya Marine
and Fisheries Research Institute

KMFRI

©2026