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Cover image: Intense Tropical Cyclone Idai approaching the Sofala province of Mozambique on 14 March 2019, shortly after reaching its peak intensity. MODIS image captured by NASA's Aqua satellite. Adapted from https://pt.m.wikipedia.org/wiki/Ficheiro:Idai_2019-03-14_1135Z.jpg

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Original Article

A decade of the Blue Economy concept in the western Indian Ocean region: research and technology perspectives

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Abstract
The World Bank defines the Blue Economy as “the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem”. The implementation of Blue Economy concept at global, continental, regional and country levels have had mixed results since its origin in 2012. Here, a systematic review of progress in the western Indian Ocean region is undertaken, focused on research and technology between 2012 and 2021. Apart from applications to ocean modelling, big data and satellite data, the term Blue Economy did not appear as a key term in most publications from the region, suggesting that it is not well understood or researched. Existing studies aligned with three Africa Blue Economy Strategy thematic areas: (1st) fisheries, aquaculture and ecosystem conservation; (3rd) environmental sustainability, climate change and coastal infrastructure; and (5th) policies, institutional and governance. Multi-disciplinary and multi-institutional collaborations focusing on technology are required to boost Blue Economy implementation in the Western Indian Ocean region, including for thematic areas for shipping transportation and trade (2nd) and sustainable energy, extractive minerals, gas, and innovative industries (4th).

Keywords: Blue Economy, ocean economy, ocean model, satellite data, western Indian Ocean, Africa Blue Economy Strategy

Introduction
The concept of the Blue Economy originated from the United Nations Conference for Sustainable Development held in Rio de Janeiro in Brazil in 2012 (UNCTAD, 2014). Although the concept is interchangeably referred as “Ocean Economy” or “Marine Economy”, the term “Blue Economy” is currently widely used at international, regional and national levels. It is considered as the mid-neutral factor to resolve the two long term competing/conflicting discourses around opportunities of growth and development through ocean resources, and protection of the healthy ocean ecosystems threatened by socio-economic activities (Voyer *et al.*, 2018). The United Nations concept paper defined the Blue Economy as an ocean economy that aims at “the improvement of human well-being and social equity, while significantly reducing environmental risks and ecological scarcities” (UN, 2014). In 2017, the World Bank provided a comprehensive definition of the Blue Economy as “the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystem” (World Bank, 2017). This definition was further emphasized in World Bank (2020).

Growth and development using ocean-based economic activities conflicts with the balance of the long-term capacity and protection of the health of ocean ecosystems to support the activities in a sustainable manner. Human activities are responsible for about 80 % of ocean pollution through dumping waste products including sewage, pesticides, industrial chemicals, and other solid waste, as well as through climate change, other forms of environment pollution, unsustainable fishing and unregulated coastal development (WWF, 2014; Tirumala and Tiwari, 2022). The Blue Economy is further defined as a "practical ocean-based economic model using green infrastructure and technologies, innovative financing mechanisms, and proactive institutional arrangements for meeting the twin goals of protecting our oceans and coasts, and enhancing their potential contribution to sustainable development, including improving human well-being, and reducing environmental risks and ecological scarcities" (PEMSEA, 2012; Tirumala and Tiwari, 2022). Therefore, the Blue Economy posits the inherent conflicts of ocean activities for economy and protection of the health of ocean ecosystems to support the activities in a sustainable manner.

Since the introduction of the Blue Economy concept in 2012, different studies have been conducted mainly with a focus at global and continental levels to achieve different objectives. For example, Lee *et al.* (2021) described the Blue Economy and the total environment through mapping the interface between the two, and Tirumala and Tiwari (2022) reported fewer financial flows for Blue Economy projects as compared to others types of investments. Furthermore, Lee *et al.* (2020) compared the scope and boundaries as well as the key stakeholders and their interests and roles between the Blue Economy and the United Nations Sustainable Development Goals (UN SDGs) which were launched by the United Nations General Assembly (2015). Lee *et al.* (2020) found that the Blue Economy is highly associated with SDGs 14-17 although most stakeholders with direct or indirect involvement in the Blue Economy prefer to associate Blue Economy with SDG 3-Good health and well-being, and SDG 8-Decent work and economic growth.

At continental level, the Africa Blue Economy Strategy as narrated by Sacko (2020) indicates five critical blue economy sectors, considered as thematic areas including: a) fisheries, aquaculture and ecosystem conservation; b) shipping transportation and trade; c) sustainable energy, extractive minerals, gas, and innovative industries; d) environmental sustainability, climate change and coastal infrastructure; and e) policies, institutional and governance (https://www.au-ibar.org/strategy-documents). These critical thematic areas for the Blue Economy in Africa are considered to play significant roles for socio-economic development in different countries and should be of high priority for scientific research. The current development in computing (numerical modelling) in conjunction with the theories, observations and satellite data in the Blue Economy research field helps to avoid difficulties associated with each approach when used separately. Consequently, a better understanding of different aspects/factors related to the Blue Economy can be achieved, including perspectives in research and applied technology on this important topic, which is the subject of this study.

Blue Economy contribution and management approaches

The Blue Economy concept emphasizes the importance of embracing the opportunities related to economic activities from ocean resources and environments while recognizing and addressing ocean threats in order to preserve healthy ocean ecosystems in a sustainable manner. The contribution of the coastal and marine resources and related industries to the market value is estimated as USD 3 to 5 trillion making up about 5 % of the global Gross Domestic Product (GDP) (UN, 2015) and 15 %–20 % of GDP in some East Asian countries (Pauli, 2010).

The estimation of annual value generation in 2018 for the Africa Blue Economy sectors was USD 296 billion with 49 million jobs (AU-IBAR, 2019; Sacko, 2020). Such contribution to the African continent involves USD 80 billion from offshore oil and gas exploration, USD 80 billion with 24 million jobs from the tourism sectors, and about 3 % of the global shipping value with about 500 million tonnes of goods handled through the African harbours. Furthermore, fishing contributes to about USD 15 billion with about 13 million employees where the marine capture fisheries product is about 10 million tonnes providing food and nutritional security to 200 million Africans, contributing about 20 % or more of the animal protein consumed in Africa (AU-IBAR, 2019; Sacko, 2020). However, Agnew *et al.* (2009) reported that the illegal catch of seafood in world was at least 20 % leading to losses of about US$ 10 and $ 23 billion per year.

In Tanzania, Jiddawi and Öhman (2002) reported fishing as the main food source and commercial activity in the coastal communities which contribute about

2.1-5.0 % to the country's gross domestic product for mainland Tanzania and about 2.2-10.4 % for Zanzibar. Manyilizu *et al*. (2014; 2016) pointed out the recent discoveries of offshore oil and gas near Mtwara on the southern Tanzanian shelf are expected to boost the country's economy substantially. Moreover, marine and coastal shipping through the four major ports of Dar es Salaam, Zanzibar, Tanga and Mtwara, contributes significantly to the country's trade and income. These ports provide transport services to local communities as well as transit goods to land-locked countries such as Uganda, Rwanda, Burundi, Democratic Republic of Congo, Zambia and Malawi. The aforementioned socio-economic activities fall in the Blue Economy concept and involve formal planning and managing of marine fisheries, ecosystems and shipping as well as oil and gas extraction in the region.

There are different instruments and institutions supporting sustainable development of the Blue Economy from a global scale to national levels. The UN SDGs, endorsed by all member states in 2015, advocate potential solutions regarding the Blue Economy at the global level. The notable endorsement is through SDG-14-Life below water for conserving and sustainably use the oceans, seas and marine resources for sustainable development by 2030. The United Nations (UN) declared 2021-2030 as the "Decade of Ocean Science for Sustainable Development" to support efforts to reverse the cycle of the decline in ocean health and gather ocean stakeholders worldwide behind a common framework. Such a framework is aimed to ensure ocean science can fully support countries in creating improved conditions for sustainable development of the ocean.

The African Union Agenda 2063, the Africa we want, goal number 7 calls for accelerated economic growth of marine resources, renewable energy, ports operations and marine transport. This agenda is in line with the Policy Framework and Reform Strategy for Fisheries and Aquaculture in Africa (PFRS) as stated in AUC-NPCA (2014), the 2050 African Integrated Maritime Strategy (AIMS 2050) published in African Union (2012), Lome Charter on maritime security and safety and development in Africa 2016, the Africa Blue Economy Strategy launched in February 2020, and is supported by eight Regional Economic Communities (RECs), Regional Fisheries Bodies and Regional Seas Programmes. All these programmes support Blue Economy research and applications at the continental and regional levels in line with the Blue Economy Strategy as narrated by Sacko (2020), with the five critical blue economy sectors which are considered as thematic areas. Thus, this study focuses on studying the Blue Economy concept in the context of research and the corresponding technology used in research in the countries of the Western Indian Ocean (WIO) region.

Research gaps

The five critical thematic areas for the Blue Economy in Africa are considered to play significant roles for socio-economic development in different countries and should be earmarked as high priority in scientific research.

The roles of research and development (R&D) as well as technology for the Blue Economy related studies should be addressed at regional and country levels. Furthermore, technologies applied to the Blue Economy concept like satellite and big data as well as modelling have not been given strong attention in research. The information technology stakeholders working to support Blue Economy studies appear to have be overlooked in previous analyses. Thus, this study applies a systematic review after a decade of the Blue Economy concept in the western Indian Ocean region in relation to research and technology from 2012 to 2021. The study is guided with the five critical blue economy sectors which are considered as thematic areas from Africa Blue Economy Strategy as narrated by Sacko (2020). The study aims at addressing the following specific research questions:

- To what extent has the Blue Economy concept been associated with research conducted in the WIO from 2012 to 2021 based on the thematic areas of the African Blue Economy Strategy?

- What has the involvement been of each country in research on the Blue Economy concept in the WIO in terms of institutions and authors from 2012 to 2021?

- What technology has been used in research related to the Blue Economy concept in the WIO from 2012 to 2021?

Addressing these research questions provides insight into the Blue Economy concept in the region in order to assist researchers and policy makers in their work in this field.

Materials and Methods

Study area

This study applies a systematic review of a decade of the Blue Economy concept in the WIO with regard to research and technology from 2012 to 2021. The Western Indian Ocean Marine Science Association (WIOMSA) is a leading non-governmental organization promoting science and research in the WIO. The WIOMSA was established as a regional, non-profit, membership organization in 1993 and registered in Zanzibar, Tanzania in 1994 (https://www.wiomsa.org/).The WIOMSA focuses on supporting and promoting the educational, scientific and technological development of all aspects of marine sciences in the WIO region which includes 10 countries: Somalia, Kenya, Tanzania, Mozambique, South Africa, Comoros, Madagascar, Seychelles, Mauritius, Réunion (France).

In the region, the organization is interested in connecting research skills and knowledge generated from marine and coastal ecosystems in the region with management and governance issues (https://www.wiomsa.org/). The WIOMSA has managed to promote different activities regarding marine and coastal ecosystems in the region. Since its establishment, the number of members has significant increased especially from 1999 to 2014. Furthermore, the organization has broadened the scope of research in the region by supporting multidisciplinary, interdisciplinary and transdisciplinary (MIT) research approaches in order to have significant impacts to the communities. Previously, the focus was on natural science only while nowadays the organization supports work on ocean governance, accounting and social sciences in the region.

In order to accelerate research in the region, the organization provides grants for research and conference/training participation for members in the region. Furthermore, the organization has launched its own symposium with the 12th WIOMSA Scientific Symposium held in October 2022 in Nelson Mandela Bay in South Africa, as well as the Western Indian Ocean Journal of Marine Science (WIOJMS). Both the symposium and the journal facilitate disseminate of research in the region and bring together different stakeholders in the field of marine and ocean sciences. The scope of this study includes the 10 countries in the WIO and extensive review of the publications in the WIOJMS has been undertaken.

Research dataset and identification of literature

The WIOMSA is well recognized as an organization which promotes and supports research activities in the WIO through different approaches. As mentioned, this study was based on research published in the WIOJMS with Journal Identifiers eISSN: 0856-860X, print ISSN: 0856-860X. It should be noted that the analysis does not include research that may have been conducted in the WIO but has been published in other journals besides the WIOJMS.

The WIOJMS provides an avenue for the wide dissemination of high-quality research generated in the region targeting the sustainable use of coastal and marine resources. It deals with original research articles in all aspects of marine science and coastal management. The journal mainly focuses on topics including, but are not limited to theoretical and empirical studies in oceanography, marine biogeochemistry, legal and institutional frameworks as well as interactions/relationships between humans and the marine environment.

The journal features state-of-the-art review articles and short communications with special issues on major events or important thematic issues. It is noteworthy that the submitted articles are subjected to standard peer-review prior to publication (https://www.ajol. info/index.php/wiojms/index).

Data analysis

The database of journal articles from the WIOJMS was analyzed for 10 years from 2012 to 2021. Network analysis has evolved as a methodology for the study of social structure using VOSviewer version 1.6.18. The most significant feature of network analysis is the use of relational data.

The people, organizations, and objects that form a network are referred to as nodes, and a network structure is that which expresses the position and relation between nodes (Scott, 2012). For network analysis, it is important to determine the nodes and links of the network. Here, community analysis is an analysis that detects the community structure at the substructure level of the network. A community structure in a network is a subgroup (community or module) in which the relationships among specific nodes (local communities) are dense internally but not externally (i.e., with other communities) (Newman, 2010).

In the analysis, the meaning of the community structure is the identification of conceptual groups that form a contextual cluster (Paranyushkin, 2011). VOSviewer calculates the community, or cluster, based on modularity (Newman and Girvan, 2004). VOSviewer also improves the accuracy by adding a smart local moving algorithm (Waltman and van Eck, 2013), and adjusts the number of clusters by adjusting the resolution parameter γ in the Modularity function (Yan *et al.*, 2012).

The analysis of the WIOJMS database involved articles from 2012 to 2021 using VOSviewer software to create a co-occurrence map based on text data downloaded through API Crossref through Search Query searching. About 85 journal articles were retrieved to which co-occurrence terms in title and abstract fields were extracted with conditions of ignoring structured abstract labels and copyright statements. Basing on the threshold with the minimum number of occurrences of term 10 of the total 2583 terms, 33 terms met the threshold and were selected for analysis. Statistical descriptions were used to evaluate trends in temporal growth, and geographical and national interests in the Blue Economy literature. Bibliometric analyses based on keywords conducted in VOSviewer software (Van Eck and Waltman, 2014) were employed to scrutinize interrelations and patterns of knowledge production. Co-occurrence analysis was employed to analyze networks in respect of the intellectual structure and terminological interrelation that have evolved in this knowledge base (Udomsap and Hallinger, 2020).

Furthermore, the analysis of the WIOJMS database involves journal articles from 2012 to 2021 using VOSviewer software to create a co-occurrence map based on bibliographic data for authors downloaded through API Crossref through Search Query searching. About 85 journal articles with 252 authors were retrieved based on counting their main authorships with a minimum of two documents for an author. About 52 authors were calculated according to the total strength of the co-authorship links with other authors. However, some of the items in the network were not connected to each other; thus, the largest set of connected items consists of 23 items which were considered to show the set of items instead of all. Statistical descriptions were used to evaluate trends in temporal growth, geographical and national interests in the Blue Economy literature. Bibliometric analyses based on authors conducted in VOSviewer software (Van Eck and Waltman, 2014) were employed to scrutinize interrelation and patterns of knowledge production. Co-occurrence analysis was employed to analyse networks in respect of the intellectual structure and terminological interrelation, that have evolved in this knowledge base (Udomsap and Hallinger, 2020). To visualize a network, the relatively different size of each node-assigned keyword expressed that keyword in a bigger node and indicated it occurred across the whole network as compared to the smaller sized ones. Link strength was expressed as the relative width of the line in the network structure. Altogether, occurrences, link strength to the Blue Economy, and total link strength of keywords were analysed and organized using cluster analysis.

Results and Discussion

The results and discussion of this research focuses on systematic research of key terms and key authors in the research conducted in the WIO region. Furthermore, the extent to which technology has been utilized in the regional research is presented. Generally, the term Blue Economy did not appear in the majority of the studies conducted in the region. Thus, the study considers terms related to the five thematic areas identified by the Africa Blue Economy Strategy as reference to the Blue Economy concept. As mentioned above, the thematic areas are 1) fisheries, aquaculture and ecosystem conservation; 2) shipping transportation and trade; 3) sustainable energy, extractive minerals, gas, and innovative industries; 4) environmental sustainability, climate change and coastal infrastructure; and 5) policies, institutional and governance (https://www.au-ibar.org/strategy-documents).

Blue Economy vs key research terms

Density visualization of the keywords in the study are portrayed in Figure 1. Basing on the five thematic areas of the African Blue Economy Strategy, the keywords appeared to relate to the first, fourth and fifth thematic areas of fisheries, aquaculture and ecosystem conservation; environmental sustainability, climate change and coastal infrastructure; and policies, institutional and governance, respectively. However, no key term appeared to be associated with the second and third thematic areas of shipping transportation and trade; and sustainable energy, extractive minerals, gas, and innovative industries, respectively.

The first thematic area on fisheries, aquaculture and ecosystem conservation relates to key terms including species, fishery, fish, habitat, catch, mangrove, *S. commersonnii*, and fishing area. In this thematic area, the term species appeared to be the central key term among the other key terms in the largest cluster with about 81 frequencies. This finding suggests that much

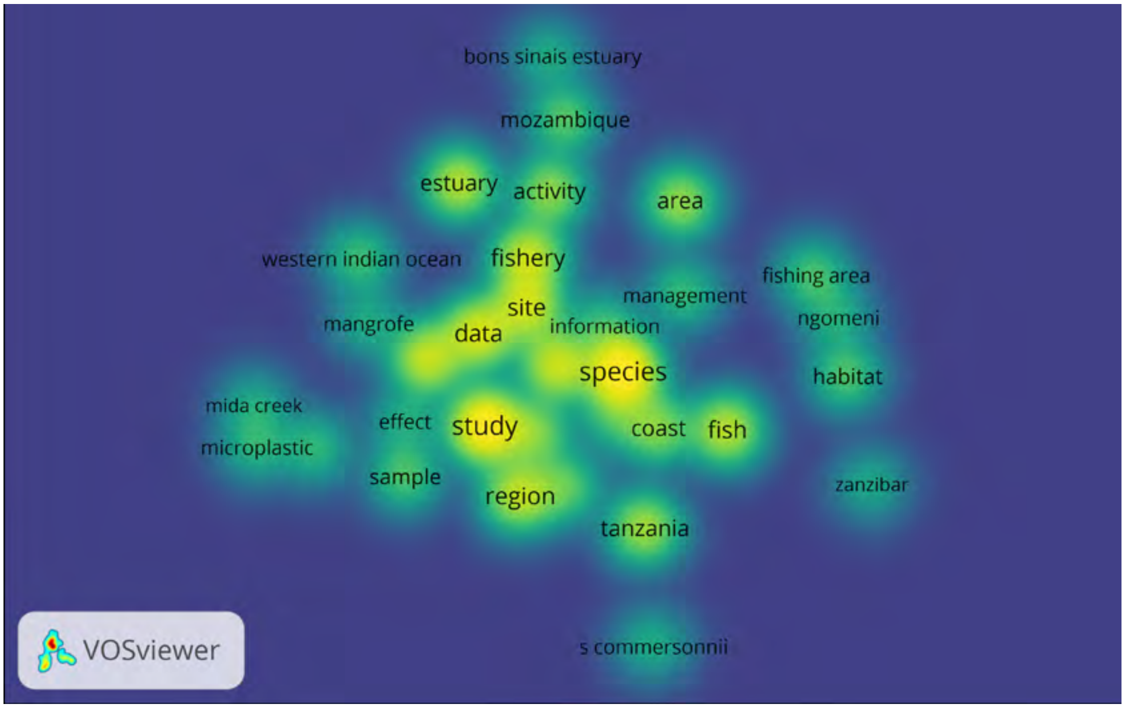

Figure 1. Density visualization of research keywords for publications on the Blue Economy concept in the western Indian Ocean region.

of the research focused on species and that the majority of the research focused on marine biology.

The fourth thematic area of environmental sustainability, climate change and coastal infrastructure is reflected by the key terms water, estuary, activity, coast, western Indian Ocean, Kenyan coast, microplastic, community, and Bons Sinais Estuary. The keyword water appeared very frequently on about 44 occasions. The key terms in this thematic area include microplastics, as a ocean/sea pollutant. Furthermore, the term community which could be associated with coastal infrastructure in the region appeared in this thematic area.

The fifth thematic area which is about policies, institutional and governance is reflected by the terms data, study, site, area, sample, year, region, information, effect, management, Mida Creek, Ngomeni, Zanzibar, Kenya, Mozambique, and Tanzania. In this thematic area, the terms study, data, site and Kenya appeared more frequency with 75, 49, 45 and 45 occurrences, respectively. This suggests that many of the studies might have focused on Kenya. Moreover, terms like Zanzibar, Tanzania, and Mozambique indicate their coverage in studies related to the Blue Economy in the region.

To understand links and clusters among the key terms in the study, a network analysis diagram with different colours was created (Fig. 2). In VOSviewer, creation of a network picture (also known as Label view) circles or labels important items (in this case, key terms with many simultaneous links) which appear large. In Figure 2, the link strength, which calculates the distance between nodes, is extracted by the full counting method. As the similarity of the items increases, the distances appear closer, but the minimum distances are maintained to prevent complete overlap (Van Eck and Waltman, 2010).

Cluster 1 (in red) consists of the eight key terms of activity, community, data, management, mangrove, region, study and year reflecting the fourth thematic area relating to environmental sustainability, climate change and coastal infrastructure and the fifth thematic area for policies, institutional and governance from the Africa Blue Economy Strategy.

Cluster 2 (in green) consists of the seven key terms of area, catch, coast, fishing area, Kenya, Ngomeni and species reflecting the first thematic area for fisheries, aquaculture and ecosystem conservation, the fourth thematic area environmental sustainability, climate change and coastal infrastructure, and the fifth thematic area for policies, institutional and governance .

Cluster 3 (in blue) consists of the six keywords of effect, Kenyan coast, microplastic, Mida Creek, sample and water reflecting the fourth thematic area environmental

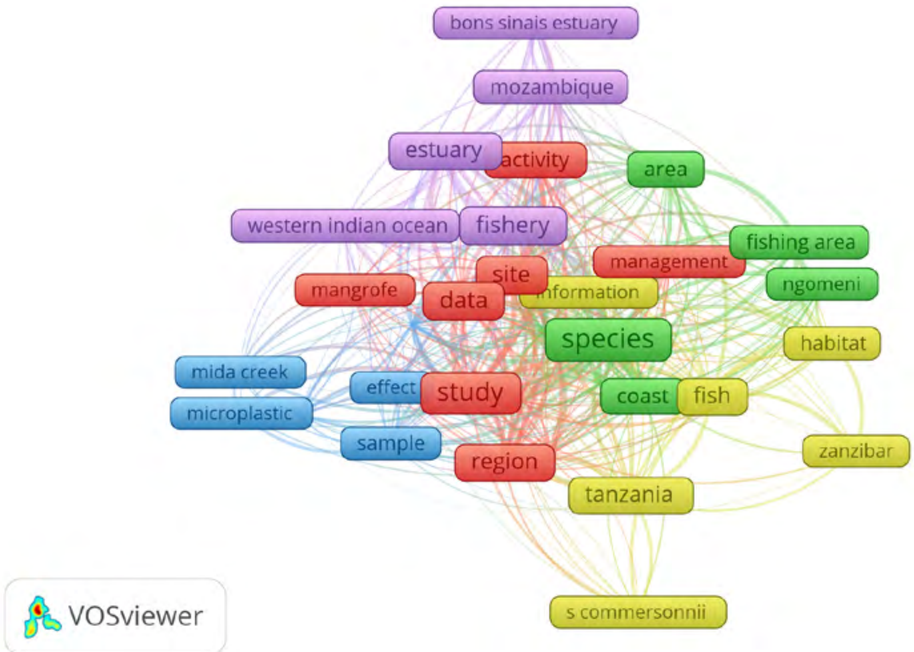

Figure 2. Network visualization of research key words for publications on the Blue Economy concept in the western Indian Ocean region.

sustainability, climate change and coastal infrastructure, and the fifth thematic area for policies, institutional and governance from the Africa Blue Economy Strategy.

Cluster 4 (in yellow) consists of the six keywords of fish, habitat, information, *S. commersonnii*, Tanzania and Zanzibar reflecting the first thematic area for fisheries, aquaculture and ecosystem conservation, and fifth thematic area for policies, institutional and governance from the Africa Blue Economy Strategy.

Cluster 5 (in blue) consists of the 10 keywords of Bons Sinais Estuary, estuary, fishery, Mozambique, Western Indian Ocean fish, habitat, information, *S commersonnii*, Tanzania and Zanzibar reflecting the first thematic area for fisheries, aquaculture and ecosystem

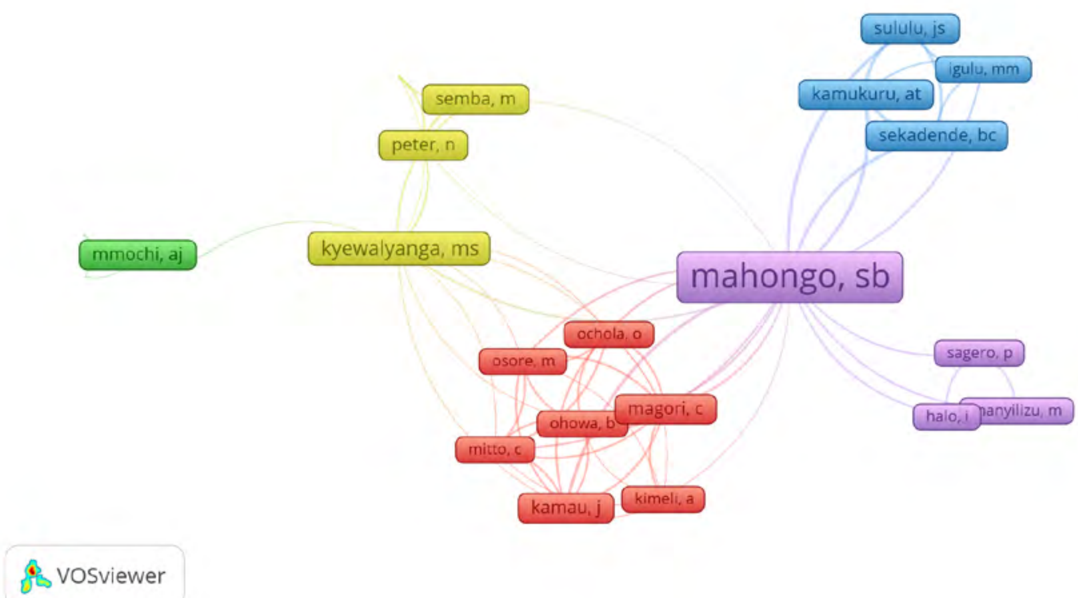

Figure 3. Authorship network visualization for publications on the Blue Economy concept in the western Indian Ocean region.

conservation, and the fourth thematic area environmental sustainability, climate change and coastal infrastructure. Moreover, the cluster indicates the fifth thematic area for policies, institutional and governance from Africa Blue Economy Strategy.

Blue Economy vs researchers and institutions

Five clusters of research authors were formed from the network analysis diagram with different colours (Fig. 3). Also in Figure 3, the link strength, which calculates the distance between nodes, was extracted by the full counting method. As the similarity of the items increases, the distances appear closer, but the minimum distances are maintained to prevent complete overlap (Van Eck and Waltman, 2010).

Cluster 1 (in red) consists of the seven authors J. Kamau, A. Kimeli, C. Magori, O. Ochola, B. Ohowa and M. Osore and Cluster 2 (in green) consists of the four authors N.S. Jiddawi, A.J. Mmochi, M.S. Mtolera and S.A. Yahya. Both these clusters focus mainly on the first thematic area for fisheries, aquaculture and ecosystem conservation.

Cluster 3 (in blue) consists of the four authors M.M. Igulu, A., Kamukuru, B.C. Sekadende and J.S. Sululu addressing the first thematic area for fisheries, aquaculture and ecosystem conservation in conjunction with the fifth thematic area for policies, institutional and governance from Africa Blue Economy Strategy.

Cluster 4 (in yellow) consists of the four key authors M.S. Kyewalyanga, C. Lugomela, N. Peter and M. Semba reflecting the first thematic area for fisheries, aquaculture and ecosystem conservation, and the fifth thematic area for policies, institutional and governance.

Cluster 5 (in blue) consists of the four arthors I. Halo, S.B. Mahongo, M. Manyilizu and P. Sagero reflecting the fourth thematic area environmental sustainability, climate change and coastal infrastructure, and fifth thematic area for policies, institutional and governance. S.B. Mahongo appeared the most in all clusters (11 documents and 35 total link strength).

In order to gain insights into the instruments and institutions supporting research in the WIO the authors'

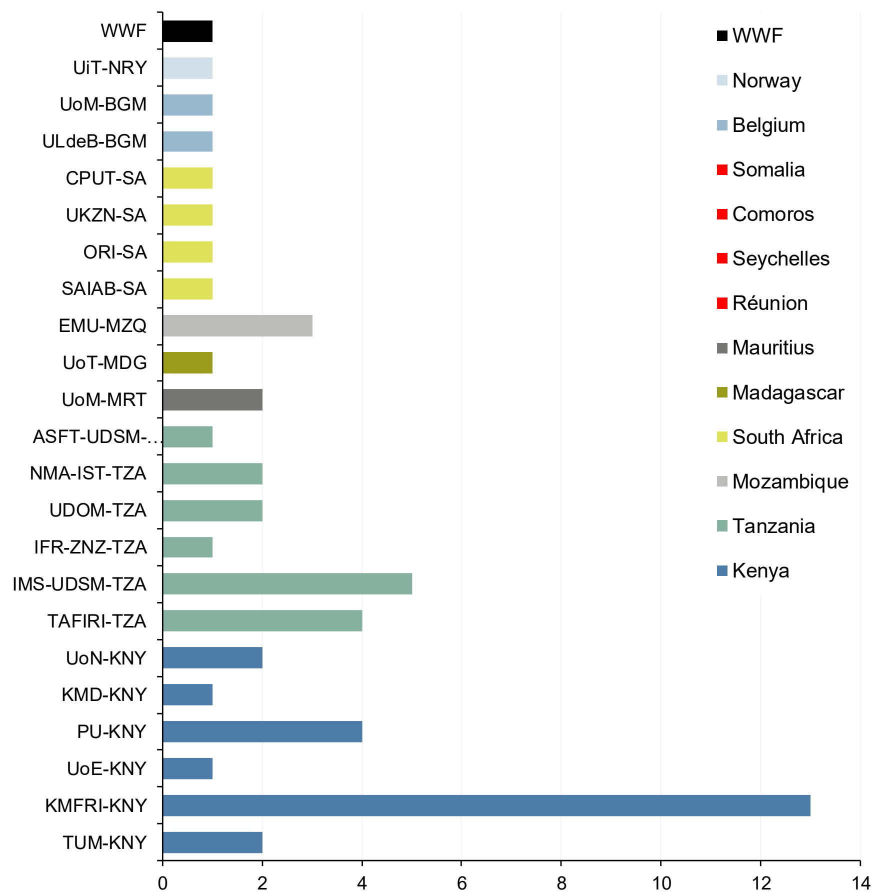

Figure 4. Number of authors per institution per country for publications on the Blue Economy concept in the western Indian Ocean region.

affiliations and their respective countries were considered (Fig. 4). Kenya appears to have had six active research institutions from 2012 to 2021 with the Kenya Marine and Fisheries Research Institute (KMFIRi) having the highest number of authors, with about 13 active researchers. The other institutions were the Technical University of Mombasa (TUM, two authors), University of Eldoret (UoE, one author), Pwani University (PU, four authors), Kenya Meteorological Department (KMD, one author) and the University of Nairobi (UoN, two authors).

In Tanzania, six institutions appeared to have active authors with the Institute of Marine Science at University of Dar es Salaam leading (IMS-UDSM, five authors), followed by the Tanzania Fisheries Research Institute (TAFIRI, four authors). Other active authors came from the Institute of Fisheries Research in Zanzibar (IFR, one author), the University of Dodoma (UDOM, two authors), Nelson Mandela Africa-Institute of Science and Technology (NMA-IST, two authors), and the Aquatic Science and Fisheries Technology Department, University of Dar es Salaam (ASFTD-UDSM, one author).

One, two, and three authors appear from the University of Toliara in Madagascar, the University of Mauritius (UoM) in Mauritius and the Eduardo Mondlane University (EMU) in Mozambique, respectively.

Each of four research institutions in South Africa had one author. These were the Oceanographic Research Institute (ORI), University of KwaZulu-Natal (UKZN), and South African Institute for Aquatic Biodiversity, and Cape Peninsular University of Technology (CPUT). Similarly, one author each appeared for UiT – the Arctic University of Norway, WWF Tanzania office, the Université Libre de Bruxelles, and the University of Mons from Belgium. However, among the ten states of the WIO, the five states of Somalia, Comoros, Madagascar, Seychelles, and Réunion (France) did not appear in the screened documents suggesting either low levels of publication in the WIOJMS or poor research capacity on issues regarding the WIO Blue Economy.

Blue Economy vs technology

Utilization of different technological research approaches by authors in respective countries is depicted

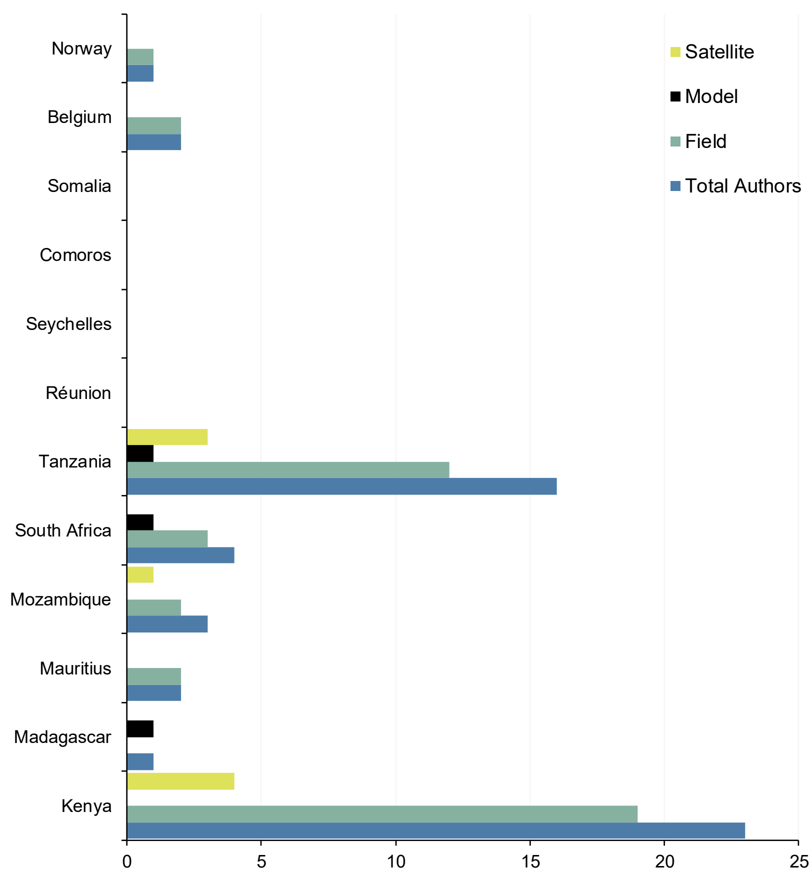

Figure 5. Number of authors per approach used for research and their country for publications on the Blue Economy concept in the western Indian Ocean region.

in Figure 5. The three approaches used in research are field/in-situ, model and satellite modes. The field work approach appeared to dominate in the WIO research and was used by 41 authors (79 % of all authors), and eight authors used satellite and three model approaches. With advances in computing, numerical modelling combines the theories, observations and satellite data into Blue Economy field helping to overcome difficulties associated with each approach when used separately. As a result, a better understanding of ocean dynamics and properties such as sea surface current, sea surface height and sea surface temperature may be achieved.

Of the 23 authors/researchers in Kenya, there were 19 that used the field approach compared to four authors who used satellite data, and none used the model approach. For authors from Mauritius, Mozambique, as well as those from Belgium and Norway most studies focused on in-situ/field approaches involving fisheries, aquaculture and ecosystem conservation. A small number of users of the model and satellite approach appeared in Tanzania (field-16, satellite-3, and model-1). The reasons for such small numbers could be a lack of computing knowledge and/or facilities in the institutions as well as human capacity for these approaches.

Conclusions

The Blue Economy concept has become a popular term used in discussions involving ocean and environmental issues in relation to economic development. The term posits the inherent conflicts of ocean activities for economic development and protection of the health of ocean ecosystems to support the activities in a sustainable manner. This study used a systematic review to analyze a decade of the presence of the Blue Economy concept in the WIO from the perspective of research and technology from 2012 to 2021. It focused on the research and technological perspectives of the Blue Economy concept in the WIO in relation to the five critical blue economy sectors which are considered as thematic areas in the Africa Blue Economy Strategy.

The results indicate that the term Blue Economy does not appear as a key term in most publications in the region, which implies that it is either not well understood or researched. Furthermore, most of the research utilized by authors from Kenyan Institutions use the field approach with no or poor support of technology like models, big data and satellite data. Predominant challenges for ocean modelers are a lack of human capacity, storage capacity, bandwidth and internet connectivity, availability of in-situ data for model evaluation and training/knowledge transfer.

As far as the five thematic areas of the Africa Blue Economy are concerned, it appeared that research has been conducted mainly in the first, fourth and fifth thematic areas of fisheries, aquaculture and ecosystem conservation, environmental sustainability, climate change and coastal infrastructure, and policies, institutional and governance, respectively. However, no key term appeared to be associated with the second and third thematic areas of shipping transportation and trade; and sustainable energy, extractive minerals, gas, and innovative industries, respectively.

Thus, multi-disciplinary and multi-institutional collaborations and management as well as identifying proper technology and its utilization will enhance research in support of Blue Economy development, particularly in all five thematic areas of the Africa Blue Economy Strategy. Ocean science accompanied by innovation and technology should be used in studies to enhance research capacity in the region by supporting multidisciplinary, interdisciplinary and transdisciplinary (MIT) research approaches.

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Original Article

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Suitability of a superheated steam dryer for drying sardines

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Abstract
The suitability of a superheated steam dryer for drying sardines was investigated. Proximate composition (moisture, crude protein, crude fat, ash, and crude fibre; minerals-calcium, zinc, iron) for fresh, oven dried (OD) at 100 °C, oven dried (OD) at 120 °C and superheated steam dried (SSD) sardines at 120 °C was evaluated and the results reported on a dry matter basis. There were significant differences ($p<0.05$) in moisture, crude fat, and ash content among fresh and dried samples, but not for crude protein or crude fibre. The crude protein % content of fresh, OD at 100 °C, OD at 120 °C, and SSD, was 78.17, 78.40, 75.77, and 76.05 and crude fibre % was 0.59, 0.12, 0.02, and 0.13, respectively. The SSD sardines had the highest fat content (11.8 %) and the fresh sardines had the lowest (8.1 %). There was a significant difference in calcium content ($p<0.05$) but not for zinc and iron content. Overall, SSD retained the nutrients of sardines well.

Keywords: superheated steam dryer, sardine, proximate composition, micronutrients, oven drying

Introduction
Sardines are among a group of small pelagic fish namely including Herrings, Anchovies, and Sardines (HAS) (Kripa *et al.*, 2019). In Tanzania sardines are harvested from marine waters of the Indian Ocean in the five regions of Tanga, Pwani, Dar es Salaam, Lindi, and Mtwara. However, Zanzibar, Pemba, and Mafia Island are the major producing areas (Sekadende *et al.*, 2020). Marine sardines make up about 1/3 million tons of the annual catch, according to the official statistics (SWIOFP, 2012). Small pelagic fish, particularly sardines, contain a significant amount of polyunsaturated fatty acids (PUFAs) of the omega-3 series in the form of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) responsible for the development and functioning of the brain and retina (Njinkoue *et al.*, 2016). These PUFAs play a crucial role in the prevention of atherosclerosis, heart attack, depression, stroke, diabetes, obesity, premature aging, hypertension, and cancer in humans and improve visual power and memory (Stephen *et al.*, 2010). In addition, PUFAs are essential for normal growth, development, and reproduction in all vertebrates, including fish and humans, and must be supplied through diet. Small pelagic fish contain all the elements of a healthy and nutritionally optimal food source for humans and are an important contributor to the food and nutritional security of many poor, low-income households in developing countries (Isaacs, 2016). Moreover, fish protein is of high biological value due to the presence of essential amino acids in the right proportions (Hoffman and Falvo, 2004). Lysine, methionine, and cysteine are important essential amino acids that can significantly raise the value of cereal-based diets, which are poor in these essential amino acids (Kasozi *et al.*, 2014).

Fish is a highly demanded and nutritious food product as detailed in the previous section, yet perishability remains the biggest challenge for its preservation (Tavares *et al.*, 2021). Since fish are not normally eaten raw, processing and preservation measures are employed in preparing them for consumption (Okpanachi *et al.*, 2018). Sun drying, salting, and boiling followed by sun drying, smoking, and chilling are methods used by processors to extend the shelf life of fish and fishery products. These traditional preservation techniques have some drawbacks like exposing the product to rain, foreign matter like dust, microorganisms like bacteria and fungi, birds, and rodents. In addition, existing conventional hot air drying is an energy-intensive technique that consumes around 15–25 % of national industrial energy in most developing countries; Tanzania being an example (Sehrawat *et al.*, 2016). Using air as a drying medium leads to oxidation and combustion reactions which pollute the environment by releasing undesirable components, and its operation needs continuous improvements to reduce energy consumption and preserve quality (Sehrawat *et al*., 2016). It also often results in loss of nutrients, colour degradation and non-uniform product quality (Sehrawat and Nema, 2018). Recent studies have also shown that traditional processing methods can cause a loss of nutrient availability in processed fish (Ayinsa and Maalekuu, 2013; Sehrawat *et al.*, 2016).

In Tanzania, particularly at Mafia Island, small pelagic fish processing is carried out by boiling in sea water mixed with salt using firewood as a source of energy before sun drying on racks or the ground (Fig. 1). This technology is not ideal because it has the potential to significantly lower the quality of the final product (dust, sand, flies). Additionally, the majority of small pelagic fish that are boiled fragment in the process of boiling. They also lose the silvery colour and once dried they are very difficult to chew due to shrinkage as a result of salting. During the rainy season, the process ceases as there is no alternative drying method, especially at Mafia Island.

Fortunately, there are some solutions available. Technologies such as heat pump drying, and superheated steam drying (SSD) have been proven to reduce nutrient loss and extend the shelf life of dried products. SSD is an affordable way of drying foods/fish using steam to dry the foods/fish. The benefits of SSD in food drying include minimizing energy consumption (Alfy *et al.*, 2016), reducing lipid oxidation, and preserving food nutrient substances, colour, and texture (Idrus and Yang, 2012).

The present study aimed to investigate the suitability of the application of a superheated steam dryer for drying sardines through the determination of proximate composition (moisture, protein, fat, ash, and crude fibre) and mineral content (calcium, iron, and zinc).

Materials and methods

Study location

This study was carried out on Mafia Island (Fig. 2) at Kilindoni Village (landing site). The Island is one of the six districts of the Pwani region with a coverage area of 972 km^2 of which 407 km^2 is dry land while 565 km^2 is covered by water (Kweka, 2017).

Collection of raw material

Fresh sardines for this study were bought from the local fishermen in Mafia Island and hygienically

Figure 1. Traditional small pelagic processing technique practiced by indigenous people on Mafia Island. From left to right: boiling process; boiled sardines ready for drying; fresh sardines under shade.

packed in a cool box containing flaked ice and then transported to the Department of Food Science and Technology Laboratory, College of Agriculture and Food Technology, University of Dar es Salaam for analysis. On arrival at the laboratory, the sardines were divided into two portions with the first portion subjected to proximate analysis before drying. The remaining portion was divided into three for Oven Drying at 100 °C, Oven Drying at 120 °C, and SSD at 120 °C.

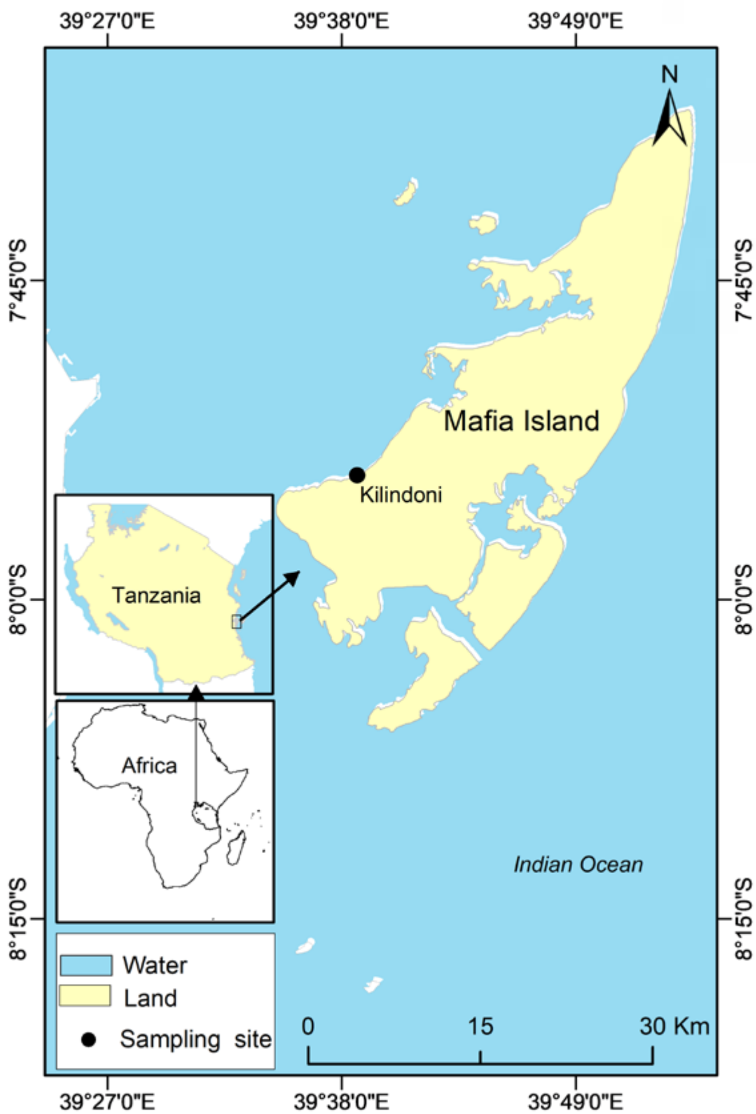

Figure 2. Map of Tanzania showing the location of the sampling site on Mafia Island (Shape file source: National Bureau of Statistics –Tanzania).

Superheated steam drying

Figure 3 represents a schematic diagramme of the superheated steam dryer and associated units. The dryer consists of a boiler, an air exchange pipe, and a drying chamber. The drying chamber is a stainless steel vessel with two partitions equipped with perforated stainless steel trays for holding food products during drying. It is 1.5 m × 1.5 m with the capacity of holding 24 trays of 60 × 30 cm. After preparing the dryer for operation, the boiler is started by heating the air exchange pipes and at the same time generating steam. The fresh sardines are spread on trays in the air chamber for drainage purposes for 30 min at 50 °C air temperature and a flow rate of 4 l/min. The drained sardines are shifted to the steam chamber only once the boiler pressure is about 7 bars. Water is boiled under atmospheric pressure conditions to a temperature of 100 °C, using liquefied petroleum gas as a source of energy. The generated steam is then further

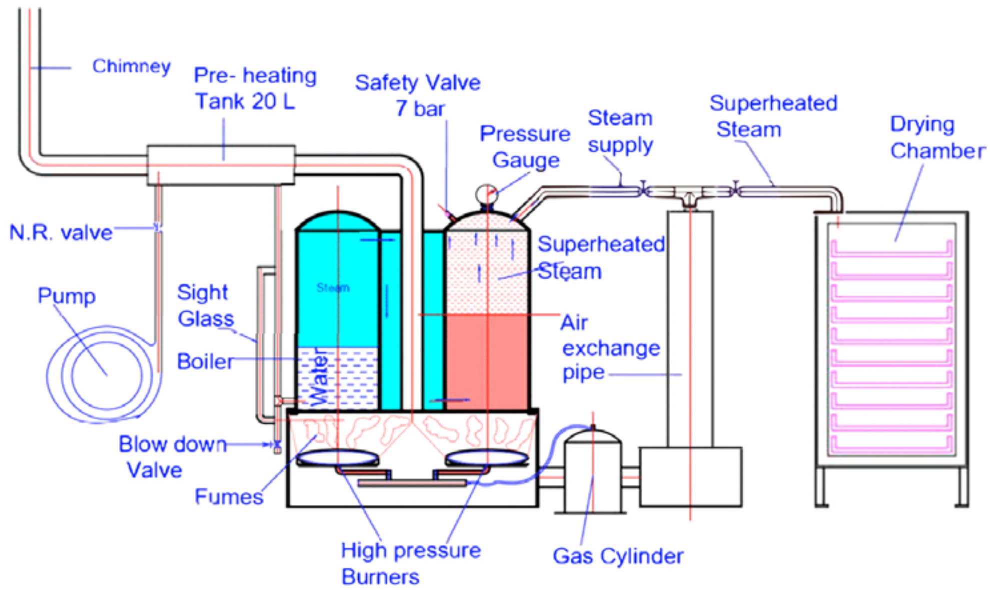

Figure 3. A schematic diagramme of a superheated steam dryer and associated units.

heated at a pressure of 7 bars in the drying chamber. The sardines are first moistened by steam exposure owing to condensation, but when the temperature rises to 120 °C, the water in the sardines is evaporated. The water condenses on the drying chamber walls and is collected at the steam trap as condensate. The sardines are dried for one hour in the drying chamber before being shifted to the hot air chamber for surface water removal. In the chamber, the sardines are exposed to heated air for an hour. Sardines are then moved to a conditioning room where they are kept for four hours before packaging for further analysis.

Oven drying

Sardine samples were dried in an oven at two different temperatures and times (100 °C for 90 min and 120 °C for 60 min). Once the sardines were dried, the packaging procedures were followed (Fig. 4a and b) and stored in the refrigerator at 4 °C for further analysis.

Proximate composition analysis

Proximate composition (moisture, protein, fat, ash, and crude fibre) was carried out on the samples of fresh, oven dried (OD) at 100 °C for 90 min, OD at 120 °C for 60 min, and SSD at 120 °C for 60 min.

Determination of moisture content

Approximately 2 g of each sample was weighed in preconditioned Petri plates that were pre-heated in an oven set at 105 °C for 2 h and cooled in a desiccator for 2 h. The samples were dried in a hot air oven (Model Memmert 854) at 105 °C overnight until constant weight was attained. The moisture content was calculated as a percentage loss in weight using Eq. (1).

$$Moisture\ content\ (\%) = \frac{W_2 - W_3}{W_2 - W_1} \text{ x } 100 \qquad (1)$$

Where W_1 = weight of the weighing dish (g),
W_2 = weight of the moist dish and sample before drying (g), and
W_3= weight of the dish and sample after drying (g).

Determination of protein content

An aliquot of 2 g of each sample was placed into a labeled Kjeldahl tube followed by adding Kjeltec catalyst [3 selenium oxide (2 g) tablets] and 20 ml of concentrated sulfuric acid (98 %). The tubes and the contents were inserted in the digestion unit (Foss Tecator™ Digester) and digested completely (until white fumes and blackish mass were absent) for 2 h at 400 °C. The digests were cooled to 29 ± 2 °C and then distilled for 5 min using an auto-distillation unit (Foss Kjeltec™ 8200) that had been rinsed and calibrated using the following setup: 80 ml of dilution volume (deionized water); 90 ml of sodium hydroxide (alkali solution 40%); and 3 ml of mixed indicator (70 ml of 0.1 g methyl red and 100 ml of 0.1 g bromocresol green dissolved in 100 ml methanol). The distillate was collected in the flasks. In addition, it was titrated with 0.104 M hydrochloric acid solution. The protein content in the sample was calculated and expressed on a dry basis, according to Eq. (2).

$$Crude\ protein\ (\%) = \frac{((T-B) \times M \times 14.007 \times 6.25 \times MCF)}{W} \times 100 \quad (2)$$

Where T = volume of the standard hydrochloric acid used in sample titrations (mL),
B = volume of the standard hydrochloric acid used in blank titrations (ml),
M = molarity of the acid used in the titrations (mol/L),
W = mass of the sample used in grams (g),
MCF = the moisture correction factor [100/ (100 – % moisture content)],
6.25 = factor used to convert percent N to percent crude protein, and
14.007 = molecular weight for N (g/mol).

Determination of crude fat

The fat content of samples was determined using the Soxhlet system (Foss Soxtec™ 2043, Hilleroed, Denmark). Aluminum cups were pre-heated in an oven set at 105 ± 2 °C for 2 h, and thereafter cooled in a desiccator for 30 min. Each aluminum cup was filled with 30 ml of petroleum ether and placed under an adapter holding thimble loaded with 2 g of the sample. Each thimble was submerged in boiled petroleum ether for 20 min to extract fat. Fat remaining in the samples was rinsed out by reflux using boiling petroleum ether for 45 min. Excess petroleum ether was recovered by evaporation from each cup into the condenser unit of the Soxhlet system for 10 min. The fat extract was dried in a hot air oven set at 105 °C for 30 min. The fat content was expressed on a dry matter basis, as shown in Eq. (3).

$$Fat\ content\ (\%) = \frac{W_3 - W_1}{W_2} \times 100 \quad (3)$$

Where W_1= weight of the aluminum cup (g),
W_2= weight of the sample (g), and
W_3= weight of the aluminum cup plus dried fat (g)

Determination of ash content

About 2 grams of each sample was weighed into preconditioned porcelain crucibles that were pre-heated in an oven set at 105 ± 2 °C for 2 h and cooled in a desiccator for 2 h. The samples were placed in a temperature-controlled muffle furnace (Nabertherm GmbH, Lilienthal, Germany) and incinerated at 550 °C for 5 h. The crucibles were transferred to a desiccator, cooled to 29 ± 2 °C, and reweighed. The ash content of the samples was calculated on a dry matter basis using equation (4).

$$Ash\ content\ (\%) = \frac{W_3 - W_1}{W_2 - W_1} \times 100 \quad (4)$$

Where W_1 = weight of the crucible (g),
W_2 = weight of the crucible and sample before incineration (g), and
W_3 = weight of the crucible and sample after incineration (g).

Determination of crude fibre

Fibre content was determined following Foss Fibertec system instructions. Fibre crucibles were first preheated in an oven set at 105 °C for 2 h and then filled with 2 g of sample and weighed. The fibre crucibles containing the samples were then fixed underneath glassier columns (Foss Fibertec™ 1020). Then, 100 ml of hot H_2SO_4 (1.25 %) was added to the glassier columns to hydrolyze organic substances (e.g., protein, carbohydrate) with occasional auto-heating for 30 min. Resultant residues were washed with hot deionized water followed by adding hot NaOH (1.25 %) to affect the saponification of fat in the sample over 30 min. The sample residues were further washed with hot water and then dried for 2 h in a hot air oven at 130 °C. The crucibles containing the dried sample residues were ignited in a muffle furnace at 550 °C for 5 h and weighed again after cooling following incineration. The crude fibre content of samples (dry matter basis) was then calculated using Eq. (5).

$$Crude\ fibre\ content\ (\%) = \frac{W_3 - W_2}{W_1} \times 100 \quad (5)$$

Where W_1= weight of the sample cup (g),
W_2= weight of the sample after drying (g), and
W_3= weight of the sample after incineration (g).

Determination of calcium, zinc, and iron

Half a gram (0.5 g) of each sample was digested with 10 ml nitric acid and 5 ml hydrogen peroxide at 200 °C for 90 min for complete digestion. After cooling to room temperature, the digest was filtered and made up to 100 ml with distilled water and analyzed for Ca, Zn, and Fe using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (iCAP 6300 England). The concentration of each mineral was expressed in parts per million (ppm).

Statistical analysis

Minitab Statistical software version 17 was used for analysis in which all data were reported as means +

standard deviation of duplicate determinations. One-way ANOVA was used to compare means of collected data and the significant difference between means was determined by Turkeys test. Differences were considered to be significant when $p<0.05$.

Results and discussion

Proximate composition

The proximate composition of the raw and dried sardines with different methods is presented in Table 1. Fresh fish is highly perishable and also cannot be consumed without cooking. Therefore, subjecting foods, especially meat and fish, to cooking makes them edible and enhances their digestibility. Fish is thus a product that needs proper handling and processing to preserve nutrients and its functional components that promote good health (Sulieman and Mustafa, 2012). However, the nutritional composition of fish is affected by processing temperature and time (Abraha *et al.*, 2018). Drying is a common practice for meat, fish, and other animal protein, as it preserves the quality of the product for an extended time, with minimum deterioration and insignificant changes in the product (Aberoumand and Karimi reza abad, 2015).

Moisture content

It is well understood that moisture content occupies the largest part of the fish body. In this study, moisture content of fresh samples was 72.61%, compared to 17.22%, 9.82%, and 9.45% for the SSD at 120 °C for 60 minutes, OD at 100 °C for 90 minutes and OD at 120 °C for 60 minutes, respectively. There was a significant difference ($p<0.05$) in the moisture content of the fresh and SSD sardines ($p<0.05$), however, there was no significant difference ($p>0.05$) between the oven-dried samples. The moisture content of the fresh sample is similar to that reported by Feng *et al.* (2012) who found that most fish contain 60 % to 80 % moisture content. According to Sheeba *et al.* (2021), two species of sardines (*S. fimbriata* and *S. longiceps*) had a moisture content of 69.8 and 78.2 %, respectively. It was also previously reported by Bagthasingh *et al.* (2016) that the value of the moisture content of sardine (*Sardinella gibbosa*) ranged from 70.79-78.16 %. In the present study, the highest moisture content was recorded in the fresh sardine sample (72.61%) and the lowest in the oven-dried sardine samples. The lowest moisture content in OD sardine samples is due to the high processing temperature applied which facilitated heat transfer. It is well understood that the drying process results in a significant decrease in moisture content while increasing other nutrients (protein, ash, lipids) (García-Arias *et al.*, 2003), as observed in this study. Among the dried sardine samples, SSD sardines had the highest moisture content (17.22%) because superheated steam retains more moisture than other processing methods. Similarly, Yu *et al.* (2017) reported the lowest moisture loss (46.84%) in superheated steam oven-cooked fillet when compared to convection oven cooking (50.13%).

Protein content

The protein content for the fresh and dried sardine samples is presented on a % dry matter basis (Table 2). Protein forms the largest quantity of dry matter in fish (Bagthasingh *et al.*, 2016). The protein content of the studied sardine samples ranged from 75.77 to 78.40 %, and there was no significant difference between them. The protein content of the fresh sardine sample was 78.17 %. The present study is in agreement to Owaga *et al.* (2010) who reported high protein content in the fresh fish sample (74.4 % dry weight basis) and the lowest in the retail market (62.5 % dry weight basis). According to Wisuthiphaet *et al.* (2015), the protein content of the fresh sample was 72.1 %. Daramola *et al.* (2007) also reported the protein content in five fish species ranging from 54.71 to 72.78 %. The highest value of protein was observed in OD at 100 °C, 78.40 %, followed by SSD, 76.05 %, and then OD at 120 °C, 75.77 %. It was reported by Immaculate *et al.* (2012) and Aberoumand (2020) that the increase of protein was due to the dehydration of water molecules present between the proteins causing aggregation of protein and therefore resulting

Table 1. Proximate composition (% dry matter basis) of both fresh and dried sardine samples.

Sample	Moisture	Protein	Fat	Ash	Fibre
FRESH	72.61±0.030^{a}	78.17±1.100^{a}	8.10±0.019^{d}	11.99±0.062^{b}	0.59±0.828^{a}
OD 100 °C	9.82±0.816^{c}	78.40±0.027^{a}	10.63±0.022^{c}	10.24±0.017^{c}	0.12±0.011^{a}
OD 120 °C	9.45±0.381^{c}	75.77±1.064^{a}	11.38±0.001^{b}	12.48±0.041^{ab}	0.015±0.021^{a}
SSD 120 °C	17.22±0.072^{b}	76.05±1.994^{a}	11.81±0.001^{a}	13.60±0.406^{a}	0.13±0.177^{a}

Results expressed as mean (n=3) ± standard error of the mean; samples with different superscript letters across the column indicates statistical difference according to Turkey's Honest Significance difference test ($p<0.05$).

Table 2. Mineral content (% dry weight basis) of fresh and dried sardine samples.

Sample	Ca	Zn	Fe
FRESH	24.94±0.947[b]	0.24±0.025[a]	0.11±0.025[a]
OD 100 °C	30.35±0.269[a]	0.42±0.024[a]	0.00±0.000[b]
OD 120 °C	13.67±0.147[c]	0.29±0.019[a]	0.00±0.000[b]
SSD 120 °C	25.24±0.177[b]	0.36±0.042[a]	0.02±0.000[b]

Results expressed as mean (n=3) ± standard error of the mean; samples with different superscript letters across the column indicates statistical difference according to Turkey's Honest Significance difference test (p<0.05).

in the increase in protein content of dried fish. The lowest protein content in OD at 120 °C might be due to denaturation as a result of the high processing temperature. However, there was no significant differences (p<0.05) between the three drying methods. The study of Steiner-Asiedu *et al.* (1991) reported the protein content of flat sardine (g/100 g dry matter basis) in fresh, cooked, fried, and smoked samples as 84.1, 82.0, 56.7, and 84.7, respectively. Flowra *et al.* (2012) reported the protein content of sun-dried fishes ranging from 60 to 80 %. Sablani *et al.* (2001) reported the highest protein content of 71 % dry matter basis in freezer-dried sardines and the lowest was 50-65 % dry matter basis in traditionally dried sardines. Sultana *et al.* (2011) reported the protein content of the dried SIS fish ranged from 52.66 to 72.45 %. According to Ayinsa and Maalekuu (2013), different fish processing presents different effects on the nutritional quality of the final product. According to Sultana *et al.* (2011), good quality dried fish can provide 52-73 % of human protein requirements, suggesting that eating 100 g of dried fish in a day provides the required protein for the body.

Fat content

The fat content of the fresh and dried sardine samples varied significantly (p<0.05) with the highest value found in SSD (11.81 %) and the lowest in the fresh sample (8.10 %). It has been reported that fat content is inversely proportional to moisture content (Palani kumar *et al.*, 2014) and this was similarly observed in this study. This could be the reason for low-fat content (8.10 %) in the fresh sample compared to the dried samples.

According to Sablani *et al.* (2001), sardines processed in the freeze dryer had a 10 % crude fat content. In the present study, the values of crude fat in the sardines are lower than those reported by Owaga *et al.* (2010) in the fresh sample (14.8 %) and the market sample (13.9 %). According to Shija *et al.* (2019), different cooking processes could lead to biochemical changes which include oxidation during heating. Moreover, the fat content may be reduced with the evaporation of moisture and increase during heat treatment (Immaculate *et al.*, 2012). It has been previously reported that cooking releases bound lipids as free lipids making them easier to extract (García-Arias *et al.*, 2003; Yu *et al.*, 2017). However, this is dependent on the method of cooking used. One advantage of using superheated steam for food drying is that the procedure has little impact on the fat content of sardines. The crude fat content of the sardine samples was 11.81 %, 11.38 % and 10.63 % for SSD at 120 °C, OD at 120 °C and OD at 100 °C, respectively.

Superheated steam drying normally operates under anoxic conditions which means oxidation and combustion reactions are prevented. Sutikno *et al.* (2019) reported that the superheated steam system was better than traditional cooking methods in reducing lipid oxidation and preserving food nutrient substances, colour, and texture. In contrast, fish processed in the oven presented low-fat content (32.99 %) compared to frying (37.33 %) (García-Arias *et al.*, 2003). According to the level of fat content fish can be grouped into four: lean fish (<2 %); low fat (2-4 %); medium fat (4-8 %); and high fat (>8 %) (Ackman, 1990). In the present study, sardines are grouped as medium-fat fish with 8.10 % fat content (fresh sardines). Bagthasingh *et al.* (2016) reported that the fat content of sardine (*Sardinella gibbosa*) varied from 1.25 % to 6.77 %. Sheeba *et al.* (2021) reported the fat content of *Sardinella fimbriata* and *Sardinella longiceps* as 2.7 % and 22.9 %. The variation in lipids has been explained by Bagthasingh *et al.* (2016) who reported that variation is due to season, temperature, feed intake, age, sex, and size.

Ash content

There was a significant difference (p<0.05) between the ash values. The ash content of the fresh, OD at 100 °C, OD at 120 °C, and SSD at 120 °C were 11.99 %, 12.48 %, 10.24 %, and 13.60 %, respectively. The study by Sablani *et al.* (2001) reported an ash content of 15 %

in freeze-dried sardines. It is well known that ash content increases as the moisture content decreases. This was true for all samples except the SSD sardine sample which despite the highest moisture content (17.22 %), presented the highest ash content of 13.60 %. This study is in contrast with Yu *et al.* (2017) who reported an ash content of 1.22% in superheated steam oven cooked fillet which was significantly lower ($p<0.05$) than that found in convection oven cooked fillet (1.43 %). However, all the fresh and dried sardine samples in this study presented high ash content. According to Steiner-Asiedu *et al.* (1991), the higher ash content (13.1 %) in the fresh sardine samples is due to the presence of bones. The total ash content in the fresh sardine (10.3 % dry weight basis) was significantly lower ($p<0.05$) than the values in the sun-dried market samples (13.5 % dry weight basis) (Owaga *et al.*, 2010). In addition, marine fish show higher values of ash content due to the different content of seawater (García-Arias *et al.*, 2003) which includes mineral salts and other contaminants. According to Islam *et al.* (2013), the ash content of the dried fish ranged from 29.34-34.49 % on a dry matter basis and associated this with sand and dirt contamination. The ash content of the five dried fish species reported by Flowra *et al.* (2012) ranged between 11.21 and 28.15 %.

Crude fibre

The crude fibre content of the fresh, OD at 100 °C, OD at 120 °C, and SSD at 120 °C sardine samples were 0.59 %, 0.12 %, 0.02 %, and 0.13 %, respectively. There was no significant difference ($p>0.05$) among them. According to the literature, the amount of crude fibre in fish is very low or sometimes absent (Effiong and Fakunle, 2011; Olopade, 2015). The fresh sample had the highest crude fibre content (0.59 %) as compared to the processed samples, which is consistent with the findings of Okpanachi *et al.* (2018). This is attributed to the effect of different cooking methods that affected the concentration of proximate composition (Abraha *et al.*, 2018).

Mineral elements

Minerals represent 0.2–0.3 % of the total intake of all nutrients in the human diet and are so important that without them, the remaining 99.7 % of food intake would be difficult to utilize (Yetunde, 2016). Minerals in sardines are stored mainly in the skeleton (Bouderoua *et al.*, 2011), therefore, when eaten whole they are good sources of these minerals. The results of calcium, zinc, and iron for the present study are shown in Table 2.

Calcium content

The present study noted a significant difference ($p<0.05$) in calcium content between fresh and dried sardine samples. The highest value was observed in OD at 100 °C (30.35 ppm) and the lowest in OD at 120 °C (13.67 ppm). The lowest levels of calcium in OD at 120 °C might be due to leaching as explained by Kirk (1984) and also destruction by high processing temperatures. The study by Shija *et al.* (2019) reported that processing methods have little or no effect and sometimes may increase the mineral content. Small pelagic fish are a rich source of high bioavailable calcium compared to larger fish (Reksten *et al.*, 2020).

Zinc content

There was no significant difference ($p>0.05$) in zinc content between the fresh and dried samples. However, there was an increasing trend due to processing (Table 2). The amount of zinc was highest in OD at 100 °C (0.42 ppm), then in SSD (0.36 ppm), and lowest in OD at 120 °C (0.29 ppm). Zinc plays an important role in the promotion of normal growth and development and is an element in the enzymes that work with red blood cells, which move carbon dioxide gas from tissues to the lungs (Ekweagwu *et al.*, 2008). In malnourished children zinc deficiency contributes to growth failure and susceptibility to infections since it is associated with complications of childbirth (Ekweagwu *et al.*, 2008).

Iron content

There was a significant variation ($p<0.05$) in iron content among the fresh and dried samples. However, sardines treated in the oven and SSD did not show any significant difference ($p>0.05$) in iron content. The concentration of iron in the present study was higher in the fresh sample (0.11 ppm) compared to SSD (0.02 ppm). In OD the iron was not detected in samples treated under either of the two temperatures. This might be due to the leaching of the element during processing. Iron is an important component for the synthesis of hemoglobin in red blood cells (RBCs) which helps to transport oxygen to all parts of the body. The deficiency of iron can cause anemia, impaired brain function, and in infants, it causes poor learning ability and improper behavior (Mishra, 2020).

Conclusions

The suitability of a superheated steam dryer for drying sardines was studied by investigating the proximate composition and mineral contents of the dried sardines. The study observed that using a superheated steam in drying fish resulted in better preservation of nutrients, especially protein and lipids, with lipids being highly susceptible to oxidation due to their long-chain carbon bonds. In addition, protein constituted a large portion of the fish studied. Although all methods were good in the preservation of nutrients in terms of protein, fat, and crude fibre, SSD is highly recommended because apart from reducing lipid oxidation, it maintains the silvery colour, aroma, and texture of the sardines. In addition, little or no breakage of SSD sardines was observed. This study recommends more testing to be carried out on the SSD technique for its efficiency in other food drying applications. Moreover, more research is needed on the use of other environmentally friendly and cost-effective energy sources apart from liquefied petroleum gas (LPG). Consuming sardines regularly for all age groups will reduce the complications of protein-calorie malnutrition which is a problem in Tanzania and in developing countries at large.

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Original Article

Hydrodynamics of nearshore coastal waters: Implications for marine cage farming in Kenya

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Abstract
Hydrodynamic characteristics are important considerations in the design of cages used for fish farming in nearshore marine environments. The hydrodynamics of sites in mangrove creeks and comparatively open water channels in Kilifi and Kwale Counties in Kenya were sampled across tidal cycles and seasons using an Acoustic Wave and Current Profiler (AWAC). Water temperature ranged between 25.9 °C and 33.0 °C, and was lower in deeper areas with larger tidal heights than in shallower areas with smaller tidal heights. The water column height ranged between 9.68 - 14.69 m at Kijiweni, 1.16 - 6.7 m at Kibokoni and Tsunza, and 0.72 - 2.57 m at Dabaso. Maximum current speeds were 0.83 - 0.87 m/s at Kijiweni, 1.1 m/s at Kibokoni, 0.89 m/s Tsunza, and 0.34 m/s at Dabaso. Wave height reached 0.35 and 0.36 m at Kijiweni, 2.7 m at Kibokoni, 1.3 m at Tsunza, and 1.6 m at Dabaso. The considerable difference in hydrodynamic characteristics between the sampling sites indicate that cages for marine fish farming should be designed specifically for local conditions in mangrove creeks and Cages for fish farming therefore require specific design and structural features depending on the local hydrodynamic conditions.

Keywords: hydrodynamics, marine, cage, culture, Kenya

Introduction
Capture fisheries on the east African coast provide support to a large number of communities. They are mostly artisanal, underdeveloped, over exploited and associated with coral reef, seagrass and mangrove ecosystems that are faced with challenges of degradation and climate change effects among other stressors (McManus *et al.*, 1997; Jiddawi and Öhman, 2002; Kaunda-Arara *et al.*, 2003; Worm *et al.*, 2006; McClanahan *et al.*, 2008; Mirera *et al.*, 2013). Indeed, primary producers working in the agriculture, forestry and fisheries sectors are more vulnerable to climate change since they are dependent on climate-sensitive natural resources; a situation which therefore impacts food security and livelihoods (IPCC, 2007; Cooper *et al.*, 2008; Stokes and Howden, 2010).

Global fish consumption has increased significantly since 1960 (9.0 kg per capita per year) to current (20.5 kg per capita per year). Per capita fish consumption in Africa is nearly half the global average (9.9 kg per capita) and accounts for 30 – 50 % of all the animal protein in many coastal countries (UN Nutrition, 2021). In the early 1980s per capita fish consumption in Kenya was estimated at 4.3 kg whereas demand for fish was estimated at 9.5 kg/person/year which implied a deficit in fish production that needed aquaculture intervention (Balarin, 1985). Currently, per capita fish consumption is estimated at 8 kg/person in Tanzania and 5.5 kg/person in Kenya thus creating a fish deficit of 230,000 MT in Tanzania and 150,000 MT in Kenya (Pauly *et al.*, 2003; FAO, 2018). Globally it has been observed that low fish supply could lead to malnutrition, under nutrition, and micronutrient deficiencies, which will consequently lead to poor health (Golden *et al.*, 2016). It is therefore evident that addressing food and especially protein insecurity in east Africa requires a sustainable and multi-faceted approach rather than dependency on freshwater systems where most of the aquaculture is currently practiced, wild fish capture, fish imports and terrestrial agriculture that depends on rain and other water sources that are impacted by climate change (Mmochi, 2015). Despite aquaculture being one of the frontiers for food production in the world (UN Nutrition, 2021), it is faced with several limitations with regard to sustainable development that need to be addressed (Troell *et al*., 2009).

Consequently, there is a need to develop strategies to adapt and mitigate climate change impacts and reduce social vulnerability from fish deficits to be able to attain the United Nations Sustainable Development Goal (SDG 14). Mariculture development is one of the strategies proposed to reduce pressure on near-shore fisheries in coastal east Africa (Troell *et al*., 2011). Mariculture in Kenya was conceptualized in 1976 through farming of prawns in intertidal earthen ponds at Ngomeni after failure of soil suitability tests at Dabaso in addition to seasonal fluctuations in temperature and salinity that impacted growth and survival (FAO, 1977). To date mariculture production has remained low in the country even though more species have been recruited into culture (Mirera, 2011, 2019; Mirera *et al*., 2020). Also, progress has been made in development of hatcheries to supply fingerlings to farmers (e.g. National Mariculture Resource and Training Centre (NAMARET, Shimoni). However, there is a need to focus on suitability of sites assessments for cage farming.

The development of marine cage farming will complement previously used intertidal earthen ponds in mangrove systems mainly used to farm milkfish, mullets, marine tilapia, mud crab and prawns extensively at small scale (Mirera, 2011, 2019; Mmochi, 2015). To embrace marine cage farming, a holistic knowledge of the ocean systems (near shore and offshore) is required to help tap into the Blue Economy potential and contribute to the sustainable development agenda (Österblom and Folke, 2013). Therefore, there is need for data on the physical and chemical dynamics of the ocean waves and currents in coastal creeks, channels, estuarine river systems, near shore and deep water systems to inform cage farming and ocean governance (Campbell *et al*., 2016; Halpern *et al*., 2019). Hydrodynamic characteristics like multidirectional, nonlinear combination of both waves and currents will inform cage engineering designs (mooring systems, cage shape, floater system, tension response, net blockage) through development of numerical models to cost effectively withstand extreme conditions and provide a suitable fish growing environment (Aarnses, 1990; Gignoux and Messier, 1999; Colbourne and Allen, 2001; Faltinsen and Shen, 2018). It is recognised that industrial marine cage fish farming is young globally but has significantly advanced in many regions of the world other than east Africa where it produces 6.6 million tons of fish per year (FAO, 2020). Indeed, cage technology genesis is traced back to the Antlantic salmon farms in Norway and Scotland in 1960s and 1970s respectively and has benefited from innovations over the years to achieve the currently engineered structures available in the market (Fredheim and Langan, 2009; Tilseth *et al*., 1991; Bao-Tong, 1994; Chen, 2007).

Using previously designed cage structures and learning from other regions like Norway, and understanding the prevailing physical and chemical dynamics of coastal sites in east Africa will inform mitigation measures through cage design, deployment, management, culture system and species to be farmed (Neori *et al*., 2004; Troell *et al*., 2009; O'Donncha *et al*., 2013). Studies undertaken in other regions indicate that water exchange rate can reduce to approximately 59 % due to increased bottom friction from suspended aquaculture in marine bivalves indicating that drag net effect influence water exchange rate and renewal of nutrient and food supply (Grant and Bacher, 2001; Shi *et al*., 2011; Cranford *et al*., 2014). Similarly, feed spills, cage waste diffusion and disposition is affected by direction and velocity of water current therefore influencing distribution of particulate organic wastes that may affect the health of benthic organisms and habitats (Holmer and Kristensen, 1994; Findlay *et al*., 1995; Wu, 1995; Petrell and Alie, 1996; Karakassis *et al*., 2000; Abreu *et al*., 2009; Faltinsen and Shen, 2018). A good current flow will ensure sufficient water exchange (good oxygen supply and well-being of fish) in a cage system.

Provision of hydrodynamic data will ensure that cage systems are installed properly to mitigate challenges associated to placement of net cage systems in areas that experience seasonal monsoon seasons and unpredictable wave behaviour or local tidal and strong ocean currents (Kawakami, 1964; Milne, 1972). The stability of marine cage culture systems will cushion farmers from major economic losses due to damages and collapses of floating fish farms that lead to escape of fish, breaking of mooring lines, anchor pull out or sliding, leading to cage movement to undesired locations with possible collisions with other maritime users, contacts between chains or ropes with the fish net leading to net tears (Faltinsen and Shen, 2018). Therefore, the current study sort to document the hydrodynamic characteristics of different near shore marine waters in coastal Kenya with the aim of delineating salient features (like depth, current strength, direction, wave height, tidal height and temperature) to inform site selection, design and deployment for marine culture cages.

Kibokoni Umoja to Tsunza Pennisula was 109 km; and from Tsunza to Kijiweni mariculture cages, Shimoni was 92 km. Kijiweni 1 and 2 were separated by a distance of less than 50 meters. The sites were categorized into three, based on the habitat and perceived hydrodynamic characteristics: (1) mangrove channels; (2) relatively sheltered near shore; and (3) sheltered creek/bays. Detailed characteristics of each of the sites is provided in Table 1.

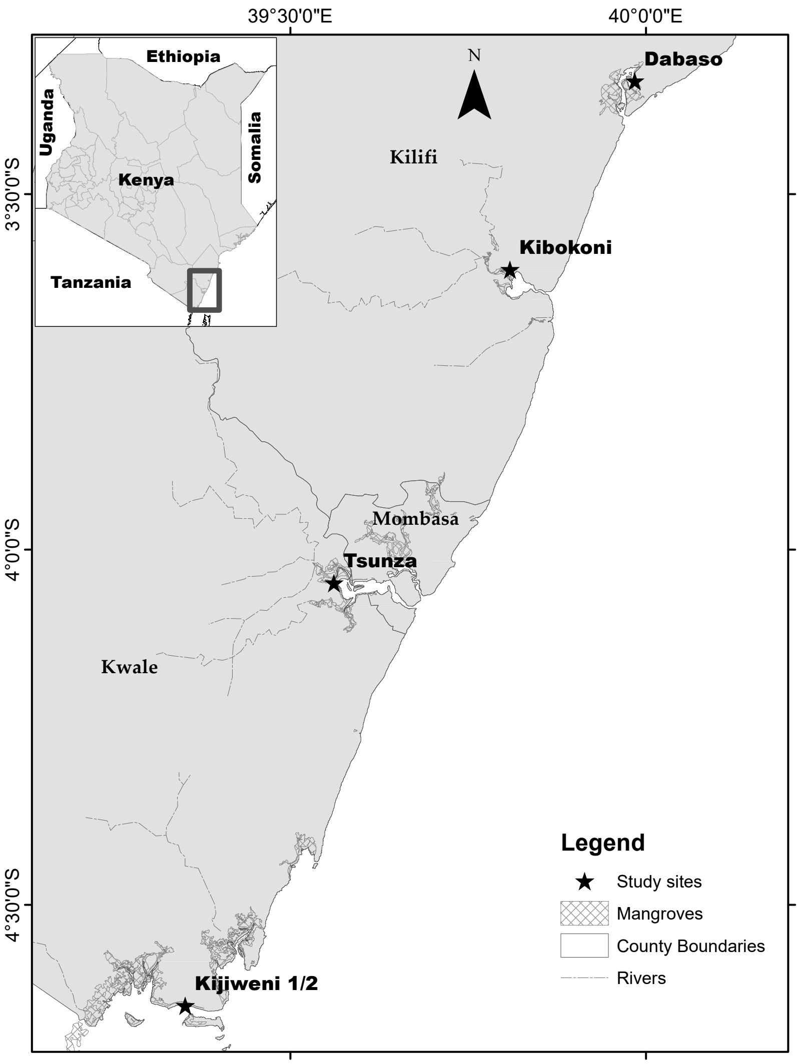

Figure 1. Map of the Kenyan coast showing the potential floating cage sites.

Methodology

Study sites

The study assessed the suitability of near shore marine waters for cage culture in Kenya. A total of five sites from the two counties of Kwale and Kilifi were involved in the study (Fig. 1). The distance between the study sites varied. From Dabaso at Mida Creek to Kibokoni Umoja group at Kilifi Creek was 54 km; from

Experimental design

Acoustic Wave and Current Profiler (AWAC)

The study used an Acoustic Wave and Current profiler (AWAC), model WAV 7499 developed by NORTEK to obtain hydrodynamics characteristics at the potential cage sites. AWAC has the capability to measure tidal variation (m), waves (m), temperature (°C), current speed (m/s) and direction (degrees). Quality control

Table 1. Characterization of the different sites assessed for cage suitability using hydrodynamic parameters along the coast of Kenya.

Study sites/ Characteristics	Shimoni	Mwache creek	Mida creek	Kilifi creek
Location	**Kijiweni**	**Tsunza**	**Dabaso**	**Kibokoni**
County	**Kwale**	**Kwale**	**Kilifi**	**Kilifi**
Description	- Relatively open near shore waters - Thin mangroves dominated by Sonneratia alba and Avicennia marina - Substrate is mud sand - Bathymetry has gentle slope near shore but drastically steep ocean wards	- Sheltered mangrove channel - Dense mangrove species dominated by Rhizophora mucronata and Ceriops targal - Mud substrate - Bathymetry is gentle sloping	- Sheltered mangrove creek - Dense mangrove species dominated by Rhizophora mucronata and Avicennia marina - Mud substrate - Bathymetry is gentle sloping with pockets of channels	- Sheltered mangrove channel - Dense mangrove species dominated by Rhizophora mucronata and Ceriops targal - Mud substrate - Bathymetry has gentle slope near shore but drastically steep ocean wards
Fishing activities	- Artisanal fishing of different marine species mainly rabbitfish	- Artisanal fishing dominated by prawns	- Artisanal fishing dominated by snappers	- Artisanal fishing dominated by prawns and mud crabs
Mariculture activities	- Seaweed farming - Interest in cage farming	- Pond milkfish farming - Interest in cage farming	-Mud crab farming -Interest in cage farming	- Prawn farming, marine tilapia - Interest in fish cages

on data was conducted by the use of storm-64 software while data retrieval used AWAC AST software. The AWAC system can resolve waves from 1 to 100 seconds and measure current speed and direction in 1 m thick layers from the bottom to the surface. The AWAC equipment was deployed at the maximum recorded depth of the different study sites to collect data over a period of 4 – 19 days to capture spring and neap tide variation. Seasonal variability (NEM and SEM) was captured at one site that was relatively exposed (Kijiweni).

Equipment was prepared for use by assembling the frames using bolts and nuts and bolting the battery that runs the equipment onto the frame. It is then connected to a laptop using a serial port connector cable and configured using AWAC AST software to collect data. The AWAC equipment is carried to the site by boat and lowered to the ocean floor with the help of divers where it would remain for the whole experimental period (4-19 days). Weights were added to enhance sinking capacity and the equipment was anchored at the bottom with more weights to minimize the tilt effect (tilt angle to be less than 30 degrees at all times). A buoy was attached to the AWAC with rope for easy visibility by any other ocean users and for easy identification during retrieval.

Sampling design

The Kenyan coast is characterised by neap and spring tides which influence movement of water to the shore. Also, the coast experiences a tropical climate influenced by monsoon winds with two distinct seasons (NEM and SEM). The NEM is characterized by hot and calm weather and the SEM by strong winds, cool temperatures and rough seas (Linden and Lundin, 1996). Sampling was designed to capture data for the different seasons and tidal cycles to inform cage culture interventions (Table 2). To provide a broader view of the effect of tide and season on hydrodynamic characteristics, sampling was carried out for shorter periods of four days (covering only one neap of spring tide) and long periods of 19 days (covering full neap and spring tide cycles). At one site sampling was repeated after a year to assess if there were variations between years. The AWAC captured the same data for all sites even though sampling days were different at sites. It was anticipated that such robust sampling could provide data that could inform future site assessments for cage farming.

Stakeholder involvement was conducted through focus group discussions with the ocean users at each site, especially fishermen, to identify the most viable areas. This involved identification of sheltered areas, areas not close to known fishing areas and navigation routes, and areas that remained relatively deep at low tides (Beveridge, 2004). Random sampling was undertaken using a handheld eco sounder to establish depth gradients (Turner, 2000). Before deployment, fishers were engaged to monitor the equipment as a mitigation against vandalism.

Table 2. Acoustic wave and current profiler deployment period (days) and season at the different study sites on the coast of Kenya.

Sampling sites	AWAC deployment period (days)	AWAC deployment Month	AWAC deployment season
Shimoni, Kijiweni 1	14	March	Northeast Monsoon
Shimoni, Kijiweni 2	19	July	Southeast Monsoon
Kilifi creek, Kibokoni	14	February	Northeast Monsoon
Mwache creek, Tsunza	4	September	Northeast Monsoon
Mida creek, Dabaso	4	September	Northeast Monsoon

Data analysis

The AWAC data was analyzed and visualized using the programming and numeric computing platform MATLAB and presented graphically.

Decomposition of tidal currents

Tidal current velocities measured by the AWAC profiler were decomposed in order to determine the horizontal velocity components within the main channels. Main direction of flow was determined by plotting current velocities against respective directions. This was also used to determine the dominant current velocities during the period of measurements. The along channel velocity component (u) was determined from the current velocity record as

$$u = U\cos\left(\pi\frac{\alpha}{180}\right) \quad (1)$$

The cross-channel velocity component (v) was determined by using the equation

$$v = U\sin\left(\pi\frac{\alpha}{180}\right) \quad (2)$$

Where U is the current speed record and α is the direction angle measured in degrees.

Harmonic analysis

Harmonic analysis was carried out to establish the influence of the external factors on water velocity. The analysis is a mathematical method of extracting sinusoidal components of specific frequencies from, e.g. a water level record. In this case, it was based on the "method of least squares". Instead of fitting a straight line to the data by varying its slope and intercept, a set of cosine (or sine) curves with given frequencies ω were fitted by varying amplitudes and phases, minimizing the sum of deviations from the original curve.

Given a time series *Z* (*t*) of data points, the tidal part can be expressed as a combination of sine and cosine functions (*cf.* Dronkers, 1964) as:

$$Z(t) = \sum_k a_k \sin(\omega_k t) + \sum_k b_k \cos(\omega_k t) \quad (3)$$

The value of ak and bk can be calculated for the given frequencies, ωk by minimizing the sum of squares of the differences between the assumed function and the given time series Zn.

Least square fit requires that the following function is

$$f(a_k, b_k) = \sum_{n=1}^{N}\left(z_n - \sum_k a_k \sin(\omega_k t_n) + \sum_k b_k \cos(\omega_k t_n)\right)^2 \quad (4)$$

This requirement is satisfied by

$$\frac{\partial f}{\partial a_i} = 0 \qquad i = 1,\ldots,k \quad (5)$$

and

$$\frac{\partial f}{\partial b_i} = 0 \qquad i = 1,\ldots,k \quad (6)$$

Where

$$\frac{\partial f}{\partial a_i} = -2\sum_{n=1}^{N}\cos(\omega_i t_n)\left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n)\right) = 0 \quad (7)$$

and

$$\frac{\partial f}{\partial b_i} = -2\sum_{n=1}^{N}\sin(\omega_i t_n)\left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n)\right) = 0 \quad (8)$$

The above equations can be rewritten as

$$\sum_k a_k \sum_{n=1}^{N}\sin(\omega_k t_n)\cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N}\sin(\omega_i t_n)\sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \sin(\omega_i t_n) \quad (9)$$

$$\sum_k a_k \sum_{n=1}^{N}\cos(\omega_k t_n)\cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N}\cos(\omega_i t_n)\sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \cos(\omega_i t_n) \quad (10)$$

This can be simplified by introducing the notation

$$C_{in} = \cos(\omega_i t_n),\ S_{kn} = \sin(\omega_k t_n) \quad (11)$$

$$\sum_k a_k S_{kn} C_{kn} + \sum_k b_k S_{in} S_{kn} = \sum_n Z_n S_{in} \quad (12)$$

$$\sum_k a_k C_{kn} C_{kn} + \sum_k b_k C_{in} S_{kn} = \sum_n Z_n S_{in} \quad (13)$$

Results

Temperature and tidal variation

Relatively sheltered near shore waters (Shimoni – Kijiweni)

The depth of water at low tide was higher in Kijiweni 1 (12 meters) compared to Kijiweni 2 (8 meters) (Table 3). Higher variation in daily temperature was observed in Kijiweni 1 compared to Kijiweni 2 (Fig. 2 A, B). A consistent incremental trend was observed in temperature in Kijiweni 1 sampling site with a minimum of 25.9 °C, maximum of 27.6 °C and an average of 26.64 ± 0.37 °C. Kijiweni 2 recorded a minimum temperature of 28.1 °C, maximum 28.93 °C and an average of 28.42 ± 0.14 °C (Table 3). There was a difference in the behaviour of daily water column heights observed in the different sampling sites with clear distinctions between neap and spring tides (Fig, 2 C, D). The highest water column height in Kijiweni 2 was 13.568 m and the lowest 9.684 m, 14.691 m and 10.894 m respectively for Kijiweni 1 (Fig. 2 C, D).

Mangrove creek channels (Kibokoni and Tsunza)

Temperature variations at Kibokoni mangrove channel showed a distinct trend that resonated well with neap and spring tides with a maximum of 33.0 °C, minimum of 29.69 °C and an average of 30.98 ± 0.69 °C, while the highest water column height was 6.7 m and lowest 3.1 m (Fig. 3 Kibokoni A, B). At Tsunza, the sampling period was four days and temperature variations were minimal and lacked a trend with a maximum of 29.4 °C, minimum of 27.8 °C and an average of 28.64 ± 0.12 °C (Fig. 3 Tsunza A). Similarly, the highest water column height at Tsunza was 4.46 m and lowest 1.16 m but there was no tidal trend (Fig. 3 Tsunza B).

Mangrove creek bay (Dabaso)

Over the four days sampling period, temperature fluctuated between a maximum of 30.2 °C, minimum of 27.5 °C and an average of 29.54 ± 0.48 °C . The highest recorded water column height was 2.57 m and the lowest 0.72 m (Fig. 4). No specific trend was observed in the variation of the two parameters.

Tidal current speed dynamics

Relatively sheltered near shore waters (Shimoni – Kijiweni)

Water currents in the area can be classified as unidirectional caused by tides and wind. At Kijiweni 2 the current had a maximum speed of 0.8690 m/s and spread towards northeast (NE) or seawards and northwest (NW) or landwards (Fig. 5A-Direction) while in Kijiweni 1 maximum speed was 0.83 m/s and spread towards the west (W) or landwards (Fig. 5B- Direction). Current speed across the channel (V) was relatively lower than along the channel (U) (Fig. 5A -U&V, B- U&V). Flood (incoming) current dominated the site that led to an inverse correlation of the V-Velocity vs U-Velocity (Fig. 5 A – V vs U, B – V vs U). There were observed variations in wave heights over the two sampling points with highest wave height of 0.36 m in Kijiweni 2 (Fig. 6 A-W) and 0.35 m in Kijiweni 1 (Fig. 6 B-W).

Table 3. Hydrodynamic characteristics obtained in the four assessed sites along the coast of Kenya.

		Sampling sites				
Parameter	**Details**	**Kijiweni 1**	**Kijiweni 2**	**Kibokoni**	**Tsunza**	**Dabaso**
Current (m/s)	**Direction**	**W - Landwards**	**NE-seawards NW-landwards**	**SE-seawards**	**NE- seawards**	**NW – landwards E - landwards**
	Max V (across channel)	0.64	0.65	0.75	0.49	0.24
	Max U (along channel)	0.83	0.869	1.113	0.89	0.344
	Bottom water	0.541	0.41	1.195	0.89	0.344
	Intermediate	0.584	0.45	-	-	-
	Surface water	0.869	0.815	1.113	0.89	0.344
Wave height (m)	Mean	0.35	0.36	2.7	1.3	1.61
Depth (m)	At low waters	12	8	6.7	4.1	2.0
Tidal height (m)		4.0	3.89	3.6	3.42	1.87
Temperature (°C)	Max	27.6	28.93	33.0	29.4	30.2
	Min	25.9	28.1	29.69	27.8	27.5

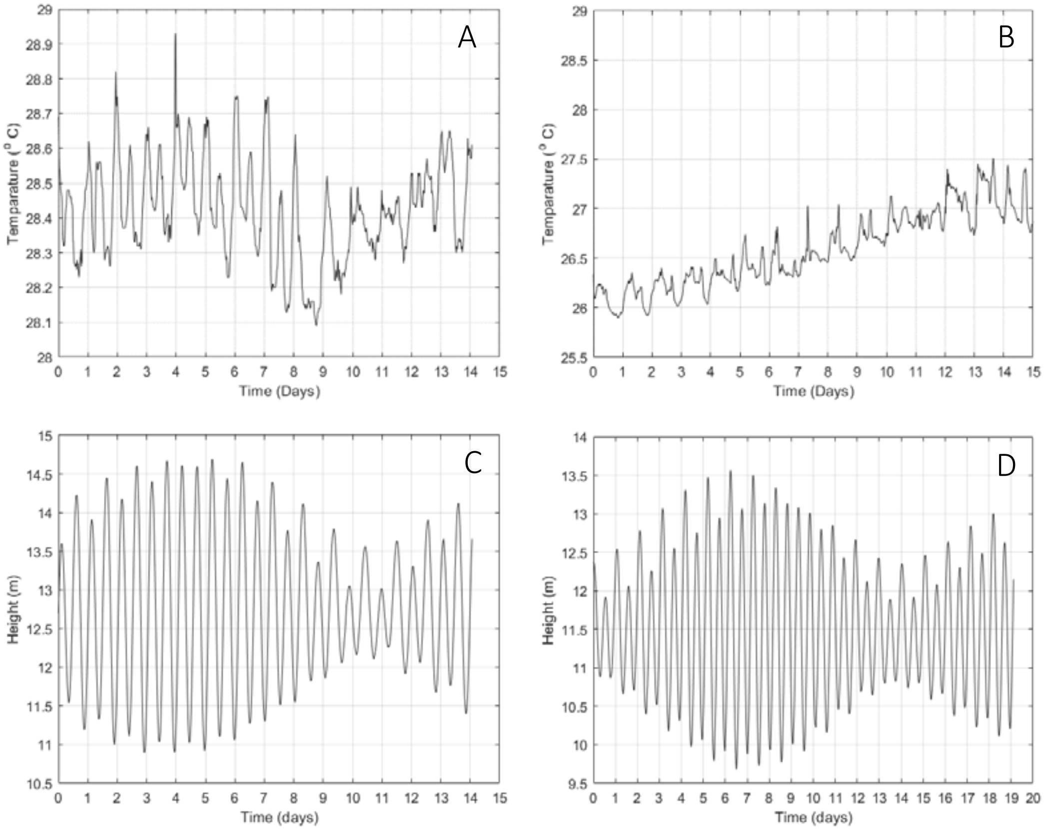

Figure 2. Water temperature (A and B) and water column height (C and D) variation in a relatively sheltered nearshore system at Kijiweni - south coast of Kenya monitored for two different points (Kijiweni 2-AD, Kijiweni 1-BC) for a 19 days sampling period.

Mangrove creek channels (Kibokoni and Tsunza)

The maximum current speed at Kibokoni was 1.113 m/s flowing towards the southeast or seawards (Fig. 7 A, C, E) and Tsunza 0.89 m/s flowing towards the east northeast or seawards (Fig. 7 B, D, F); an indication that ebb or receding currents dominate at the two sites. The relationship between V-Velocity vs U-Velocity at Kibokoni indicates a negative (inverse) relationship (Fig. 7 G) while that of Tsunza indicates a positive (direct) relationship (Fig. 7 H). The maximum wave height recorded at Kibokoni was 2.7 m (Fig. 8 K-W) while at Tsunza it was 1.3 m (Fig. 8 T-W).

Mangrove creek bay (Dabaso)

Water movement along the mangrove creek bay was relatively slow with a maximum current speed of 0.344 m/s and spread towards the northwest or landward (Fig. 9 A, B) while the maximum current speed across the bay was 0.24 m/s spreading towards the east or landward (Fig. 9 A, C). There was an inverse relationship when comparing V-Velocity vs U-Velocity. The maximum wave height (Hs) recorded at Dabaso over the four-day sampling period was 1.61 m (Fig. 9 D).

Relationship of depth and current

There was an observed trend of current and depth that was unique to the different sites studied. Mangrove sheltered sites like Kibokoni exhibited higher water current in the bottom waters and lower current in the surface waters. There were also observed spikes in wave height in sheltered mangrove creeks compared to open sites. In relatively open sites at Kijiweni the water current was higher in surface waters and decreased with water depth (Table 3).

Discussion

Three categories of cage site selection criteria need to be addressed for effective cage farming: physico-chemical (temperature, salinity, oxygen etc) suitable for the species under culture; oceanographic factors (waves, currents, weather, shelter, depth, substrate, winds etc); and profitability factors (legal aspects, access, land-based facilities, security, economic and social considerations). Therefore, cage design and deployment are site specific and guided by the knowledge of the site oceanographic conditions (Siddiqui and Nagarajan, 2016). A floating cage system has four main components which have distinct functions and

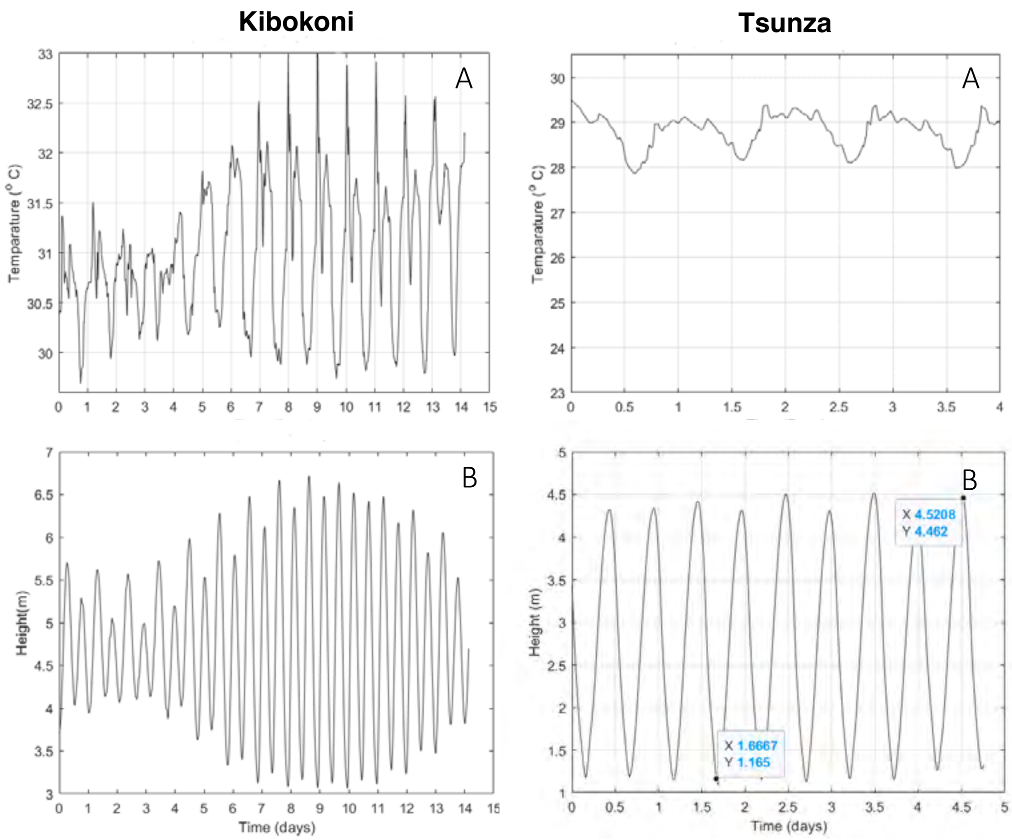

Figure 3. Temperature (A) and water column height trends (B) in two mangrove channels (Kibokoni and Tsunza) sampled at different time periods (15 and 4 days respectively).

roles: the flotilla/floating collar provides buoyancy, provides shape of the cage net and may be used as a working platform (Liu *et al.*, 2019); the cage net holds the fish that are farmed in the cage system and the netting dimensions determines the volume available for fish culture while the water exchange inside a cage is inversely proportional to the volume of the net and is influenced by the speed of the current (Piccolotti and Lovatelli, 2013); the anchors will provide the sinking effect to help bring the shape of the cage and hold it in place; while the mooring provides the connection between the sinkers and the flotilla to keep the cage in place. These aspects require understanding of the hydrodynamic characteristics that will inform the wave force acting on the cage to guide cage engineering (Kumar and Karnatak, 2014). Based on the resistance effect of cages, circular cages are more preferred since they can withstand dynamic stress and thus are

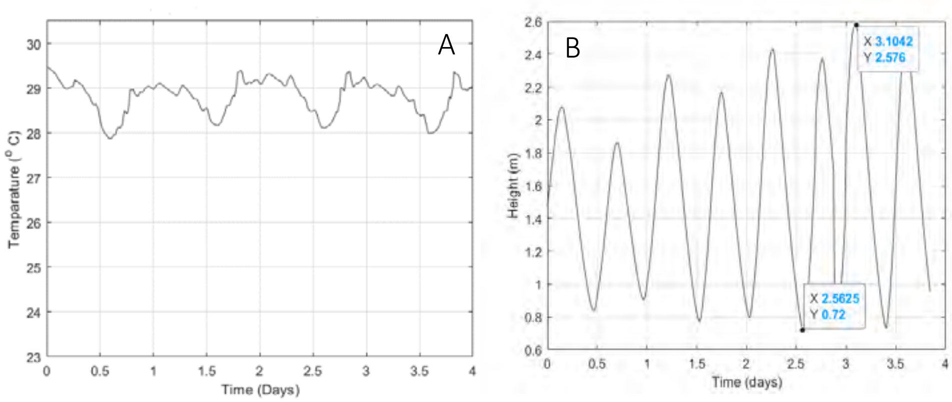

Figure 4. Changes in temperature (A) and water column height (B) over the four days experimental period at Dabaso mangrove creek bay.igure 5. Changes in U and V speed, direction and correlation between U and V velocities in a relatively sheltered nearshore system at Kijiweni - south coast of Kenya monitored at two different sampling points (Kijiweni 1 – B, Kijiweni 2 - A) over a 19 days sampling period.

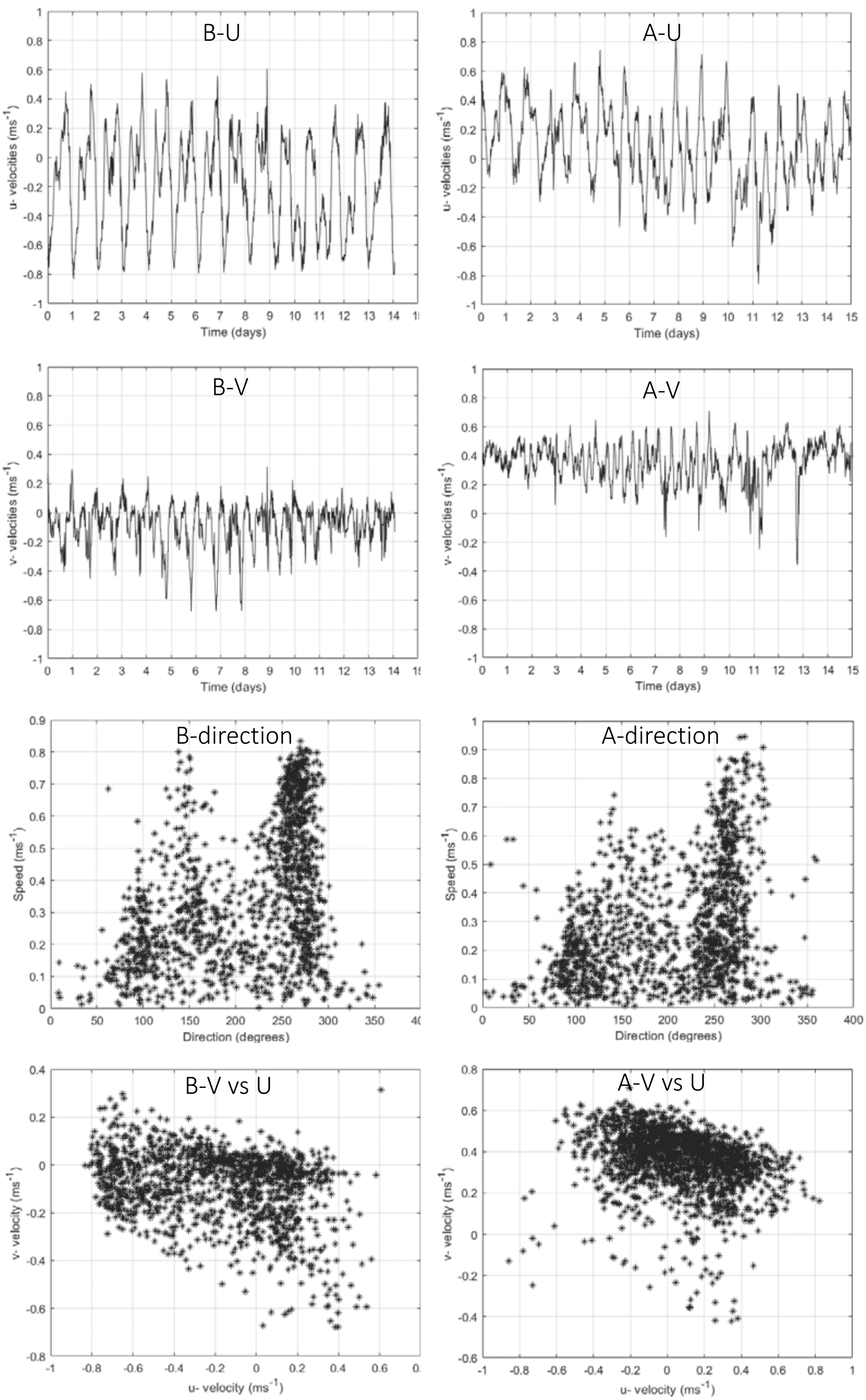

Figure 5. Changes in U and V speed, direction and correlation between U and V velocities in a relatively sheltered nearshore system at Kijiweni - south coast of Kenya monitored at two different sampling points (Kijiweni 1 – B, Kijiweni 2 - A) over a 19 days sampling period.

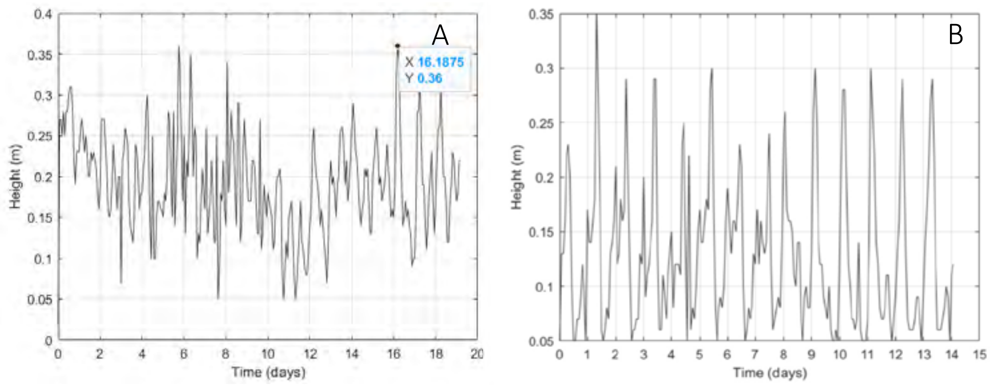

Figure 6. Variations in wave height at Kijiweni – south coast of Kenya at two different sampling points (Kijiweni 2 – A, Kijiweni 1 – B) monitored over a period of 19 days.

more suitable in less sheltered sites while square or rectangular cages will have large forces in the corners that can eventually lead to breakage and thus only suitable to sheltered sites. However, rectangular or square cages are preferable since they are easier to construct, have a higher water exchange rate within the net and can be constructed in large sizes (Piccolotti and Lovatelli, 2013).

In most coastal regions tidal currents are the predominant source of surface water currents where wave height is referred to as tidal range. This are influenced by the attractive forces, exerted by the moon and sun thus producing tidal waves during spring and neap tides with extreme long wavelengths with oscillation period of 12 h 25 min (crest and trough) being termed as high and low tides. The tidal created waves present minor problems for cage fish farms though they can create very strong tidal currents. In practice, ebb and flood tidal currents in the range 0.1–0.6 ms^{-1} and mean tidal currents of 0.03–0.2 ms^{-1} have been found to be satisfactory for good water exchange; sites where currents exceed 1ms^{-1} are not generally recommended (Braaten and Saetre 1973; Chen 1979; Chua and Teng 1980; Kerr *et al.* 1980; PPD 1986; Ikenoue and Kafuku, 1988; Rudi and Dragsund 1993; Turner, 2000). In the current study ebb and flood tidal currents in the range of 0.24 - 1.113 m/s were found at all the sites assessed. There were no sites with water currents lower than 0.1 m/s; a condition that would prevent good water exchange for oxygen supply and poor transport of faeces and excess feed, leading to a build up at the bottom of the cages creating anaerobic conditions and hydrogen sulphide in the sediments that is toxic to fish (Beveridge, 1996; Huguenin, 1997).

Areas characterized with U velocities of 1.0 – 1.5 m/s and more than 1.5 m/s are described as highly and extremely exposed respectively (Faltinsen and Shen, 2018). In one of the study sites, the along the channel current/velocity (U) recorded was higher (1.113 m/s) which could be associated with the steep topography observed in the creek (Turner, 2000). The current was above 1m/s which is problematic because of the likelihood of very large forces on the cage structure and mooring system that may lead to breakage or shifting of cages or cage deformations; this is relevant for cage design and instalments at Kibokoni mangrove channel, Kilifi Creek (Lader and Enerhaug, 2005; Huang et al., 2008; Lader *et al.*, 2008; Holmer, 2010; Moe *et al.*, 2010). Aarsnes *et al.* (1990) observed that up to 80 % of the expected volume available to hold fish in gravity cages may be lost in currents of 1 m/s. Current speeds of 0.13–0.35 m/s were observed to reduce the cage volume by 20–40 % by causing the cage bottom to be pushed upwards. Further, currents influence fish behaviour, affecting social hierarchies, growth and growth disparities among stock (Phillips *et al.*, 1985; Leon, 1986; Jobling, *et al.* 1993; Jobling, 1995) and, reportedly, flesh quality. Also, excessive currents are associated with skeletal deformities in cage-reared carp.

The present study provides information on currents that, if well understood, will improve the marine cage resistance to dynamic stress caused by swells and currents in addition to informing suitable cage dimensions for each site. Sheltered sites with weaker currents as in the current study will require smaller cage sizes compared to exposed sites. Further, cage design will also be informed by the cost implication of making cages since the cost per cubic meter of cage volume reduces as the size increases. According to Kumar and Karnatak (2014), the cost of making a 100 m^3 cage is less compared to making two cages of each 50 m^3. Larger cages will save cost of material used to make cages and cost of management and maintaining one unit of cage compared to separate small cages even

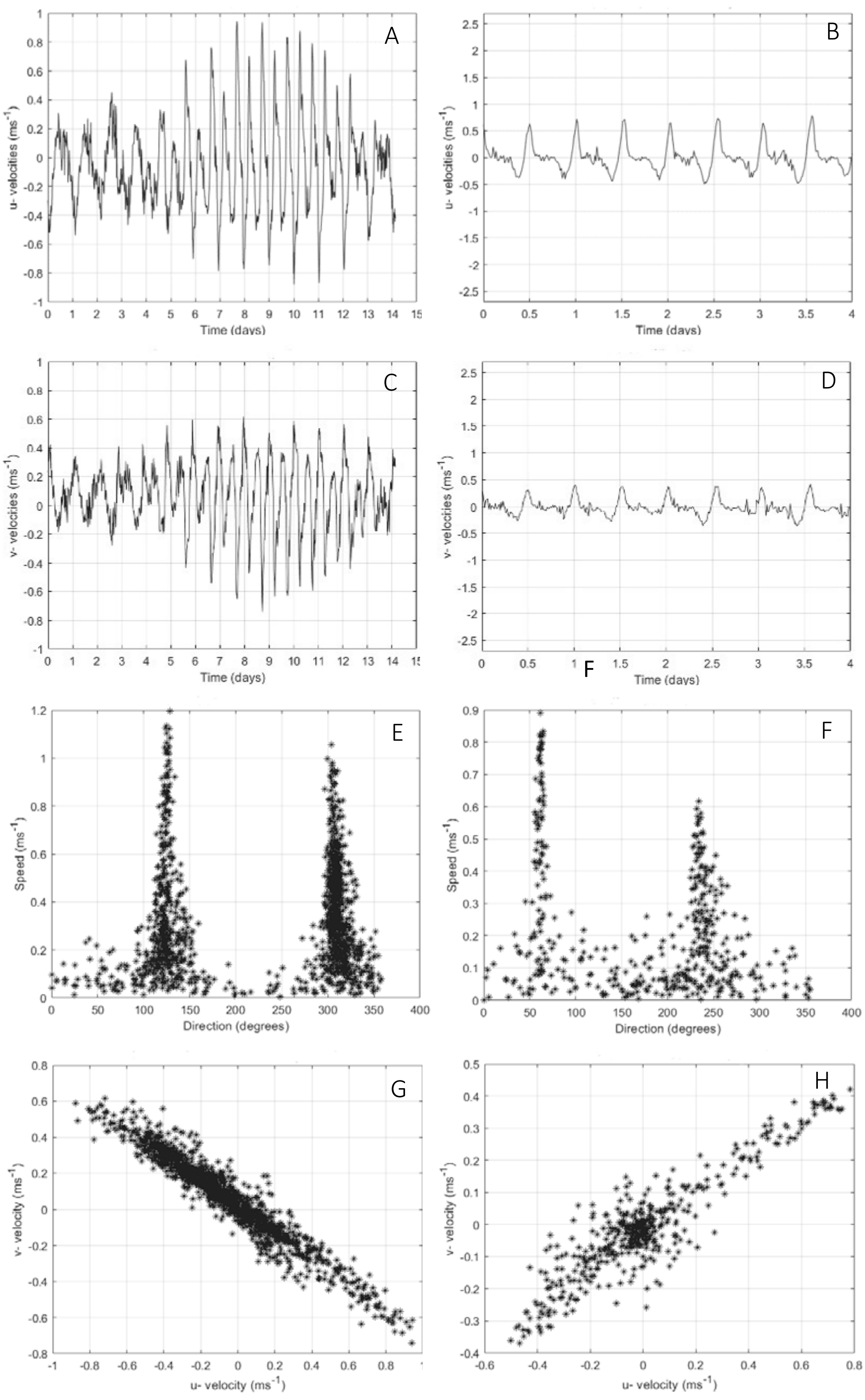

Figure 7. Changes in U and V velocity, direction and relationship between U and V velocities in the mangrove channels of Kibokoni (Kilifi creek – A, C, E, G) and Tsunza (Mwache creek- B, D, F, H) in Kenya monitored at different time periods.

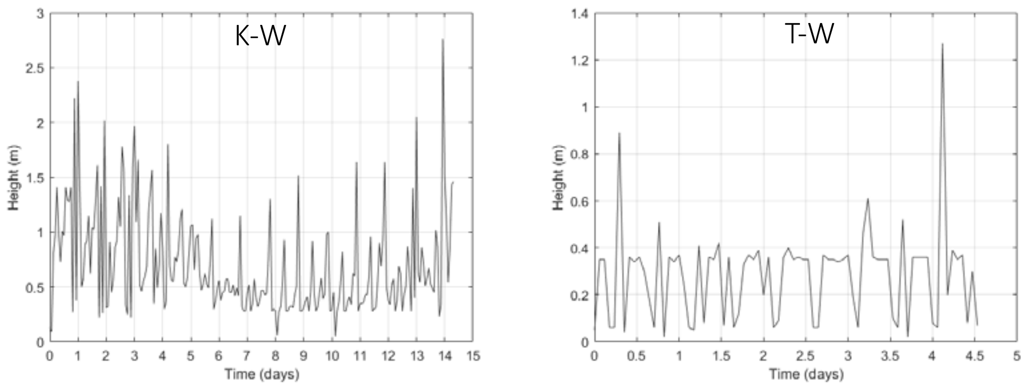

Figure 8. Variations in significant wave height at Kibokoni (K-W) and Tsunza (T-W) monitored over 14 days and 4 days respectively.

though the losses could be huge in the event of torn nets or replacements (Piccolotti and Lovatelli, 2013). Also, in smaller cages the stocking density may be increased (200 kg/m^3) compared to bigger cages (25 kg/m^3), but smaller cages could lead to bigger losses of feed which is pushed quickly out of the cage by currents before consumption by fish. For these reasons currents are important in cage site selection and design (Piccolotti and Lovatelli, 2013).

Wind is the main ingredient in the formation of waves in the open ocean which are the greatest determinant of site selection in cage farming. When winds blow across water, a drag is applied on the surface and pushes the water up, creating a wave. The height will increase as long as the wind is strong enough to add energy to the wave. Once a wave is generated, it will travel in the same direction until it meets land or is dampened by an opposing force such as winds blowing against it in the opposite direction, or by friction (Bascom, 1964). The height of wind-created waves depends on the wind velocity, the duration of the wind, the fetch length (distance where wave development can take place) and the presence of other waves when the wind begins to blow. The current study recorded wave heights of between 0.35 and 2.7 m in the four sites assessed which are within the mean wave height recommendations of other studies (Beveridge, 1996; Huguenin, 1997; Aguilar-Manjarrez *et al*, 2013). The site with the highest wave height is a mangrove creek which by its nature is well sheltered though the steep bathymetry of the creek might be associated with the attained wave height. According to Faltinsen and Shen (2018), wave heights of more than 2.0-3.0 m and more than 3.0 m are found in areas described as highly and extremely exposed, respectively. Significant wave heights of 2 m are most suitable for cage farm sites since cages can tolerate such heights. However, it is advisable to construct cages that can tolerate significant wave heights of 4 – 5 m. Some ocean cages may be constructed to tolerate significant wave heights of 7 - 8 m but in such cases there is need for special considerations of how such cages can be operated before selecting such sites. Such extreme wave heights were not recorded in the current study. Cage farms set in areas with high wave heights are difficult and expensive to operate since operational access is reduced and thus not an option for small scale fish farmers since they can only be operated with large and expensive boats. Therefore, knowledge of the wave climate of an area helps in choosing the correct cage technology and mooring system that will ensure integrity of the cage (Cairns and Linfoot, 1990; Pérez *et al.*, 2003).

Tidal heights significantly influence movement of cages and the recommended heights are between 2-3 m (Francesco Cardia *et al*, 2015). Tidal ranges of 1.67 m have been observed to influence movement of 22 m diameter circular cages by 10.1 and 7.7 m east and north thus increasing the effective area under the cage available for fish waste deposition by 72 % (Corner *et al.*, 2006). The current study established a tidal height range of between 1.87 and 4.0 m in all assessed sites. This is suitable for cage drainage although it may lead to significant cage movements that require adjustments to the mooring system to avoid cage breakage. To mitigate against breakage and compensate for movement, rectangular cages are normally oriented with the larger dimension placed in the streamwise direction. However, with this configuration, circulation of flows around and through the entire farm becomes complex since cages downstream may experience reduced water exchange compared to the upstream cages leading to more wastes, decrease in quality of water and dissolved oxygen (Kleberta *et al.*, 2013).

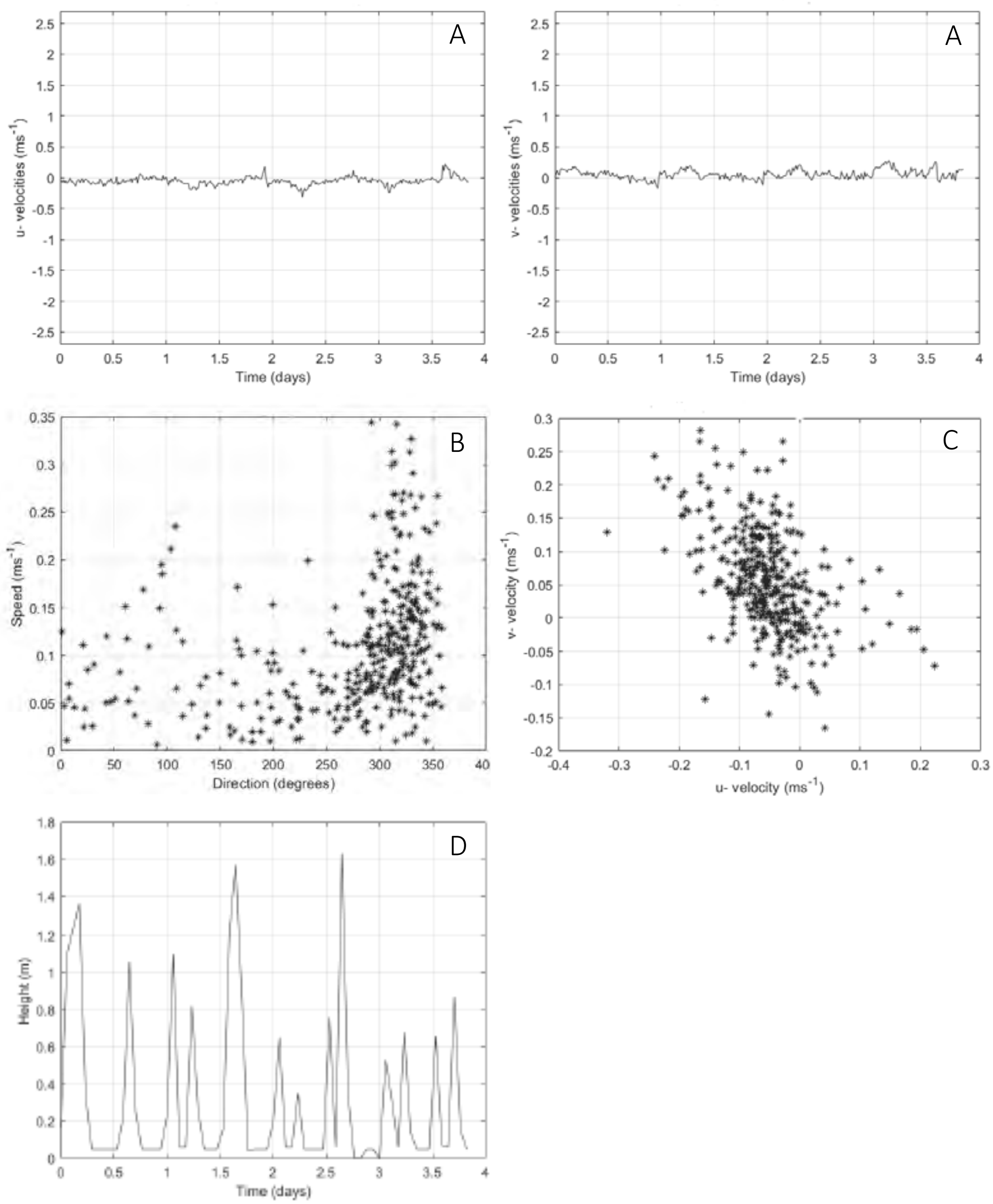

Figure 9. Changes in U and V velocity (A), direction (B) and correlation between U and V velocities (C) and significant wave height (D) at Dabaso mangrove creek bay monitored over a period of four days.

According to Li (1994), a cage should be held within the plankton- rich surface (< 2 m) waters. Very shallow cages (< 1.5 m) have been shown to affect body shape and retard growth in carp and tilapia farms (Maruyama and Ishida, 1976, 1977) although some other fish like flatfish (turbot and halibut) may prefer shallow cage depths of 0.9 – 1.6 m (Kerr *et al.*, 1980; Martinez Cordero *et al.*, 1994). In the current study varied water depth was found at low tides (ebb water) for different sites ranging from 2.0 – 12 m depending on the characteristics of the site. Taking cognizance of the fact that a cage needs to operate between 0.9 – 2 m from the water surface based on culture species, the sites assessed are suitable for cage farming though species selection needs to be undertaken based on the specific requirements. Equally, the depth of a cage site is a determinant of the mooring system to be used. Usually water depths with a distance of 2 – 5 m from the bottom of the cage to the sea bottom is recommended if the current conditions are suitable (Beveridge, 1996; Huguenin, 1997). Depths above 100 m will greatly increase the costs of the mooring system since long mooring lines will be needed.

Cages should be sited in sufficient depth to maximize the exchange of water yet keep the cage bottoms well clear of the substrate. Indeed, water is drawn into the cage not only through the sides but also through the bottom and therefore, as the cage bottom approaches the substrate, water flow is impeded thus the requirement to hold fish at least 4 – 5 m above the sediments (Chacon Torres *et al*., 1988).

The current study established an increment of water current with depth in sheltered mangrove channels that were associated to tidal currents, while in relatively open sites surface waters had stronger currents than bottom waters. The study provides new information for consideration when developing cages in mangrove channels that are assumed to be sheltered and thus less influenced by currents. Establishment of the bottom topography/bathymetry is also important as it gives information of sloping contours that will inform placement of anchors and distance of cage placement from the bottom (Turner, 2000). Depth estimations need to be well compensated with tidal fluctuations which may range from 0.5 m to over 10 m depending on the part of the world and calmness of the weather (Muir Wood and Fleming, 1981).

Conclusion and recommendations

The hydrodynamic characteristics of the different sites studied on the north and south coast of Kenya indicate that Kenyan waters are suitable for cage culture. Based on the findings, different cage designs need to be employed in each site to meet the varied dynamics in currents, waves, tidal heights, depth, flow and temperatures. Being a new potential area for cage culture in the region, more studies are required to characterize the entire nearshore coastal area to inform development of the industry in addition to provision of data for suitable species for culture and contribute to marine spatial planning to minimise user conflicts.

Acknowledgements

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Original Article

Lessons for ensuring continued community participation in a mangrove blue carbon conservation and restoration project in Madagascar

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Abstract
Successful conservation projects that restrict or change access to common pool resources require meaningful community participation not only through consultation but also by empowering communities to take a leading role from the early stages of its design. In this study, community participation was assessed in the Tahiry Honko community-led mangrove blue carbon project in southwest Madagascar using the Spectrum of Public Participation tool developed by the International Association for Public Participation. Trends of community participation at village meetings were assessed using the meeting records from 2014 to 2019. Performance in the project activities was assessed based on the indicators of success. It was learned that: (*i*) careful scheduling of meetings is crucial to avoid community fatigue; (*ii*) anonymous democratic votes are an effective, inclusive approach to address domination in a group activity and obtain informed consent; (*iii*) creating a comfortable space for women is vital to promote their participation in decision-making; (*iv*) voluntary approach with meal compensation is effective to engage all community groups in mangrove replanting; (*v*) competitive process is crucial to recruit motivated volunteers for mangrove forest patrols; and (*vi*) dissemination of patrol results is helpful in developing an adaptive strategy in the absence of effective enforcement of rules.

Keywords: community participation, Tahiry Honko, mangroves, Bay of Assassins, Madagascar

Introduction
Mangroves are among the most productive ecosystems in the world and have important economic benefits (Salem and Mercer, 2012; Rizal, 2018). They support fisheries, and provide raw material for construction, opportunities for tourism and recreation, coastal protection, erosion control, nutrient cycling and water purification (Barbier *et al.*, 2011; Barbier, 2015; ITTO, 2013). Despite the important role played by mangroves, they are threatened by alarming rates of deforestation; the area of mangroves decreased globally by 104 million ha between 1990 and 2020, with an average annual loss of 21,200 ha between 2010 and 2020 (FAO, 2020).The declining condition of mangroves has placed their ecosystem services at increasing risk and threatens the well-being of individuals and local communities (MEA, 2005) Additionally, if mangroves are degraded, the carbon stored in the soil is released, resulting in CO_2 emissions that contribute to climate change (Hamilton and Friess, 2018; Pendleton *et al.*, 2012). The conservation and restoration of mangroves has been recognised as an

important component to not only mitigate climate change (Ellison *et al.*, 2020; Taillardat *et al.*, 2018) but also to maintain the considerable ecosystem goods and services that they provide (Macreadie *et al.*, 2017; Hutchison *et al.*, 2014). Payments for Ecosystem Services (PES) schemes have been promoted as an innovative approach to provide financial incentives for protecting and restoring threatened marine ecosystems (Murray *et al.*, 2011). While the large majority of carbon-based PES projects concern terrestrial forests (Warren-Rhodes *et al.*, 2011), this approach has also been used to finance the protection and restoration of blue carbon ecosystems, such as mangroves (Alongi, 2011; Plan Vivo, 2020; Vanderklift *et al.*, 2022).

Tahiry Honko, which means 'preserving mangroves' in the local dialect, is a Plan Vivo registered community-led mangrove carbon project located in the Bay of Assassins (BoA), southwest Madagascar (Blue Ventures, 2019), established in partnership with the marine conservation organisation Blue Ventures (BV). The aim of this project is to promote a sustainable, long-term PES scheme through the sale of Plan Vivo Certificates or PVC, to reduce deforestation and degradation, and to restore mangroves in the BoA. A PVC represents the long-term sequestration or mitigation of one ton of CO2e by a Plan Vivo-certified project. Tahiry Honko generates more than 1000 PVCs per year through the conservation and restoration of over 1,200 ha of mangrove surrounding the BoA during the 20-year project period. Since this is designed as a community-led project and restricts access to the mangrove resources in the bay, participation of the community at various stages in developing the project is crucial and viewed as a basis for project success (Thwala, 2010). According to Sherry R Arnstein (Arnstein, 1969), there is a critical difference between going through the empty ritual of participation and having the real power needed to affect the outcome of the process. In the context of project development, participation refers to an active process whereby beneficiaries influence the direction and execution of development projects rather than merely receiving a share of project benefits (Paul,1987). Participation is based on the key human rights principles of individual autonomy and self-determination as part of basic human dignity (FAO, 2016; UN, 2013). The right to participate has also been included in several conventions regarding specific topical areas, most notably health and the environment. Agenda 21 of the Rio Declaration and Forest Principles recognises: indigenous rights to land, intellectual and cultural property, and the right to maintain their customary and administrative practices; the need for greater participation in decision-making; and the value of their involvement in forest management and conservation (WHO, 2002). Article 2 of the Declaration on the Rights of Persons Belonging to National or Ethnic, Religious and Linguistic Minorities affirms that persons belonging to minorities have the right to participate effectively in cultural, religious, social, economic and public life (United Nations, 1992). Aspiration 6 of Agenda 2063-African Union calls for the active involvement of all citizens in decision making in social and environmental development (African Union Commission, 2015). The United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) declares indigenous people's particular rights to free, prior, and informed consent (FPIC) in matters which affect their lives and livelihood (United Nation, 2007). In Plan Vivo Projects, FPIC principles apply to Indigenous Peoples and local communities with statutory or customary rights to land or resources in the project area (Plan Vivo, 2021). FPIC is not just a result of a process to obtain consent to a particular project; it is also a process in itself, and one by which Indigenous Peoples are able to conduct their own independent and collective discussions and decision-making (FAO, 2016)

While Rakotomahazo (2019) argues that participatory approaches were particularly well-suited to the planning and development of Tahiry Honko, the trend and level of community participation, including women, merits further examination to extract lessons for ensuring continued community participation. Women are often marginalised from participation in community decision-making (FAO, 2016), and their participation is crucial to ensure greater success and sustainability of projects because they are important mangrove resource-users, so restriction of access to mangrove impacts their livelihoods. Tahiry Honko is a performance-based PES initiative and the monetary rewards to communities are conditional on performance and indicators of success (Blue Ventures, 2019). Therefore, it is essential to examine the factors shaping community performance in project activities to understand how community participation influences performance (Wunder, 2005). Thus, this study aimed to assess community participation within the 10 partner villages in the BoA in planning and developing Tahiry Honko. During the six-year period from 2014 to 2019, from the first introduction of the concept of a carbon project to the villages to the validation of the project by Plan Vivo, lessons learned were extracted for continued community participation. Lessons were extracted by i) assessing the trend of attendance and rate of participation of community members within the 10 villages in village meetings and decision-making processes, and ii) evaluating the participation and performance of the communities in the project activities, especially in mangrove replanting, forest patrolling and Dina (local regulations designed and instituted by the community association to govern the mangrove uses in the project area) enforcement, all of which impact the expected climate benefits of Tahiry Honko and are related to the PES rewards (Blue Ventures, 2019). For this study, it was important to understand the participation of community members in mangrove replanting which is among the main project activities, as this is viewed as a key to success in ecosystem restoration (Stone *et al.*, 2008; UNEP, 2020). The assessment included forest patrols because the presence of rangers on the ground is viewed as the best way to control illegal forest activities (Covey and McGraw, 2014; Ratcliffe, 2004; Tranquilli *et al.*, 2014), and active surveillance is considered among the strongest deterrents to illegal activity (Gonedelé Bi *et al.*, 2019). The performance of the community in enforcing Dina was also assessed, as law enforcement is considered a central tenet of successful conservation (Ratcliffe, 2004; Tranquilli *et al.*, 2014).

Materials and methods

Study site

The study site is located in the BoA, or Helodrano Fagnemotse in Malagasy, situated in the Befandefa municipality and Morombe district, southwest region of Madagascar (Fig. 1). The bay lies in the southern portion of the Velondriake Locally Managed Marine Area (LMMA), which is classified as a Category V protected area under the International Union for Conservation of Nature (IUCN). The LMMA is co-managed by the Velondriake Association (VA) and BV. The BoA encompasses 10 villages, members of which are partners in Tahiry Honko. The population of the area is estimated at 3,992 residents, of which 20 % (806

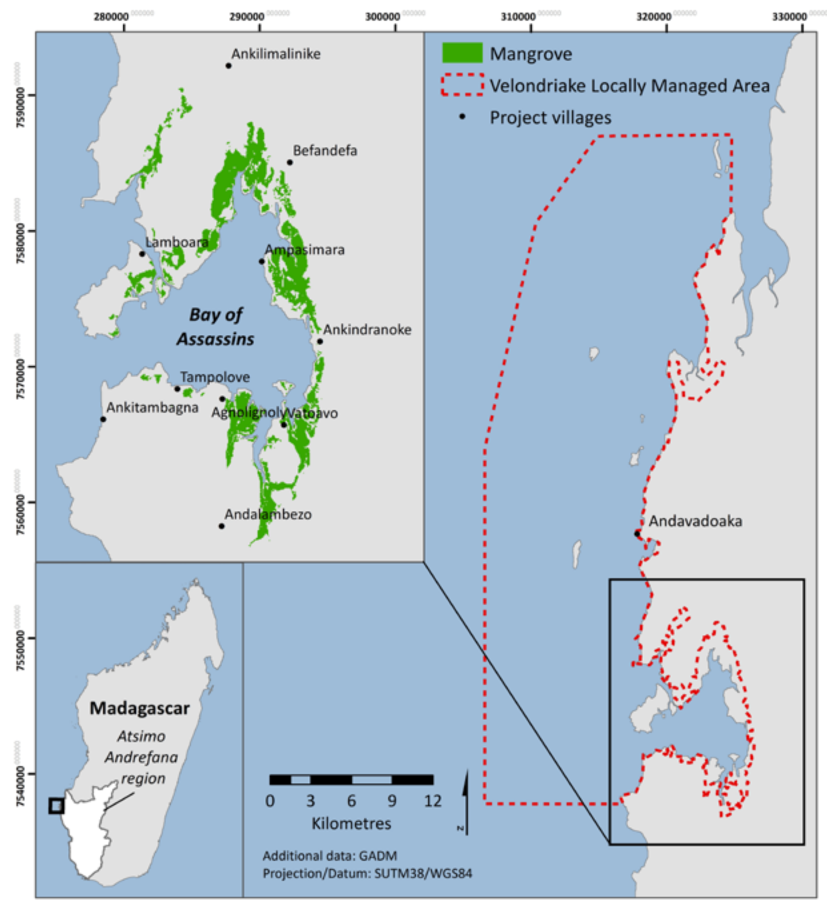

Figure 1. Map of the Bay of Assassins in relation to the Velondriake LMMA, Madagascar.

residents) are adults aged 25–49 years (Blue Ventures, 2015). Around 33 % of the adult population is illiterate and 87 % have completed only primary education (one to six years of education) (Blue Ventures, 2015). The population within the bay is composed of three main ethnic groups: the Vezo, Mikea and Masikoro. It is primarily populated by Vezo traditional fishers who depend on the harvest of marine resources for subsistence and income (Barnes-Mauthe *et al.*, 2013). Historically, the Mikea and Masikoro were more dependent on the dry forests, but due to changing rainfall patterns, resulting in drought and crop failure, many people have migrated to the coast (Stiles, 1998).

The mangrove forest in the BoA covers an area of 1,300 ha (Jones *et al.*, 2016), and has seven of the eight mangrove species found in Madagascar. Between 2002 and 2014, 3.18 % of mangroves in the BoA were lost, which equates to an annual net loss of 0.27 % (Benson *et al.*, 2017). Mangroves in the bay are harvested to provide fuelwood for domestic cooking, building material for housing and construction of lime kilns (Scales *et al.*, 2017).

In response to mangrove loss, communities in the BoA proposed education, awareness raising and law enforcement. They also established three types of management zone within their mangroves: strict conservation, reforestation and sustainable use. Within these management zones, resource use is regulated by Dina (Rakotomahazo *et al.*, 2019). As an example, in the conservation zone, no mangrove harvesting is allowed, while annual quotas were determined by analysis of the forest inventory within the sustainable use areas. In the sustainable use zones, harvesting of timber for lime production is not allowed. In this context, Tahiry Honko was implemented with the aim to incentivise the local communities to participate in and support the activities in preserving and restoring their mangrove forests also to contribute to raising awareness of the importance of mangrove ecosystems. Details of the approach and process are provided in Table 1.

Project interventions and activities

As detailed at length in the Project Design Document (Blue Ventures, 2019), the intervention undertaken in the project area included prevention of ecosystem conversion, ecosystem restoration, and improved land use (forest) management. The three main activities included mangrove replanting, forest patrols and surveillance, and Dina enforcement.

Mangrove reforestation

Degraded areas were delineated by the local community during the participatory mangrove zoning based on their local knowledge (Table 1). The indicators used by communities to identify degraded areas for reforestation were largely based on their perceptions of the clear-cutting area or high density of cut stumps (e.g., more than 50 % of the trees are cut), although this was not formally agreed upon during the mapping exercises, so there is likely some variation between communities in their definition of "degraded". Degraded areas of mangroves were replanted with species of mangrove previously present, mainly *Ceriops tagal*, *Rhizophora mucronata*, and *Bruguieria gymnorrizha*, targets for lime production (Scales *et al.*, 2017). The direct planting of mangrove propagules by hand was the approach applied to replace the harvested trees and restore the degraded area of the BoA (UNEP, 2020). The mature propagules were manually collected from the mother trees, usually a day before planting. The source of the propagules used was strictly local. The planting arrangements were random layouts, ranging from 0.5 m to 1.5 m apart and the three species were planted together. The mangrove replanting activity began in 2015, with community members from the 10 villages (adults, youth, and school children of all genders) taking part on a voluntary basis, but a meal, locally called rima, was offered to all participants after the re-planting session. For the 10 villages, the set objective for the mangrove replanting was 10 ha per year from 2016 (Blue Ventures, 2019). Mangrove planting was scheduled by the community and was usually carried out when the propagules were abundant and mature. Further, big mangrove plantation events were organised during the celebration of International Women's Day (the 8th of March) and Mangrove Day (the 26th July) to raise awareness of the importance of mangrove restoration (Ravaoarinorostihoarana *et al.*, 2023).

Forest patrols and surveillance

Patrolling of the mangrove conservation zone, where harvesting of both dead and live trees is prohibited by Dina, began in 2018 with three surveillance and evaluation committee members (Comité de Suivi et Évaluation, CSE) and one CSE supervisor. Nine additional CSE members were recruited in 2019 upon the request of the communities. The CSEs were recruited through job advertisements open to all residents in the project area, and the use of a competitive process rather than an appointment-based process previously used by the community. In total, 12 CSE members

Table 1. Purpose and approach of the village meetings from 2014 to 2019 at the 10 villages.

Year	Purpose of the village meeting	Approach adopted
2014	Introducing the concept of the Plan Vivo project.	Oral presentation at each of the 10 villages using Microsoft PowerPoint slides, followed by a question and answer session.
	Democratic vote about whether *Tahiry Honko* should go ahead or not.	Anonymous and individual democratic vote for adults at the village level, using color-coded ballots (held a month following the introduction of the concept) • green for "Yes: I want the project", • red for "No: I do not want the project" • white for "I have no idea"
	Discussing the mangrove management plan.	Open discussion to introduce and consult the community on the mangrove management plan.
	Discussing participatory mangrove zoning.	Workshops at the village level to discuss the delineation of preferred different mangrove zones on a printed map (detailed at length in Rakotomahazo *et al.*, (2019).
	Discussing participatory mangrove zoning.	Workshop to validate the participatory zoning map gathering two or three community representatives from each of the 10 villages to address the overlap of mangrove use issue between villages.
2015	Developing *Dina* for mangrove use and management.	Two rounds of village workshops in each of the 10 villages: 1. Sharing of ideas and gathering propositions of Dina for mangrove management at the village level via a working group per gender. 2. Refining the content of Dina in each of the 10 villages.
	Public consultation about *Dina* for mangrove management.	Workshop gathering local and regional authorities, NGOs, partners and community representatives from each of the 10 villages to discuss *Dina* for mangrove management.
	Disseminating *Dina*.	Outreach tours at the *Fokontany* (village council) level and in each of the 10 villages and outside of the project area.
2016	Discussing the mangrove management plan.	Village meeting to present and discuss the sustainable harvesting quota for mangrove wood per year/village and the *Dina* for each mangrove zone.
	Discussing the mangrove management plan.	Public consultation through workshops gathering local and regional authorities, NGOs, partners and community representatives from each of the 10 villages with the aim to pre-validate the mangrove management plan.
	Raising awareness about *Dina* and national law regulating the mangroves.	Village outreach tours with the regional forestry authority (*chef cantonment*) to inform communities of the national law regulating mangroves in Madagascar.
2017	Discussing the mangrove management plan.	Village outreach tours to validate the mangrove management plan and the annual quota per household per village per year, which is the harvest allowance calculated based on the capacity of regeneration of the mangrove forest and the community need.
	Discussing the mangrove management plan.	Dissemination of the validated mangrove management plan across the 10 villages.
	Discussing the sharing of project benefits.	Three rounds of village meetings to discuss and validate the benefits sharing scheme: 1. Discussion about the use and repartition of the carbon revenue. 2. Discussion about the village priority on the infrastructure project (wells, clinics and school building) and estimation of the budget for the project. 3. Final approval of benefit sharing and priorities per village (wells, clinics, school building).
	Discussing the grievance mechanism.	Workshop about the grievance mechanism with civil society organisations (CSO) gathering two community representatives from each of the 10 villages in one village.
2018	Discussing performance indicators for the project rewards.	Village meeting to discuss performance indicators and the conditions attached to the rewards (performance in activities).
	Discussing the grievance mechanism.	Village outreach tours to discuss and present the outcome from the workshop and about grievance mechanisms and validate the procedures.
	External validation of the *Tahiry Honko* project.	Village outreach tours to inform and update the community on the external validation through an oral presentation.
	Raising awareness about the *Dina* and national laws.	Village outreach tours with the regional forestry authority and VA executive committee about *Dina* and national laws.
2019	Raising awareness about the launch of the *Tahiry Honko* project.	Village outreach tour across 10 villages to inform and raise awareness about the official launch and celebration of the project.
	Disseminating the achievements of the project.	Dissemination of updates about the project's achievements through video.
	Discussing carbon revenue.	Village meeting to discuss with the parents of school children about the school subsidiary arrangement of the carbon revenue.

were responsible for the surveillance of the strict protection zone for any infractions, recording the number of cut mangrove stumps they observe on a field sheet. The set objective for the forest patrols was 16 patrols per month (Blue Ventures, 2019) but upon recruitment of additional surveillance and evaluation committee members (Comité de Suivi et Évaluation, CSE), the target was changed to one patrol per CSE member per month for the 12 CSE.

Dina enforcement

The Dina Enforcement Committee (Komity Mpampihatra Dina, KMD) was formally created in 2012 and subsequently restructured in 2016. The KMD is responsible for enforcing or resolving Dina infractions within the LMMA, including illegal mangrove logging once they receive a complaint or report, but is not responsible for surveillance or patrols. There are 30 KMD members, who were democratically elected in 2021 in the Velondriake LMMA; 14 of them were residents of the BoA. The set objective was to enforce and charge over 80 % of the infraction against Dina (Blue Ventures, 2019).

Data collection

Assessing community attendance at village meetings and workshops

From 2014 to 2019, from the first introduction of the project to the official launch of the project, BV supported the organisation of 20 meetings at each of the 10 villages (i.e., 200 village meetings; Table 1). Additionally, four workshops were carried out, gathering representatives of the community from each of the 10 villages to discuss the overlapping of mangrove zones across villages, validation of the mangrove zoning, public consultation about the Dina and a grievance mechanism (a procedure and transparent system for addressing grievances related to the project (UN-REDD, 2013).

Using an attendance sheet, the name and gender (Men/Women) of the adult community members (above 18 years old) who attended the village meetings, as well as the date, the name of the village and the purpose of the meetings was recorded by the BV staff leading and facilitating the meetings. Then, the hard copy of the attendance sheet was scanned for records and evidence. All data were entered into a Microsoft Excel spreadsheet and the total number of attendees across the 10 villages over each year was calculated. To avoid an over-count, as there are multiple village meetings in one year, the average of the total number of attendees within the 10 villages per year was used. The general trend of community attendance per year and per the purpose of the meetings over six years (2014 to 2019) was assessed by calculating the total number of participants across the 10 villages. The rate of attendance at the meetings was assessed by calculating the ratio of the total attendees per year (total average of the ten villages) and the total number of adult residents within the 10 villages. The relation between the trend of participation and per number of meetings carried out per year and per purpose of the meeting were also assessed. Women's participation in the meetings was assessed by calculating the ratio of women and men attending meetings.

Assessing community participation in mangrove replanting

At each routine mangrove replanting session, the name, gender, and groups participants belonged to (e.g., women's association, school children, and those from conservation clubs) was recorded on a printed field data collection sheet, as well as the number and species of mangrove planted. The coordinates (latitude and longitude) of the boundary of the replanted area were recorded into a GPS Garmin device. Data was entered into a Microsoft Excel spreadsheet. The same data were collected at major mangrove replanting events, for example, during the celebration of International Women's Day, World Environment Day and World Mangrove Day. These events gathered many invitees, including officials, partners and community representatives from outside of the 10 villages Using the mangrove replanting database, the trend of the number of community members participating in mangrove replanting per year for seven years (2015-2021) was assessed by calculating the average of total participants within the 10 villages per year. If the village undertook more than one session in a year, the number of participants was averaged to avoid double counting of the same person participating in multiple sessions. Then, the ratio of adult women to men and adults to youth was calculated, and the rate of participation in mangrove replanting assessed by calculating the ratio of adult participants to total adults in the project area.

Assessing performance of the community in the project activities

Performance here is defined as the ability of the community to achieve the set objectives in the project activities. When the communities within the 10 villages fail to meet the set objective, the climate benefits expected from the project activities are not reached.

• Mangrove replanting

Community performance was assessed based on the set objective to replant 10 ha per year, as defined as follows: (i) high, if replanted 10 ha or more; (ii) medium, if replanted between 8-10 ha; and (iii) low, if replanted below 8 ha. Data in the Blue Ventures mangrove replanting database (detailed in section 2.2.1) were analysed using Microsoft Excel, and the total area (ha) replanted per year over seven years (2015 to 2021) was calculated. Accomplishment per group, namely adults, youth and invitees for the special events, was measured. The rate of participation and the total area (ha) replanted per year was calculated by dividing the total participants by the total adult residents in the project area to understand if the rate of participation was impacting performance of mangrove replanting.

• Mangrove forest patrols and infraction surveillance

A Microsoft Excel spreadsheet was used to record the number of patrols that occurred every month and served as a database for the forest patrollers. The total number of patrols conducted over four years, from 2018 to 2021, was calculated for the 12 CSE. The performance of the community in the patrol activities was categorised as: (i) high, if the number of patrols was 144 and above per year (over 12 patrols/year/CSE); (ii) medium, if the number of patrols was between 84 and 144 per year (7 to 12 patrols/year/CSE); and (iii) low, if the number of patrols was below 84 per year (below 7 patrols/year/CSE).

• Dina enforcement

The number of complaints received was recorded in a spreadsheet along with details about the enforcement of Dina charges made by the KMD, date, village, nature, action taken, resolution, and fine amount. Infractions/complaint data were filtered and the percentage of complaints received by Dina enforced and charged was assessed using a Microsoft Excel spreadsheet. The performance of the community in Dina enforcement was categorised as: (i) high if over 80 % of Dina infractions are enforced and charged; (ii) medium if 50-80 % of Dina infractions are enforced and charged; and (iii) low if below 50 % of Dina infractions are enforced and charged.

Level of community participation

The level of participation of the community in implementing the project and the decision-making processes at various stages of the project development and activities was assessed using the Spectrum of Public Participation developed by the International Association for Public Participation (IAP2). The spectrum describes five levels of participation: inform, consult, involve, collaborate and empower (Fig. 2). The relevant level of community participation was selected based on the various village meeting approaches adopted and the expected outcomes from the village meetings and workshops outlined in Table 2, referring to guidelines developed by the United States Environmental Protection Agency in Figure 3 below (US-EPA, 2017).

INCREASING IMPACT ON THE DECISION →

	INFORM	CONSULT	INVOLVE	COLLABORATE	EMPOWER
PARTICIPATION GOAL	To provide the public with clear and relevant information to assist them in understanding the project and the intended outcomes. Pitch information to a wide audience and potential stakeholders.	To obtain public feedback on analysis, approaches, and/or decisions.	To work directly with the community throughout the process to ensure their opinions, concerns, and aspirations are consistently heard and considered.	To partner with the community in each aspect of decision including the development of alternatives and the identification of the preferred solution.	To place final decision making in the hands of the community.
PROMISE TO THE COMMUNITY	We will keep information accessible, clear, and updated.	We will keep you informed, listen to and acknowledge concerns and aspirations, and provide feedback on how community input influenced decisions.	We will work to ensure that your concerns and aspirations are directly reflected in the alternatives developed and provide feedback on how public input influenced the decisions.	We will look to you for advice and innovation in formulating solutions and incorporate your advices and recommendations into the decisions to the maximum extent possible.	We will implement what you decide.

Figure 2. Spectrum of Public Participation used to assess the level of community participation adapted from IAP2 (©International Association for Public Participation www.iap2.org)

Table 2. Number of village meetings from 2014 to 2019 in each of the 10 villages (200 total).

Year	2014	2015	2016	2017	2018	2019	TOTAL
Number of meetings	4	2	2	5	4	3	20

Extracting lessons learned

Lessons learned were extracted through the analysis of the records of attendance sheets at village meetings, participation and performance in the project activities, as well as through informal conversations with the community members within the project area about topics unrelated to this study. The lessons learned that are shared in this paper were not derived through a formal process but rather based on an understanding of the best practices to ensure continued community participation in Tahiry Honko.

Results

Trend of attendance rate of community at village meetings

A total of 20 village meetings were held from 2014 to 2019 across all of the 10 villages (Table 2). The maximum number of meetings per year was five, which was achieved in 2017.

The results show that the rate of participation every year from 2015 to 2019 was higher than that recorded in the first year (2014). However, despite an increase in community attendance rate at the village meetings for the first three years (2014 to 2016), a decrease in attendance rate was recorded in 2017 when large numbers of meetings (five) were held in each of the 10 villages (Table 2, Fig. 4).

The attendance rate at village meetings ranged from 29 % in 2014 to 43 % in 2016, with 234 and 350 adults attending respectively out of a total of 806 adult residents in the BoA. The overall attendance rate across all 20 meetings held across each of the 10 villages was 37 %, of which 50 % of attendees were women (Table 3). The lowest rate of attendance was recorded at the participatory mangrove zoning meeting (18 %) whereas the highest rate was at the meeting to discuss the performance indicators (50 %).

Results from the 200 village meetings from 2014 to 2019 showed that in the BoA, women and men were proportionally represented. The attendance rate of women was very high, representing 76 % of total attendance at the consultation with parents about the school subsidies and 59 % for the anonymous democratic vote to decide whether the project should go ahead or not.

Community participation in mangrove replanting

The overall participation rate of community members in mangrove replanting from 2015 to 2021 was 35 % of the total adult population of the BoA (281 adults out of 806 adults). There was a considerable increase in the participation rate during the first

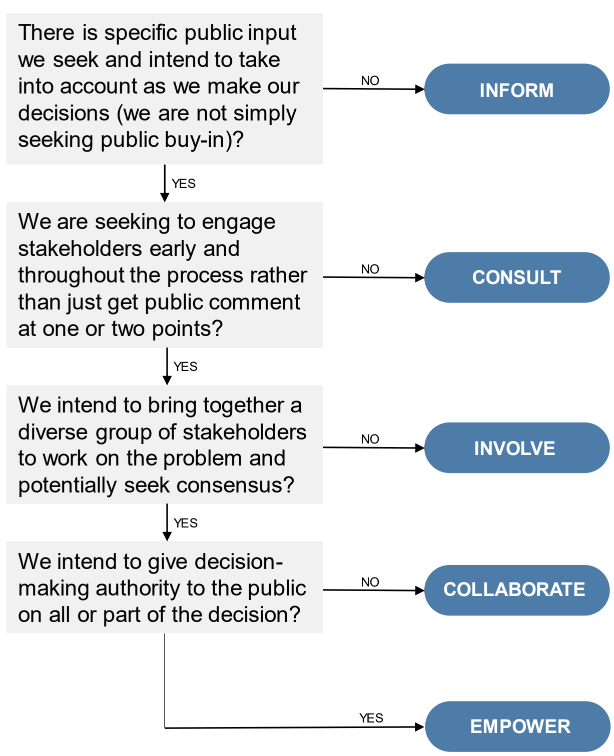

Figure 3. Flowchart used to support the assessment of the level of participation. (*adapted from*: EPA Public Participation Guide, 2017)

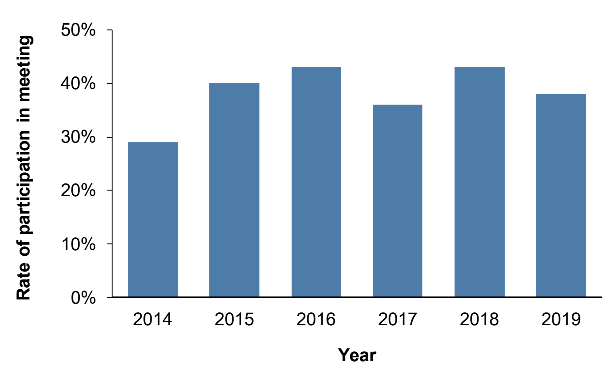

Figure 4. Rate of participation at village meetings across 10 villages between 2014 and 2019.

Table 3. Purpose of the village meetings and the total number and percentage of attendees by total population and the percentage of women attending meeting in the 10 villages.

Purpose of the village meeting	Total number and % of total adult population (men and women) attending meeting	Attendance rate of women (% of total attending meeting)
Introduction of the Plan Vivo carbon project	226 (28%)	49%
Anonymous democratic vote on the project	307 (38%)	59%
Information on the mangrove management plan	258 (32%)	40%
Participatory mangrove zoning	143 (18%)	27%
Round 1: Developing *Dina* for mangroves	354 (44%)	48%
Round 2: Developing *Dina* for mangroves	295 (37%)	53%
Developing the mangrove management plan	306 (38%)	58%
Outreach with the forestry regional authorities	393 (49%)	40%
Validation of mangrove zoning	256 (32%)	55%
Dissemination of the validated mangrove management plan	236 (29%)	50%
Round 1: Benefit sharing and priority infrastructure projects	359 (45%)	47%
Round 2: Benefit sharing and budgeting	306 (38%)	42%
Round 3: Validation of benefit sharing	284 (35%)	49%
Discussion of grievance mechanism	287 (36%)	49%
Discussion about performance indicator thresholds	400 (50%)	53%
Outreach with the regional forestry department	314 (39%)	38%
Information and update on the external validation	382 (47%)	57%
Update about project achievements	304 (38%)	50%
Update on the official launch celebration of *Tahiry Honko*	339 (42%)	58%
Consultation of the parents on the school subsidiaries	270 (33%)	76%
Average	301 (37%)	50%

four years, from 13 % in 2015 to 56 % in 2018. The rate of participation fell in 2019 but the highest rate was recorded the following year, which was 58 % in 2020 (Fig. 5). Every year, the participation of women in mangrove replanting activities was higher compared to men (Fig. 6). However, there was an increase in the participation of men from 2015 to 2018 with the highest participation recorded in 2020 (186 men). The number of youths (i.e., school children and those from conservation clubs) participating in mangrove replanting was lower compared with adults for the first six years of the project, from 2015 to 2020 but there was a considerable increase in youth participation in 2021 which was higher than adult participation (Fig. 7).

Community performance in the project activities

Mangrove replanting

From 2015 to 2021, the total degraded mangrove area replanted in the BoA was 84.2 ha. As shown in Figure 8, the smallest area replanted was recorded in 2015, the first year of the mangrove replanting, and the highest area replanted was in 2021. The adults of the 10 villages successfully replanted 59.1 ha of degraded area,

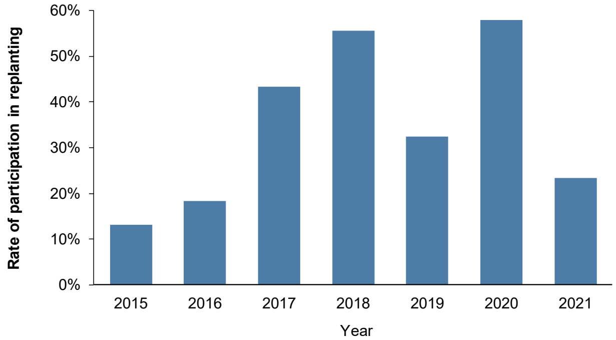

Figure 5. Participation rate of adults in mangrove replanting from 2015 to 2021.

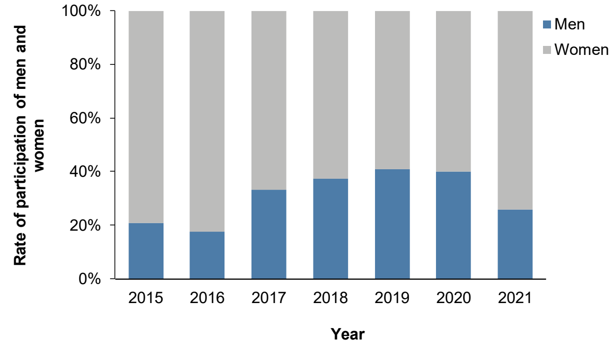

Figure 6. Rate of participation of men and women in mangrove replanting from 2015 to 2021.

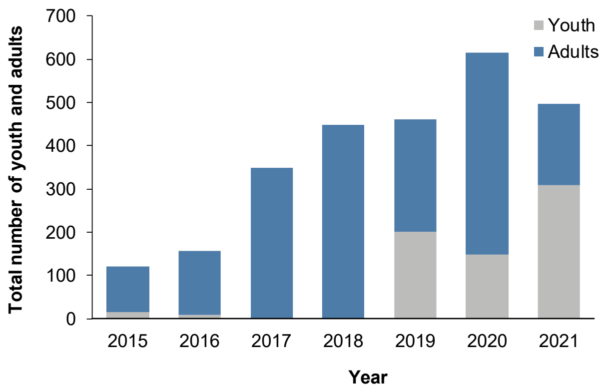

Figure 7. Participation of adults and youth in mangrove replanting from 2015 to 2021.

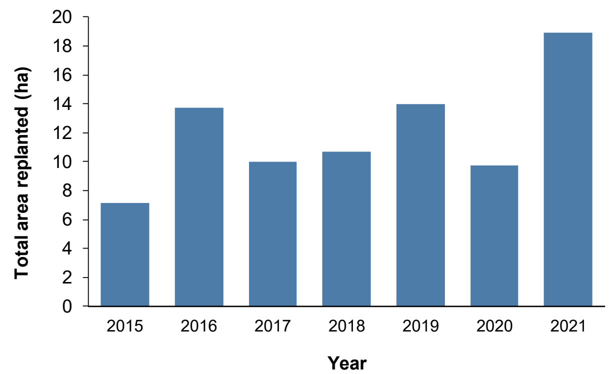

Figure 8. Degraded mangrove area replanted in the Bay of Assassins from 2015 to 2021.

which represented 70 % of the total area replanted, during the routine mangrove replanting session. The total area replanted by special invitees (i.e. other people invited from different villages that are not part of the Tahiry Honko project) during the sessions organised at international events was 16 ha, which represented 20 % of the total replanted area. The youth contribution represented 27 % of the total area planted in 2021, which was 5 ha out of the 19 ha. The performance of the communities in mangrove replanting was low in the first year (2015), less than eight ha, and was medium in 2020 which was below 10 ha (Table 4). In contrast, performance was high from 2016 to 2019, and in 2021 when the annual goal (10 ha) in mangrove replanting was reached.

Mangrove forests patrols

The performance in mangrove forest patrols was high in 2018, when the goal to carry out 16 patrols/month was reached. However, the performance was low the following year, 2019 and medium in the last two years, 2020 and 2021, when the annual goal to carry out 144 patrols and above per year (12 patrol/year/CSE) was not reached (Table 5).

Dina enforcement

The KMD received one report of infractions of illegal logging of mangroves in 2021. The KMD successfully enforced the Dina and the person that carried out the infraction paid the fine. The performance of the community in Dina enforcement was therefore high (over

Table 4. Performance of the community in mangrove replanting.

Year	2015	2016	2017	2018	2019	2020	2021
Area replanted (ha)	7.2	13.7	10	10.7	14	9.8	19
Performance	Low	High	High	High	High	Medium	High

Table 5. Performance of forest patrols carried out by the 12 CSE.

Year	2018	2019	2020	2021
Number of patrols	227	60	139	132
Number of CSE	3	12	12	12
Performance	High	Low	Medium	Medium

Table 6. Performance in *Dina* enforcement.

Year	2021
(%) of *Dina* infraction enforced	100%
(%) of *Dina* infraction charged	100%
Performance	High

80 % of Dina infractions are enforced and charged) (Table 6),

Level of participation in project development and project activities

The level of community participation ranged across each of the five stages of the Spectrum of Public Participation framework (inform, consult, involve, collaborate and empower). There were different levels of decision making at different stages of Tahiry Honko, including individual decision making by anonymous democratic vote, joint decision-making by all of the community by vote by raising hands, and decisions made by the VA, serving as the central governance body for project management and accountable for some of the final decisions (Table 7).

Discussion

Trend and rate of attendance at village meetings

Even though participation of community members is a key human right recognised by law (United Nations, 2007), and effective, meaningful and informed participation in project development is crucial to ensure greater success and sustainability (FAO, 2016; UN-REDD, 2013), there are no commonly agreed indicators measuring successful participation (Vedeld, 2001). It can be argued that there has been continued community participation in the development of the Tahiry Honko project. The decrease recorded in 2017 could be because of the amount of time that elapsed between the introduction of the carbon project concept in 2014 and the first income from the carbon project. Numerous village meetings held in this year may have resulted in a decrease in motivation to attend village meetings. This is in line with results of a participation analysis in PES projects in Uganda, which revealed that anticipated carbon payments seemed to influence community participation (Aganyira *et al.*, 2020). Therefore, careful planning of village meetings is crucial to avoid community fatigue and ensure continued participation. Planning and schedules of the village meetings should be communicated to the head of the village (for example, via letter or phone call) at least a week before the village meeting, so community members are informed well in advance and are prepared. Consolidating the number of village meetings was among the recommendations gathered from the communities in the BoA when starting a new project in another place. Some meetings, training events, and workshops should be combined to reduce and streamline the total number required. From experiences during the development of Tahiry Honko, it can be recommended that the period of time taken for community consultations should be shortened for other projects in the future, thereby avoiding meeting fatigue. The records of the number and gender of attendees, and the purpose for each village meeting, were useful documents not only to assess trends

Table 7. Level of participation of the community in implementing the project, and the different stages of the Spectrum of Public Participation framework.

Key project milestone	Stage of the Public Participation framework
Introduction of the *Tahiry Honko* carbon project *Example: Sharing information about Tahiry Honko and the national law regulating mangroves in Madagascar with the community within and outside of the project area, and the VA. Awareness raising was carried out during village outreach tours, meetings and exchange visits.*	Inform
Decision whether the project should go ahead *Example: Inputs, opinions and feedback from the communities and the VA were gathered during the introduction of the project at meetings and outreach tours. Village meetings were held to obtain community input on the suitable approach to increase participation in mangrove replanting, giving community members and VA the power to make an informed decision. Informed decision/consent from individual/ community/VA obtained. Individual democratic votes and joint votes were used to decide whether the project should go ahead or not.*	Consult
Mangrove zoning *Example: Bringing together a diverse group of community members (loggers, fishers and farmers) to work on mangrove zoning and seek consensus through village workshops and small group sessions.*	Involve
Developing *Dina* for mangrove management *Example: Bringing together a diverse group of community members (loggers, fishers and farmers) to develop* Dina *for mangrove management, and seek consensus.*	Collaborate
Benefit sharing *Example: Engaging the community and the VA to make decisions on the project activity by informing, consulting, involving and therefore empowering them to collaborate to make an informed decision on the benefits of the project and how they should be shared.*	Empower

of attendance but also important written evidence of community participation in meetings and decision-making processes.

Women's attendance in village meetings and their participation in project activities

Despite the traditional attitudes and stereotypes around women in Madagascar which could be harmful to a successful conservation initiative, such as the belief that women are incapable of participating with men in decision-making regarding natural resource management (Rojas, 2001), the records from this study showed that women and men were proportionally represented in village meetings. The participation rate of women was also higher (59 %), compared with men during the anonymous democratic vote in 2014 to decide whether the project should go ahead. This is in line with the results of a gender analysis in the same region where many women were present in meetings organised by NGOs and people from outside the communities (Ramananjohany and Razafiarimanana, 2021). It can be deduced that the approach used in designing and developing Tahiry Honko, including dividing men and women into separate groups when developing Dina governing mangrove use, and anonymous voting to decide on the project, enhanced women's participation and confidence. This approach enabled women to voice their opinions and to overcome any lack of confidence to speak in front of men. Creating a comfortable space and enabling conditions for women in group discussions with men at village meetings is vital to promote women's attendance and participation in village meetings and in the decision-making process. However, in the meetings to discuss participatory mangrove zoning, women's participation was lower than at other meetings (27 %, Table 3). This could be explained by the low number of overall attendees (% of total adult population), or the fact that this meeting took place at the start of the project, or this particular meeting wasn't as well announced. Women's participation was much higher in subsequent meetings, including the meeting to validate mangrove zoning. In Gardner (2020), social marketing initiatives promoting the participation of women in the Velondriake LMMA resulted in an increase of women representation on the Velondriake Board.

Even though women and men were proportionally represented in village meetings and number of women participating in mangrove replanting was higher than men, their involvement in mangrove forest patrols and Dina enforcement remained significantly low. Although the job advertisements to recruit the community patrollers (CSE) were open to all community members living in the BoA, irrespective of gender, to promote gender-equal opportunities (Seager, 2021), only one woman applied and was selected. This situation is in line with the global situation which estimates that only 3–11 % of the ranger workforce is women (Belecky *et al.*, 2019). Almost universally, culturally entrenched gender norms, presumptions, and traditional attitudes, which are often internalised, hold women back from participating in activities that are defined as being physically arduous (Seager, 2021). Although the sole CSE woman found that patrolling is not an easy job, she was excited and motivated. In the interview conducted with her outside of this study, she is quoted as saying that 'my favorite memory in the mangrove is the first time I went on patrol. It was not easy, but it was motivating and exciting. I feel sad that there are still people who cut down the mangroves, so I am happy to be working to protect them' (Blue Ventures, 2020).

Furthermore, while social marketing initiatives carried out in Velondriake LMMA have succeeded in increasing women's participation in the management of resources in the past (Andriamalala *et al.*, 2013; Gardner, 2020), there is still low women representation in the KMD. There are only two women in the 30-member KMD. In this study it is presumed that the prevalence of the stereotypical behaviors and socio-cultural attitudes of patriarchy in the BoA hampered women representation in KMD, given that traditionally elderly men hold power to enforce customary laws. The average age of the 30-member KMD, which was 46 years old, seemed to confirm the patriarchy barriers. Nevertheless, even though the participation of women is low, it can be argued that this does not negatively impact the performance in forest patrols and Dina enforcement (see section 4.3 and 4.4).

Participation and performance of the community in mangrove replanting

While involvement of the local community is viewed as crucial for successful mangrove restoration (Stone *et al.*, 2008; UNEP, 2020), the rate of participation required for a successful project has not previously been documented. Even though the results of this study show that the rate of participation of adults in mangrove replanting was 35 %, which was lower than the rate of participation in the village meetings (37 %), this trend did not negatively impact the performance in this activity. The annual set goal to replant 10 ha of mangrove degraded area was met except in 2015 and 2020, when financial compensation of the participants was not given. Mangrove replanting in 2015 was low because there was no annual objective fixed with the communities until 2016. The peak achievement in mangrove replanting recorded in 2021 (19 ha) can be explained by the youth involvement which contributed up to 27 % of the total area replanted (5 ha). Even though the accomplishment of adults in 2021, without accounting for the achievement of special invitees and youth, surpassed the annual objectives (10.9 ha versus 10 ha), it could be suggested that involving youth is a better approach to raise their awareness in mangrove restoration as future mangrove users, given that the lifetime of the project is 20 years (Blue Ventures, 2019). The involvement of youth in the project activities was also one of the recommendations gathered from the community when scaling up new carbon projects.

The participation of men in mangrove replanting was lower compared with the women every year. This is similar to a study undertaken in the west coast of Karnataka, India, which showed that 70 % of fisherwomen were willing to volunteer some amount of time to mangrove reforestation and only 21 % of the fishermen were willing to replant mangroves, even when paid to do so (Stone *et al.*, 2008). While fisherwomen were willing to participate in mangrove replanting to increase the availability of natural resources that will provide opportunities of alternative income to the community, such as mangrove honey production (Stone *et al.*, 2008), it was hypothesised that social norms in the BoA often suggest that mangrove replanting is a woman's duty, causing the low participation of men. However, the consultations carried out within the villages allowed for understanding of the reasons for low participation of men, and to gather propositions from the community in order to increase men's participation. Given that men might not be able to go fishing and women cannot prepare food for their family during a replanting day, they may not voluntarily participate in the mangrove replanting without a reward. Following discussions with the community, rima (community meals) were offered to all participants after the mangrove replanting sessions, as proposed by the community. As a result, there was an increase in male participation from 21 % in 2015 to 41 % in 2019 when adopting this approach, though this decreased in 2021 due to the higher rate in youth participating in mangrove replanting. Meals given to the participants after the mangrove replanting session seemed to increase the motivation of the local communities, as they had not yet received any benefits from the sale of carbon credits. Therefore, it can be concluded that a voluntary approach to mangrove replanting that includes meal compensation proved to be an effective and sustainable way to engage all community groups and reach the set goals of the project.

However, even though community participation was viewed as a key to reach the mangrove replanting set goals, Ravaoarinotsihoanara (2023) revealed a negative correlation between the number of participants and the survival rate of planted mangrove. This author also recommended that the maximum number of participants in mangrove replanting should be 38 people per hectare.

Performance of the community in mangrove forest patrols and infraction surveillance

Even though the annual goal to carry out 16 patrols per month was reached in 2018, the patrols did not cover all of the strict protection zones due to the small number of CSE (only three people). Although from 2019, the target was changed to 144 patrols per year (12 patrols/CSE/year for the 12 CSE) when nine additional CSE were recruited and assigned to work within their respective villages, high performance in forest patrols was not reached on this change. The adaptation impacted the patrols in 2020 when five of the CSE missed the monthly patrol activity. The COVID-19 restrictions also resulted in a slight decrease of the number of patrols in 2021 when patrols did not occur during lockdown. Even though a peak of number of patrols was recorded in 2020 (139 patrols), there was some illegal cutting of mangrove wood recorded by the CSE in this year. This is in line with overall trends in many regions in Madagascar since COVID-19, where many cases of illegal harvesting and transport of timber were reported from different regions (Malavika, 2020).

Despite the fact that high performance in forest patrols was not reached upon the change of approach from 2019, the CSE confirmed that from their direct observation in the forests during the patrolling activity that there was a reduction of illegal harvesting of mangrove wood in 2021. As reported by studies in different countries, having rangers on the ground is one of the strongest deterrents to illegal activity (Gonedelé Bi *et al.*, 2019; Covey and McGraw, 2014; Tranquilli *et al.*, 2014), and the authors of this paper believe that the recruitment of additional CSE resulted in a positive impact on overall reduction of illegal mangrove wood harvesting in the BoA. This is also a well-suited approach that minimizes the cost of the forest patrol activity, as accommodation and transport of the CSE did not have to be covered due to the addition of new CSE working in their respective villages, and also allowed for a shorter travel time for each patroller.

While a study carried out in India revealed that only 3 % of fishermen and none of the fisherwomen interviewed were willing to work for enforcing mangrove protection, even when paid to do so (Stone *et al.*, 2008), it is assumed that not everyone in the communities would be motivated to undertake forest patrolling without compensation, whether in the form of money or meals. While motivation is one of the forces that led to performance, as when individuals are motivated, they are productive and focus their efforts on the achievement of set goals (Chaudhary and Sharma, 2012; Sharma and Sharma, 2017; Bao and Nizam, 2015), it is believed that the approach adopted in this study to recruit CSE (through job advertisements and the competitive process) could have been a deterrent to non-motivated people.

Performance of the community in Dina enforcement

While the CSE recorded a number of cut mangrove stumps in the strict mangrove protection zone where the Dina prohibits the harvest of mangrove trees, there was only one infraction of illegal mangrove harvesting reported and enforced by the KMD. Even though law enforcement is viewed as crucial for successful conservation (Ratcliffe, 2004; Tranquilli *et al.*, 2014), it is a major challenge for protected areas worldwide, particularly in developing countries (Nolte, 2016). Despite the implementation of social marketing programmes designed to promote enforcement by villagers and local leaders (Andriamalala *et al.*, 2013), Dina application is a major challenge in the Velondriake LMMA (Gardner, 2020) because of the Fihavanana, a local concept meaning "kinship and friendship" (Andriamalala and Gardner, 2010), where community members may be reluctant to apply rules against members of their own community and do not want to report infractions committed by their friends and family. Despite the possibility that not all infractions may have been reported and recorded, the number of cut mangrove stumps counted by the CSE during the monthly forest patrols helped to assess compliance with Dina. It was found that dissemination of information from the forest patrols is helpful to adapt the management strategy in the absence of strong Dina enforcement when the number of cut mangrove stumps is shown to be increasing. When aware of the increase of illegal cutting, mitigation strategies proposed by the community included recruitment of additional CSE members to ensure that monthly patrols covered all of the strict protection zones. Additionally, some community members in each village decided to voluntarily carry out forest patrols in their respective strict protection zones in addition to the monthly patrols undertaken by the CSE. This shows that community members started to take the initiative once they were aware that illegal mangrove harvesting was taking place as they believed that the frequency of patrols was not adequate to dissuade infractions.

Level of community participation in planning and decision making in the project

While community participation has been approached differently by different project practitioners (Paul, 1987), based on the description of the IAP2 and the approach used, communities were informed, consulted, involved, and empowered, and they collaborated throughout the process in developing and making decisions for the project, although the level of participation varied at different stages. Despite the usefulness of the description of the five levels, it was found that the approach adopted from the 'inform' to 'empower' level, such as careful planning of the village meeting to avoid community fatigue and creating a safe and comfortable space for women in decision making process, is vitally important in ensuring continued community participation regardless of the level. Even though the 'inform' level is considered as a weak form of participation, comprising one-way communication where communities are passive information receivers (Arnstein, 1969; Hardy, 2015), the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) declares indigenous people's particular rights to free, prior, and informed consent (FPIC) in matters which affect their lives and livelihood (United Nation, 2007) and the United Nations Permanent Forum on Indigenous Issues (UNPFII) requires that information should be provided on an ongoing and continuous basis throughout the FPIC process (UNPFII, 2005). Given that mangrove forests are traditionally communal resources (GOM, 1997), open to villages outside of the project area, it was found that the 'inform' level is important not only to provide information to the community, enabling them to make informed decisions about the project, but also to inform the neighboring communities, especially about Dina regulating mangrove use. However, while handbooks and toolkits outlining the planning process and facilitation techniques are available (De Leiuen and Arthure, 2016; US-EPA, 2017), it was found that the complexity of the concept of carbon sequestration itself required a well-designed approach and well suited communication materials adapted to the local context. The consultations carried out with the community allowed us to gather community opinion on the suitable communication materials to share information about the project. Oral presentations in the local dialect with visual support, such as Microsoft PowerPoint presentations and videos, were highly recommended by the community. As the same information needed to be shared across the 10 villages, a pre-recorded video presentation was used when disseminating the results of accomplishments of mangrove replanting and the number of illegal harvesting incidents recorded by the CSE. The pre-recorded video was an effective outreach tool to ensure that the target audience had the same level of information and this also enabled the audience to stay focused.

As described in detail in Rakotomahazo (2019), Tahiry Honko was developed through participatory methods with the aim of promoting engagement of all community members living within the project area, regardless of gender. However, Mosse (2001) argues that participatory approaches are subject to domination by certain groups, due to being plenary and public events. Consequently, marginalised groups, such as women, may struggle to participate and make personal decisions on matters that affect their lives. As carbon projects may impact access to resources for forest-dependent community members, obtaining FPIC of all community members is required and critical for the success of the project (FAO, 2016; UN-REDD, 2013). Adjusting situations and conditions by creating safe and comfortable spaces is crucial to make marginalised groups feel more confident about participating in decision-making (Mubita *et al.*, 2017). It is believed that anonymous democratic voting, a method by which the electorate directly makes their own personal decisions, constitutes an inclusive process that is well suited to the local context in ensuring community consent on project implementation. This is an effective inclusive approach to allow the full range of community members to provide their consent and can also address the issues around often marginalised members of a community (e.g., women) to also be engaged in the decision-making process.

Conclusions

Tahiry Honko is an ongoing initiative that is yet to be systematically evaluated. However, at this stage, it is suggested that the possibility of earning carbon revenue created an incentive and promoted continued community participation in mangrove conservation and restoration in the BoA. Despite some challenges encountered in implementing Tahiry Honko, including the length of time between the introduction of the concept of the carbon project to the community and first income generated from carbon revenue, and the numerous village meetings required, continued community participation was recorded. Participation of the communities in village meetings involving decision making, and in project activities, contributed to the success of the project. To maintain and improve community participation, some meetings and workshops could be consolidated to reduce and streamline the total number required, and to reduce meeting fatigue. While participation has its own strengths and weaknesses, it is important to adopt a well suited approach to the local context in ensuring continued community participation from the ‘inform’ to ‘empower’ level. While anticipated carbon payments appear to influence community participation, the lessons learned in this study on best practices for ensuring continued community participation would be applicable to any community-led project that does not offer monetary incentives from the carbon revenue. However, this study is limited to the assessment of the level of community participation and rate of community attendance in village meetings and in mangrove replanting. Further research is needed to investigate the critical factors that influence the involvement and motivation of participants according to their gender, in particular in speaking and decision-making, and participation in activities.

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Original Article

Feeding habits and diet composition of *Octopus cyanea* (Gray, 1849) in Zanzibar waters, Tanzania

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Abstract
The octopus fishery in Zanzibar is an essential activity of coastal communities. To assist with developing fisheries management plans, baseline information on the feeding of *Octopus cyanea* (Gray, 1849) was collected in relation to sex and maturity stages. The feeding habits and diet composition of 543 *O. cyanea* were studied over a period of 12 months at Paje, Kizimkazi, Chwaka Bay and Nungwi. Samples at each site were collected on two days per month during spring tide. Digestive tract contents revealed that *O. cyanea* preyed on 36 species of crustaceans, molluscs and fishes, with crabs a major prey item. The number of prey species in a single stomach ranged from one to six. *O. cyanea* in Zanzibar is therefore a generalist predator with a mixed diet. The octopus gonadosomatic index (GSI) indicated a peak breeding season in June to October, which correlated with low prey consumption. Mature octopuses ingested a small amount of food from mainly small sessile prey. Females consumed less food than males of similar maturity stages, suggesting that they ate less or had higher digestion rates. The information is useful for developing fisheries management plans for the octopus fishery in Zanzibar.

Keywords: *Octopus cyanea*, sex, maturity stage, frequency of occurrence, Zanzibar waters

Introduction
The big blue octopus, *Octopus cyanea* (Gray, 1849), is a shallow-water species that spends its life in intertidal and sub-tidal reefs for refuging, hunting, and reproduction (Norman *et al*., 2001). It is found in different parts of the world, from East Africa (Guard and Mgaya, 2002) through Madagascar (Benbow *et al*., 2014), French Polynesia (Scheel *et al*., 2017), India (Nair *et al*., 2018), Australia, and Hawaii (Herwig *et al*., 2012). This octopus is one of the most harvested species in tropical and sub-tropical regions for commercial, subsistence, and recreation purposes (Guard and Mgaya, 2002; Herwig *et al*., 2012). It dominates the octopus catch, accounting for about 99 % of all catches in Tanzania and Zanzibar (Guard and Mgaya, 2002; Rocliffe and Harris, 2016).

Octopuses need sustainable fisheries and appropriate management measures to flourish and increase their population size (Pita *et al*., 2021). Such management undertakings have been introduced in Zanzibar based on size limits and seasonal closures (Rocliffe and Harris, 2016). However, these management measures have currently failed to satisfy the community's expectations (personal observation). It is expected that the underperformance of these management approaches is probably due to a lack of linkage between scientific information and community knowledge. Thus, there is a need to study the trophic ecology of *O. cyanea* to provide baseline information that can aid in the formulation of a management plan for the area.

The management effort needs robust information to make informed decisions about the future preservation of particular species (Herwig *et al*., 2012). Therefore, this knowledge of the trophic ecology of

O. cyanea would be used as a reference point by the managers and practitioners in the formulation of the management strategies. Moreover, the information from this study would also provide insight for the growth assessment of this species in captivity (Rosas-Luis *et al*., 2019). Despite the presence of some studies on growth, fisheries, and reproductive biology (Guard and Mgaya, 2002), catch status (Rocliffe and Harris, 2016), growth, exploitation rate, and recruitment pattern (Silas *et al*., 2021), and the environmental influence on abundance and distribution (Chande *et al*., 2021), the trophic ecology of *O. cyanea* has not yet been studied in Zanzibar.

O. cyanea is a generalist predator feeding on fish, molluscs, annelids, and arthropods (Armendáriz Villegas *et al*., 2014). Like most octopus species, its feeding preference reflects the prey composition in a given environment (Scheel *et al*., 2017). Since Zanzibar is home to a variety of marine species, *O. cyanea* is expected to exhibit a feeding pattern that reflects the prey population and composition in the environment (Scheel *et al*., 2017). The goal of this study was to examine the feeding habit and diet composition of *O. cyanea* using stomach content analysis in relation to sex and gonadal maturity stages in Zanzibar.

Materials and methods

Description of study area

This study was conducted in Unguja, one of the two sister islands that form Zanzibar (Fig. 1). Octopus samples were collected at Kizimkazi and Paje (in the southern parts), Nungwi (in the northern part), and Chwaka Bay (in the central part). All samples were collected from the artisanal fishermen, who used both on-foot and diving collection methods.

Biological sampling

The samples of *O. cyanea* were collected monthly for a period of 12 consecutive months. For each month, two days of the spring tide were spent collecting samples at each site. Once landed, all samples were taken to a laboratory where the dorsal mantle length (DML) and the total body weight (TW) were measured and the sex determined. The DML was measured using a measuring tape to the nearest 0.5 cm, while the TW was measured using an electronic digital balance to the nearest 0.5 g. Sex was determined by observing the presence of spermatophoric grooves (a whitish-gray line on the ventral surface) on the third right arm of males and their absence in females (Herwig *et al*., 2012). Once measured, octopuses were dissected, their gonads and

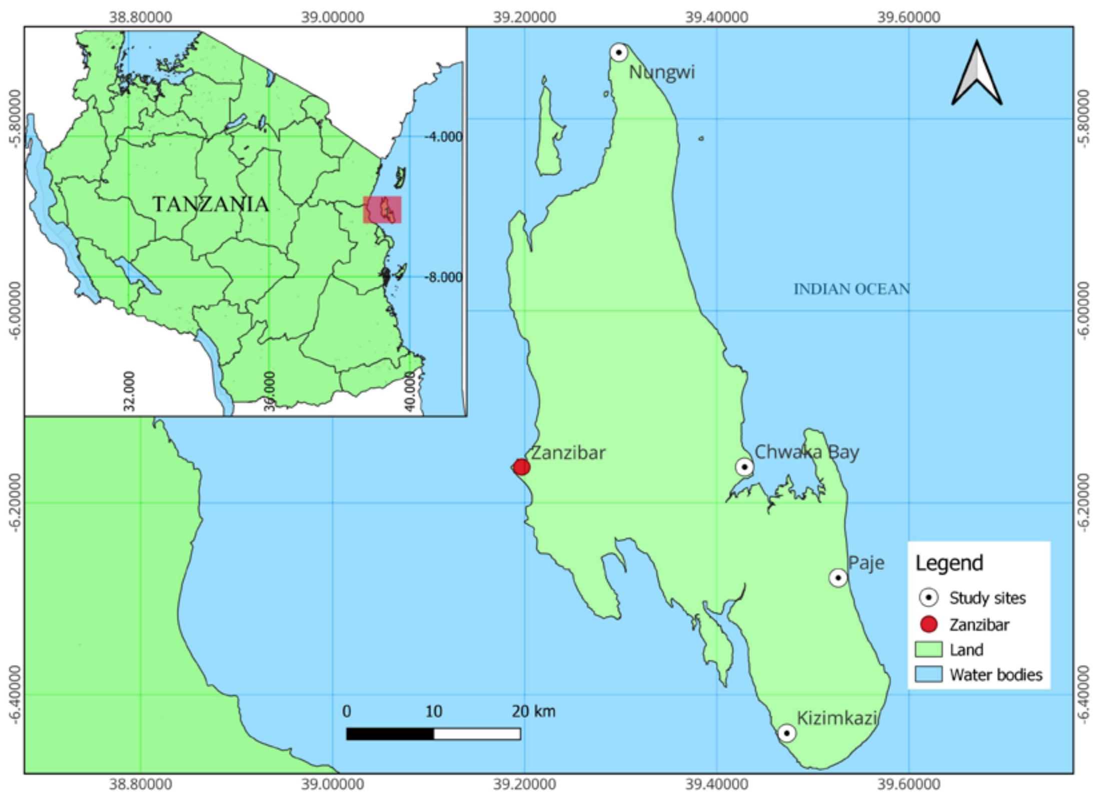

Figure 1. The Map of Unguja Island (Tanzania) showing the four sampled sites.

stomachs extracted, and preserved in a 10 % freshwater formalin solution.

Diet analysis and prey identification

The stomachs were weighed after extraction, and the prey items were identified and counted. To make them clear, all contents were flushed with fresh water and put on a tray ready for sorting. The prey items extracted from each octopus were recorded monthly. The empty stomachs were also recorded. All data pertaining to feeding was recorded by sex and maturity stage. The stomach fullness was determined and grouped into five levels (empty, ¼, ½, ¾ and bloated) based on the distension and amount of prey in the stomachs. The bloated level denoted a swollen stomach, which was completely filled with food, while the empty level denoted a stomach devoid of food. The following indices were calculated:

- Fullness weight index (FWI) was calculated as the ratio of the digestive tract content to the total weight of organisms less the empty digestive tract weight (Villegas *et al.*, 2014).
- The digestive tract weight index (DTWI) was calculated as the ratio of digestive tract weight to total weight (Quetglas *et al.*, 2005).
- Gonadosomatic index (GSI) was calculated as: GSI = Wo/(Wt – Wo) *100 Where 'Wo' is the weight of ovary and 'Wt' is the total wet weight (Guard and Mgaya, 2002).

The importance of each prey category was determined using the frequency of occurrence (FO) method. FO was calculated as the percentage ratio between the number of stomachs containing a given prey item with respect to the total number of stomachs containing food (Cortez *et al.*, 1995). The digestive tract weight index (DTWI) and the fullness weight index (FWI) were used to determine the amount of food consumed. To determine the prey species in the diet, the number of prey species was counted and recorded by the sexes and maturity stages. In order to relate feeding with maturity, GSI was used to define the peak and least breeding of *O. cyanea* in the area.

The prey items were identified to the lowest possible taxonomic group using a specialized identification key. Crustaceans were identified by the colour of their carapaces and shells and the shape and colour of their chelae (Quetglas *et al.*, 2005). Fish were identified using remaining parts of their bodies, while octopus were identified by physical observation when not under intensive digestion or by the presence of beaks in the octopus body. The foods in an advanced state of digestion were recognized as 'unidentified' but were not included in the calculation of the index. A dissecting microscope was used to examine small prey items from the octopus stomachs. All the data were grouped by sex and maturity stage.

Determination of maturity stages

The gonadal development of male octopuses was classified into three (3) maturity stages: stage I (immature), stage II (maturing) and stage III (mature), while females were classified into five maturity stages: stage 1 (immature), stage II (maturing), stage III (mature), stage IV (spawning), and stage V (spent). This classification was used as per Guard and Mgaya (2002) with a minimal modification. In males at stage III, spermatids and spermatozoa are abundant and there are no empty spaces between cells and in females at stage IV is seen when there is a significant increase in oocyte size, deeper infoldings of the follicular epithelium, as well as increased yolk production. At stage V, female oocytes have been discharged. All individual octopuses staged as stage III, IV and V were classified as mature and those with maturity stages I and II were classified as immature.

Data analysis

To analyze feeding habits and diet composition, all 543 samples of *O. cyanea* were used. The identified prey items were grouped according to taxonomic affinities, resulting in three putative groups: molluscs (bivalves, gastropods, and cephalopods), crustaceans, and fish. The comparison of the sizes of male and female octopuses was determined by means of a t-test. An analysis of the influence of maturity stages on the diet between groups was made by means of a t-test. The comparisons of fullness levels among maturity stages, sexes, and sites were made by means of a one-way analysis of variance (ANOVA). The level of statistical significance used was $p < 0.05$.

Results

Five hundred and forty-three (543) *O. cyanea* individuals were collected, with 294 (54.1 %) females and 249 (45.9 %) males. Females measured from 5 to 29 cm DML and weighed between 73 and 6300 g TW, while males measured from 4 to 24 cm DML and weighed between 64 and 3630 g TW. Based on monthly data, larger octopuses (13–15 cm DML) peaked from June to July and from October to November (Fig. 2). In the sample, the smallest individual observed to mature

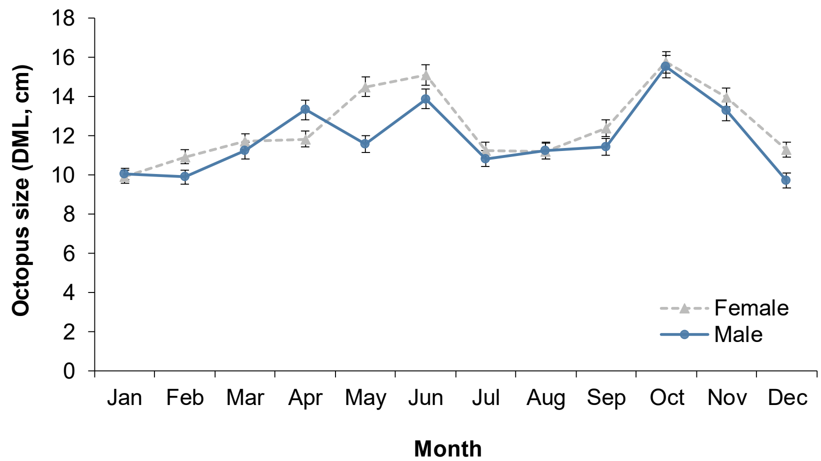

Figure 2. Monthly population size (based on DML) of *O. cyanea* in Zanzibar.

measured 7 cm DML for males and 8 cm DML for females. These smallest mature individuals were caught in October. There was no significant difference in DML between male and female individuals (t = 0.87, df = 22, p = 0.197).

Prey consumption and breeding season

The prey consumption by *O. cyanea* peaked in February (110 prey items) and May (100 prey items), while the lowest prey consumption occurred in June (37 prey items) and October (33 prey items). A sharp decline in the prey consumption occurred from May to June (Fig. 3). In comparison to average size based on DML (Fig. 2), large octopuses were caught in June and October, where a small amount of prey was consumed (Fig. 3). Based on the GSI, the breeding season peaked in June and October (Fig. 4). The least breeding season was found to be from January to March, and December for females. In males, lowest breeding was observed in May (Fig. 4).

Dietary analysis

The fullness level varied significantly between the maturity stages in females (F = 4.18, df = 3, p = 0.02) but not in males (F = 1.01, df = 3, p = 0.42). All five levels of fullness (empty, ¼, ½, ¾ and bloated) appeared in males only at stages I and II. At stage III, no male octopus appeared with a bloated level of fullness (Fig. 4 B). In females at stages I, II, and III, all five levels of fullness appeared. But females at stages IV and V did not appear with bloated levels of fullness (Fig. 4 A). However, the number of empty stomachs increased with maturity stages and was higher in females than males.

Digestive tract weight index (DTWI) and fullness weight index (FWI)

The DTWI showed a decreasing mode with maturation stages in both sexes. The value of DTWI increased slightly from stage I but reached very minimal levels at stages III in males and stages V in females (Fig. 6).

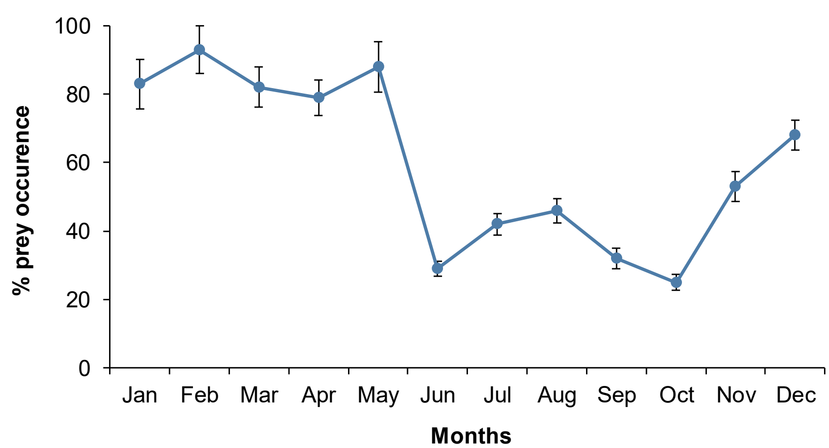

Figure 3. The monthly percentage occurrence of prey items consumed by *O. cyanea* in Zanzibar coastal waters.

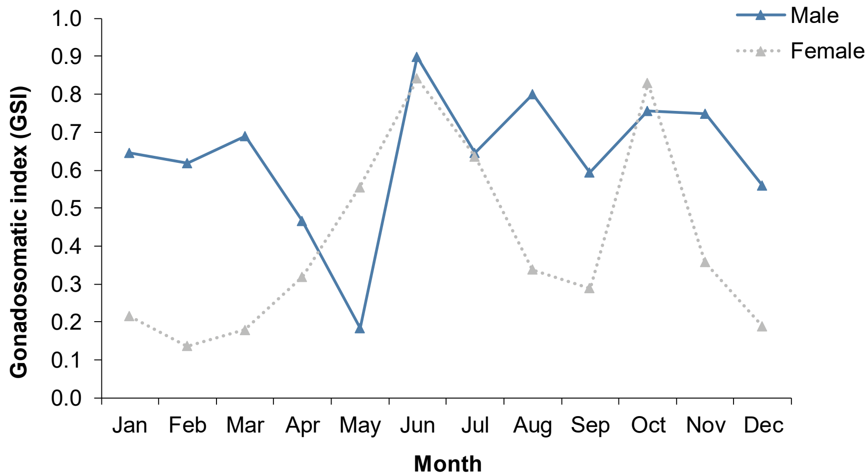

Figure 4. Monthly Gonadosomatic index (GSI) of male and female *O. cyanea* from Zanzibar.

There was no significant difference in DTWI between the sexes (t = 0.20, df = 3, p = 0.46). Between the maturity stages, significant differences were detected between stages I and III in males (p = 0.04), stages I and IV (p = 0.01), and stages II and V (p = 0.01).

The value of the fullness weight index (FWI) decreased along with maturity stages. The rate of decrement was higher in males than females. The FWI decreased from stage II to stage III in males and from stage III to stage V in females (Fig. 7). No significant difference in FWI between the sexes was detected (t = 1.94, df = 3, p = 0.45).

A total of 36 prey species were identified from three major taxonomic groups: crustaceans (83.4 %), molluscs (9.3 %), and fish (7.3 %) (Table 1).

Crabs were the preferred prey items in the diet, contributing over 63 % of all prey items. Sessile (mussels and barnacles) and slow-moving (sea snails) prey items appeared as the lowest prey groups and were only consumed at the final maturity stages (Fig. 8). Unidentified prey materials were higher, accounting for 55 % (58 % for females, 42 % for males) of all food contents. Most of the unidentified materials were a mixture of crabs, fish scales, fish eggs, and other soft-bodied prey, indicating that the octopus has high prey diversity. Cannibalism accounted for 5.32 % of all prey items and was detected in all maturity stages except at stage I in both sexes.

Diet composition

The findings from this study showed that the *O. cyanea* included up to six different prey types in its diet.

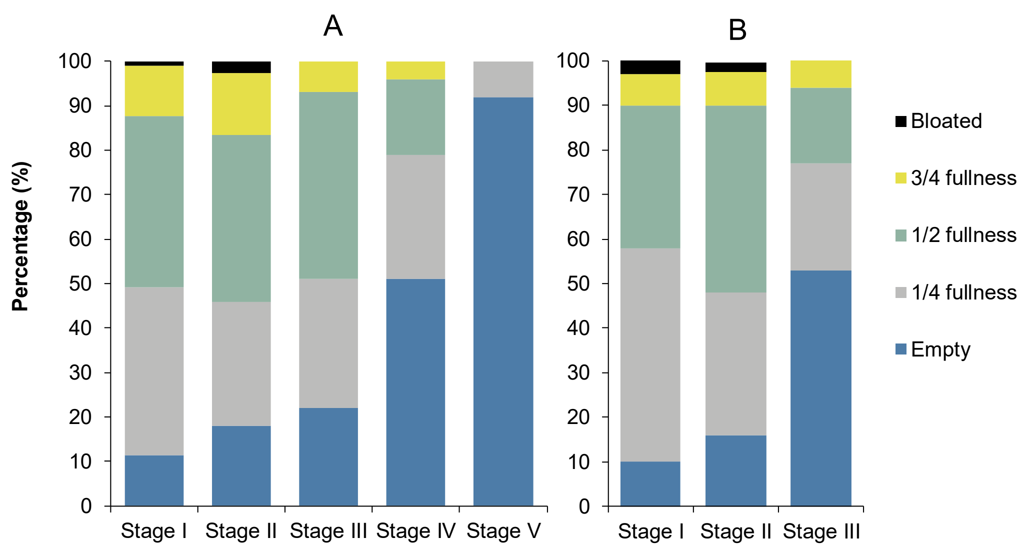

Figure 5. The stomach fullness levels of female (A) and male (B) *O. cyanea* with maturity stage.

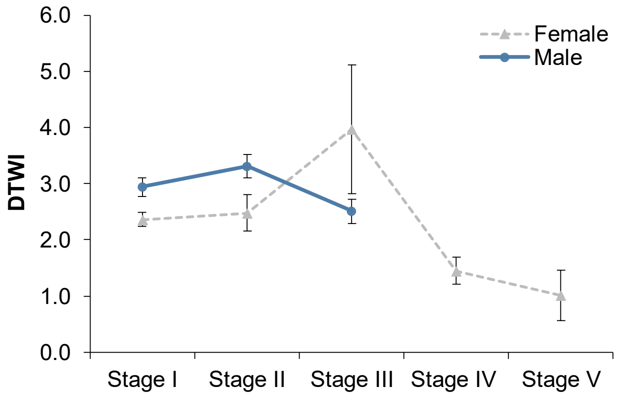

Figure 6. Digestive tract weight index (DTWI) by sex and maturity stage.

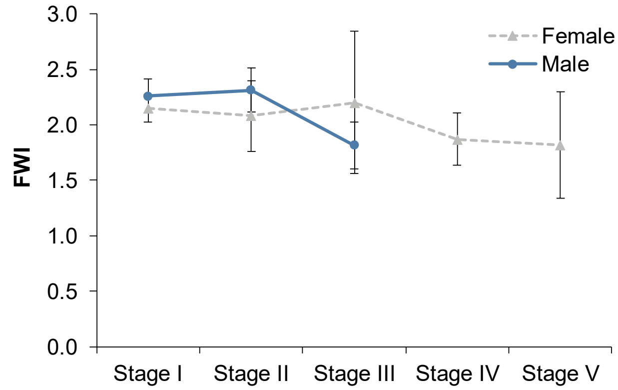

Figure 7. Fullness weight index by sex and maturity stage.

However, most of the individuals included between two and three prey species in varying quantities (Fig. 8). Mature individuals (stage III for males, stages IV and V for females) consumed a single or few sessile or slow-moving prey species in variable amounts. Single prey consumption was also observed in all maturity stages, especially when the octopus consumed large prey types or a group of prey of a single species.

Frequency of occurrence (FO)

The frequency of occurrence (FO) was presented at the family level. Portunidae (31.88 %) and Grapsidae (15.96 %) were the two most popular prey families appearing in the diet of *O. cyanea*. The most preferred prey family was Portunidae (31.88 %), followed by the family Grapsidae (15.96 %) which are a family of crabs. The least consumed prey were from families Iblidae, Muraenidae, Odontodactylidae, Oziidae, Phasianellidae, and Strombidae, each contributing only 0.25 % of the total diet of *O. cyanea.* All families are summarized in Table 2.

Discussion

The commercial value and ongoing efforts to manage octopus fisheries has increased the need to investigate various aspects of their lives. This study examines the feeding behaviours of *O. cyanea* at various stages of maturity. This information will contribute to a better understanding of the feeding ecology, nutritional profile, and energy balance of this species in relationship to their stages of maturity.

The maturity of octopuses varies with size, and the smallest mature male and female octopuses found in this study were 360 g (7 cm DML) and 610 g (8 cm DML), respectively. Guard and Mgaya (2002) reported the smallest mature male and female in mainland Tanzania, weighing 320 g and 600 g, respectively. However, the smallest mature male and female *O. cyanea* reported in other geographical areas are 350 g and 520 g in Australia (Herwig *et al.*, 2012) and 400 g and 450 g in Madagascar (Raberinary and Benbow, 2012). The largest individual of 6300 g differs from the 11700 g octopus caught in mainland Tanzania (Guard and Mgaya, 2002), the 6400 g in Madagascar (Raberinary and Benbow, 2012), the 6500 g in Hawaii, and the 1900 g in Australia (Herwig *et al.*, 2012). These variations might be due to effects of geographic location, environmental plasticity, dietary availability, and the management status of the area (Guard and Mgaya, 2002; Semmens *et al.*, 2004). The monthly size variations of *O. cyanea* (Fig. 3) could be due to the timing of reproductive onset in the cohorts.

O. cyanea in Zanzibar spawns throughout the year, with June and October being the peak breeding seasons (Fig. 4). June and October are also the months during which the octopus population is characterized by larger individuals compared to other months (Fig. 2). Simply put, June and October are the periods when large individuals experience peak breeding season in Zanzibar. Similar breeding seasons have been reported by Guard and Mgaya (2002) in mainland

Table 1. Frequency of occurrence (%) of the major taxonomic prey groups in the diet of *O. cyanea*.

Prey group	%
Crustaceans	83.4
Molluscs	9.3
Fish	7.3

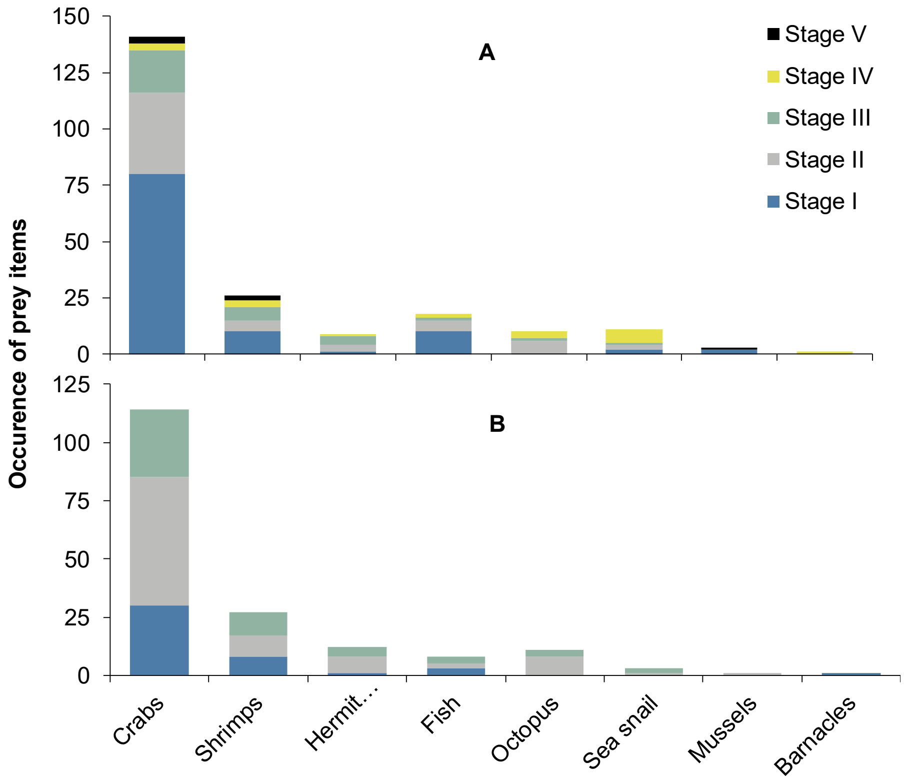

Figure 8. The occurrence of prey items consumed at various maturity stages of female (A) and male (B) *O. cyanea* in Zanzibar.

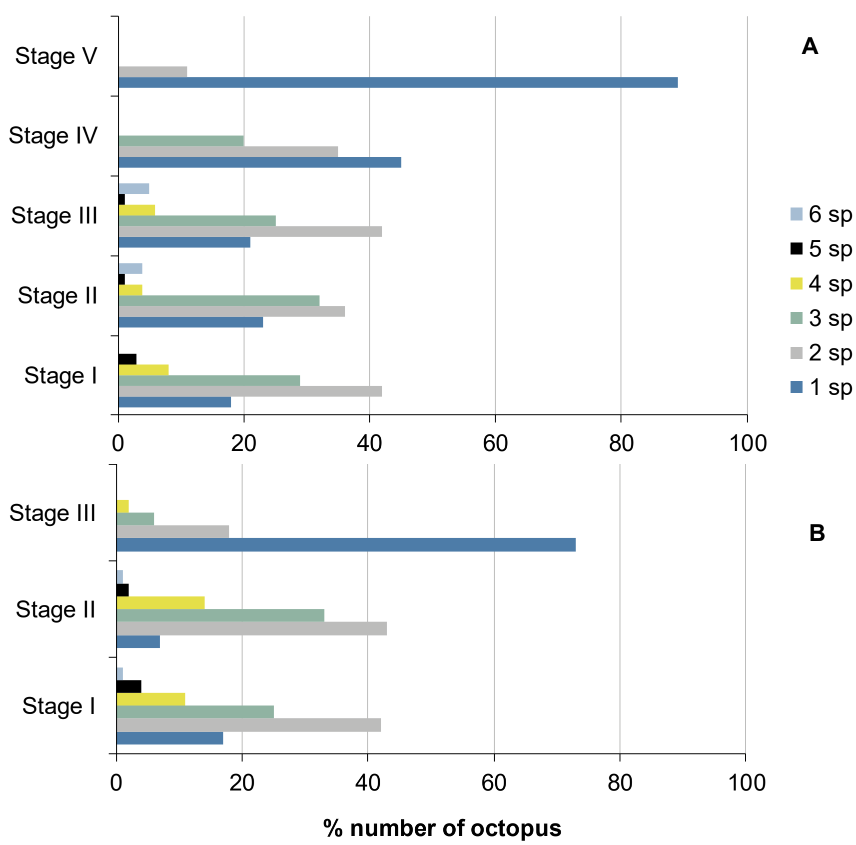

Figure 9. Percentage number of prey species found in individual stomachs during laboratory analysis for both females (A) and males (B). The prey included in the diet ranges from one species to six species in the stomach.

Table 2. Frequency of occurrence (FO) of prey families in *O. cyanea* diet by maturity stages. At stages I, II, and III, the value is the average of the male and female individuals.

Frequency of occurrence, FO (%)						
Family	Stage I	**Stage II**	**Stage III**	**Stage IV**	**Stage V**	**Total**
Portunidae	12.4	11.39	6.84	1.01	0.25	**31.89**
Grapsidae	7.09	5.57	2.02	0.6	0.6	**15.88**
Octopodidae	0	3.52	1.02	0.5	0.25	**5.29**
Penaeidae	2.79	0.51	0.76	1.23	0	**5.29**
Alphaeidae	1.52	1.78	1.04	0.25	0.25	4.84
Cancridae	1.77	1.52	1.26	0.25	0	**4.8**
Congridae	2.28	1.27	0.72	0.51	0	**4.78**
Sergestidae	1.27	0.75	0.25	1.27	0	**3.54**
Raninidae	1.52	1.26	0.25	0.25	0	**3.28**
Plagusiidae	2.28	0.25	0.51	0	0	**3.04**
Diogenidae	0.25	1.26	0.76	0.25	0.25	**2.77**
Gecarcinidae	0.76	0.76	0	0	0	**1.52**
Macrophthalmidae	0.25	1.26	0	0	0	**1.51**
Mitridae	0.25	0.52	0.25	0.25	0.25	**1.52**
Xanthidae	0.76	0	0.76	0	0	**1.52**
Littorinidae	0.25	0	0	1	0.25	**1.5**
Sesarmidae	0.2	1.26	0	0	0	**1.46**
Anguillidae	0.76	0.51	0	0	0	**1.27**
Trapeziidae	0.52	0	0	0.25	0	**0.77**
Calcinidae	0	0.51	0	0.25	0	**0.76**
Porcellanidae	0	0.51	0	0	0	**0.51**
Mytilidae	0.26	0	0	0	0.25	**0.51**
Iblidae	0	0	0	0	0.25	**0.25**
Muraenidae	0	0	0.25	0	0.25	**0.5**
Odontodactylidae	0	0.25	0	0	0	0.25
Oziidae	0	0	0	0	0.25	**0.25**
Phasianellidae	0	0	0.25	0	0	**0.25**
Strombidae	0	0.25	0	0	0	**0.25**
TOTAL	37.18	34.91	16.94	7.87	3.1	100

Tanzania at Mafia, where the peak breeding season of *O. cyanea* is June. The peak breeding season for this species has also been documented in October–November in Rodrigues (Sauer *et al.*, 2011) and April–June in Madagascar (Raberinary and Benbow, 2012). Other species like *O. vulgaris* in Kenya exhibit their peak breeding season in June and August (Kivengea *et al.*, 2015). Thus, geographical differences and the type of species influence peak spawning time.

By linking the monthly octopus population size (Fig. 2), monthly feeding schemes (Fig. 3), and monthly spawning pattern (Fig. 4), it is revealed that the large and mature individuals are associated with low prey consumption. In other words, the large and mature animals that dominate the population in June and October consume a very minimal amount of prey. Meanwhile, in February and May, the months of small-sized octopuses, the *O. cyanea* experiences its lowest GSI, indicating that the population of octopuses is dominated by immature individuals that consume more prey items. This supports the notion that small, non-spawning octopuses consume more prey to invest more energy required for the spawning process in the following months (Archer *et al.*, 2022). A similar situation has been reported for immature *O. mimus* in China that experiences high feeding intensity in April and June (Bo *et al.*, 2020). This is probably because each octopus species experiences different feeding patterns depending on the period of availability and prey abundance in a particular geographical location. In Zanzibar, prey abundance is higher in February and May.

The food content in the octopus stomach is affected by their maturity stages. The studies conducted by Cortez *et al.* (1995) and Armendáriz Villegas *et al.* (2014) revealed that the average number of empty stomachs increases as animals mature, which suggests a subsequent decrease in food intake with maturity. The current results show that empty stomachs in females ranged between 11 and 18 % for immature individuals and 22 and 92 % for mature individuals (Fig. 5A). In males, empty stomachs ranged between 10 and 16 % for immature specimens, while mature specimens had about 53 % empty stomachs (Fig. 5 B). These results provide an indication that octopuses modify their feeding with their stage of maturity. Such changes in food intake have been observed in various species in both captivity and the wild (Ernesto *et al*., 2010). For example, Quetglas *et al.* (2005) observed a high incidence of empty stomachs in ripe *O. salutii,* while Bo *et al*. (2020) noticed the presence of more than half of adult *O. minor* females with empty stomachs.

The feeding modification with maturity stages aims to accommodate the physiological requirements of octopuses (Bo *et al*., 2020). For example, during the spawning stage, octopuses stop feeding while focusing exclusively on laying and caring for eggs (Anderson *et al*., 2002). During this period of no or less feeding, octopuses rely on energy in the form of adenosine triphosphate (ATP) from body reserves (Domínguez-Estrada *et al*., 2022). Because an excessive amount of ATP is required throughout the brooding period, their muscles deteriorate and animals become physically less active, hence unable to hunt (Meza-Buendía *et al*., 2021). However, the observed empty stomachs during immature and mature stages are because the octopuses maximize digestion rate to provide energy required for growth and other metabolic activities (Archer *et al*., 2022). The reason why immature octopuses eat more food (87 % for females, 85 % for males) than mature ones is the need to accelerate their body growth and stimulate gonadal development (Villanueva *et al*., 2004; André *et al*., 2009). The observation of more bloated stomachs at immature stages indicates a high food intake. The low values of DTWI (Fig. 6) and FWI (Fig. 7) emphasize that mature individuals consume less food than immature ones.

In general, this study found more food in male *O. cyanea* than females throughout the maturity stages (Fig. 5). This could be explained by two scenarios: first, the male *O. cyanea* maximizes their food and energy investment for searching mates, attraction of females, courtship, fighting, and sperm competition so as to achieve early reproductive success (Bonduriansky *et al*., 2008; Archer *et al*., 2022; Omedes *et al*., 2022). Second, female *O. cyanea* grow to a larger body size (Fig. 2) than males, so they need an extended time to allocate resources needed to produce offspring, and in doing so, they double their physiological processes faster than males (Archer *et al*., 2022). Due to this, their food is digested more quickly than that of males (Omedes *et al*., 2022), and they invest it in the development of the vitellus (Bo *et al*., 2020). This may explain why more unidentified food remains was found in females than in males in this study, showing that their rapid digestion rates have an immediate impact on the prey they eat.

Octopuses are well-known generalist and opportunistic predators of a variety of prey species (TAFIRI unpublished data), having very high metabolic rates compared to many other benthic predators (Song *et al*., 2019). Their high metabolic processes enable them to consume more prey per unit of time in an efficient manner (Onthank and Cowles, 2011). This generalist predation assures them of their ability to search, capture, and handle a diverse range of prey types to meet their energy and nutrient demands (Scheel *et al*., 2017; Portela *et al*., 2014). The diet of *O. cyanea* in this study was composed of 36 prey species (Table 2). This finding was unsurprising because such generalist feeding has been documented in *O. cyanea* in French Polynesia (Scheel *et al*., 2017). Other octopus species, such as *O. bimaculatus* (Armendáriz Villegas *et al*., 2014), *O. vulgaris* (Smith, 2003), *O. insularis* (Rosas-Luis *et al*., 2019), *O. mimus* (Cortez *et al*., 1995), and *O. minor* (Bo *et al*., 2020), have been described as generalist predators. *O. cyanea* can include up to six different prey species in the stomach at a time, but the inclusion of 2–3 prey species in the diet is common (Fig. 9).

Crustaceans were the most abundant prey consumed by *O. cyanea* (83.4 %), followed by molluscs (9.3 %) and fish (7.3 %) (Table 1). The importance of crustaceans in the octopus diet has been reported by Smith (2003), Rosas-Luis *et al*. (2019), and Bo *et al*. (2020) in the wild, but also proved by Prato *et al*. (2010), Martnez *et al*. (2014), Caamal-Monsreal *et al*. (2016), Maselli *et al*. (2020), and Urrutia-Olvera *et al*. (2021) in captivity. Crab was the most preferred prey in *O. cyanea* (63.75 %), followed by shrimp (13.75 %). Fish and octopus contributed (7.25 %) and (5.25 %) to the diet, respectively. *Charybdis* sp. and *Grapsis* spp. dominated the diet, suggesting their suitability to satisfy the energy demand of *O. cyanea*. *Charybdis* sp., *Grapsus* sp., and *O. cyanea* are coral-associated species (Urrutia-Olvera *et al*., 2021), so the likelihood of an octopus encountering these prey species is higher during foraging time.

Crabs and shrimp were consumed at all maturity stages of the octopus, representing their important role in the energy needs of the octopus (Martínez *et al*., 2014; Caamal-Monsreal *et al.*, 2016; Urrutia-Olvera *et al.*, 2021). Most sedentary and slow-moving prey species, such as sea snails, mussels, and barnacles, are consumed by mature (mainly spawning) individuals (Fig. 8). Because of the time and energy investment in egg brooding, it becomes difficult for the spawning individuals to obtain crabs; instead, they adopt an energy-saving technique by relying on these sessile animals found within their habitats or dens (Leite *et al.*, 2009; Maldonado *et al.*, 2019). This was evidenced in the present study, where the intake of primary prey (*Charybdis* sp. and *Grapsus* sp.) was almost nill (Table 2). Cannibalism is common in octopuses, and it was found in all maturity stages except in stage I individuals (Table 2), demonstrating that the larger individuals consume the smaller ones. In general, data from this study can be included in the management plan for this species, especially when deciding the periods for implementation of management measures.

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Suplementary material

Table S.1. The prey species consumed by *O. cyanea* in Zanzibar.

Prey species		
Acetes erythraeus	*Marsupenaeus* sp.	*Portunus* sp.
Alpheus lottini	*Mitra* sp.	*Ranina ranina*
Anguilla sp.	*Neopelithes* sp.	*Sarmatium* sp.
Calcinus sp.	*Ibla cumingi*	*Penaeus* sp.
Cancer sp.	*Ilyograpsus paludicola*	*Phasianella variegata*
Cardisoma carnifex	*Liomera rugata*	*Plagusia chabrus*
Charybdis sp.	*Littoraria* sp.	*Septifer bilocularis*
Clibanarius sp.	*Lydia* sp.	*Siderea picta*
Conger sp.	*Macrophthalmus* sp.	*Strombus* sp.
Dardanus sp.	*Octopus* sp.	*Synalpheus* sp.
Geograpsus sp.	*Odontodactylus scyllarus*	*Trapezia* sp.
Grapsus sp.	*Pagurus* sp.	*Xantho* sp.

Original Article

Salinity tolerance of Nile tilapia (*Oreochromis niloticus*) to seawater and growth responses to different feeds and culture systems

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Abstract

The inability to acclimatise, feed and grow Nile tilapia (*Oreochromis niloticus*) in full seawater salinity has been a major obstacle to farming in marine waters. We investigated the salinity tolerance of *O. niloticus* and growth responses to different feeds and culture systems. Fish were first acclimatised to different salinities in laboratory aquaria, and the survival and growth performance in sea water were then assessed in aquaria, cages and ponds. Acclimatization to seawater salinity (5 – 30) took place at a rate of 5 every 9 days. Fish were stocked at densities of 5 fish/20 L in aquaria, 5 fish/m^3 in cages and 3 fish/m^2 in ponds. Replicates of 5, 3 and 3 were performed in aquaria, cages and ponds, respectively. Fish were fed on commercial (1 and 2) and locally formulated (30 % crude protein) diets. Mortality rates were higher in aquaria, when fish were introduced to salinities between 5 and 30 over 24 hours. Gradual salinity adjustments attained a stable survival rate of 78 % at salinities above 30. Aquarium experiments indicated significant negative correlation between salinity and survival ($p < 0.001$, r = 0.387) and daily growth rates varied with diet (0.01 – 0.05 g/day). Acclimatized fish showed minimal mortality in ponds and cages. Daily growth rates varied with diet and culture system; 0.54 - 2.48 g/day in cages and 1.1 - 2.5 g/day in ponds. Fish fed on commercial feed 2 showed significant growth rates for all culture methods ($p < 0.05$). *O. niloticus* could be fully acclimatised to seawater and attained promising growth rates when subjected to different commercial diets indicating potential of farming the species in marine waters.

Keywords: *Oreochromis niloticus*, salinity, survival, growth, feed

Introduction

Tilapia are tropical freshwater fish native to Africa but introduced to different global destinations for commercial production (Pillay & Kutty, 2005; Lutz *et al.*, 2010; Ninh *et al.*, 2014; Ridha, 2014). Currently, tilapia are farmed in 124 countries and ranked the fifth highly farmed species, with an annual production of 6.1 million tonnes (FAO, 2021). Farming of tilapia has been successful because of its fast growth, higher reproduction, feeding on low trophic levels, euryhaline characteristics and tolerance to adverse environmental conditions (Suresh & Lin, 1992; Morgan *et al.*, 1997; Ridha, 2004; Liti *et al.*, 2005). Furthermore, tilapia breeding innovations have been undertaken to increase economic production. These innovations include production of genetically improved male tilapia (GMT) and genetically improved farmed tilapia (GIFT), as well as attempts to farm tilapia in brackish and marine waters though still not fully developed in sub Saharan Africa (El-Sayed, 2006; Cnaani *et al.*, 2011; Ninh *et al.*, 2014 FAO, 2020).

Marine water aquaculture in sub Saharan Africa has been impacted by a lack of hatchery infrastructure which is the backbone of seed production, resulting in low fish production and increased poverty levels (Ridha, 2004; World Bank, 2016). Many authors reported that hatchery and breeding technologies for tilapia are simple and well developed globally for adoption and use in seawater (Jalabert & Zohar, 1982; Little *et al.*, 1993; Brummett, 1995; Ridha and Cruz, 1998; Bhujel, 2000). Farming of Nile tilapia (*Oreochromis niloticus*) in marine waters will maximise the use of currently underutilised ocean space for increased fish production and ensure food sufficiency to the more than 690 million people going without food daily (Editorials Nature, 2020).

Most tilapia utilised for commercial production are derived from *O. niloticus* or its hybrids and have been observed to exhibit limited salinity tolerance. The only strain that has been observed to withstand high salinities is Mozambique tilapia although its growth rates are economically not viable and its size at maturity is small (Lothian, 1960; Mateo *et al.*, 2004, Kamal & Mair, 2005). According to Watanabe *et al.* (1985b), McGeachin *et al.* (1987) and Perschbacher & McGeachin (1988), *O. niloticus* mortalities progressively increase with increasing salinities. Other studies have established that a progressive increase in daily salinities (6 g/l) tends to minimise mortalities of *O. niloticus* (Mateo *et al.*, 2004). Further studies by Lemarie *et al.* (2004) established that daily salinity increases of 2-8 g/l increased survival of *O. niloticus* while that above 8 g/l decreased survival significantly.

Over the years, farming of *O. niloticus* in brackish water systems has attained some level of success globally, while hybrids are being trialled in full seawater salinity with limited success (Stickney, 1986; Suresh & Lin, 1992; Lutz *et al.*, 2010; Ridha, 2014). The current study builds on the successes made in farming *O. niloticus* in seawater to establish a full seawater tolerant strain for marine aquaculture. A series of experiments were conducted with two objectives (1) To establish an optimal salinity acclimatization strategy based on progressive incremental salinity to support the farming of *O. niloticus* in full seawater; (2) To assess the growth response of *O. niloticus* to different diets during the acclimatization process in aquaria, net cages and intertidal earthen ponds. We discuss the results of the experiments undertaken at the laboratory (aquaria) and at the field (net cages and intertidal earthen ponds). The study provides information that will contribute towards farming *O. niloticus* in full seawater thus contributing to utilization of the ocean potential.

Materials and methods

Experimental fish and diet

The experimental fish were hatched from the broodstock collected from the National Aquaculture Research Development and Training Centre (NARDTC) in central Kenya where selective breeding is undertaken to attain fast growing freshwater *O. niloticus*. The fish were hatched in borehole water of salinity 0.63 from a coastal hatchery, and acclimatised to salinities of 30 ± 5 in laboratory aquaria. The acclimatised fish were later used in laboratory aquaria, cages and pond growth experiments. Three diets comprising of commercial feed 1, 2 and a locally formulated diet both with 30% crude protein content were used in the experiments (Table 1). According to Simon *et al.* (2019), commercial feed 2 had a marine bacteria biomass unlike commercial feed 1. Locally formulated feed was formulated with local ingredients like coconut husks, fishmeal (*Rastreneobola agentii* “Omena”/”daggaa”), maize bran and cassava flour.

Experimental design

Salinity tolerance and growth of *O. niloticus* in seawater was assessed in laboratory aquaria, cages and intertidal earthen ponds. Treatments were based on three feed diets; commercial feed 1, 2 and locally formulated feed. The level of replication varied between the different culture systems (5 for aquaria, 3 for cages and 3 for intertidal earthen ponds). Aquaria experiments were conducted in the laboratory at the Kenya Marine and Fisheries Research Institute (KMFRI) Mombasa

Table 1. Proximate composition of the three feed diets used in the *O. niloticus* experimental trials

Proximate composition	Diet treatments		
	Commercial feed 1	Commercial feed 2	Local formulated feed
Crude protein (%)	30	30	30
Fat (%)	7	7	4
Fibre (%)	9	9	3
Ash (%)	12	12	4
Moisture (%)	11	11	14
Marine bacterial biomass	Absent	Present	Absent

while cage and pond experiments at Kibokoni, Umoja self-help group mariculture farm, Kilifi creek, Kilifi County. All the fish used in field experiments (cages and ponds) were first taken through the laboratory aquaria and acclimatised to salinities of more than 30.

Experiment 1: Laboratory aquaria

Experiments were performed in 20 L glass aquaria with gentle aeration. The experimental fish varied in weight between 1.2 and 2. 0 g. They were first acclimatized for two days at 0.63 salinity, room temperature (25 - 26 °C) and fed to satiation twice a day at mid-morning and mid-afternoon. Fish were randomly stocked at 5 fish/L before subjection to different salinity levels (5, 10, 15, 20, 25 and 30) with a replication of five for each salinity level. Baseline salinity was established by subjecting all the fish directly to different salinity levels for a period of 24 hours and survival elimination was done. Subsequent experiments monitored survival and feeding at different salinity levels/gradients over a period of 216 hours at each level. During acclimatization period, slow and consistent adjustments of salinity (10 – 30%) was employed as detailed by Perschbacher (1992) and Yao et al. (2008). Attainment of full seawater stability was alluded to when (1) there was a reduction in mortality, (2) fish were observed to feed normally and attained weight as a sign of growth. Fully modified laboratory experimental fish were retained for an extra 336 hours at full seawater salinity (30 ± 5) before use in laboratory aquaria growth experiments and transportation for use in field (cage and pond) experiments. To assess the growth of fully acclimatised seawater *O. niloticus* in the laboratory, fish of weight 2.2 g – 4.7 g were used. Experiments were set and monitored over a period of 7 days at stoking densities of 5 fish/20 L at a replication of 5 for the different feed diets. The growth of fish was monitored by measuring individual weight using a digital balance of precision 0.01 g at the start and at the end of the experiment. Mortality was monitored frequently and dead fish were removed and record documented. The behaviour and response of fish to feed were observed and recorded for different salinity levels.

Experiment 2: Field cages

Cage trials were used to assess the stability of laboratory seawater acclimatized *O. niloticus*. The cages were installed in intertidal earthen ponds (120 m^2) constructed in mangrove open flats at Kibokoni Umoja fish farm, Kilifi creek. The size of experimental cages was 1 m width, x 1 m length x 2 m height. The fish with an average weight of 3.5-14.0 g were cultured at a stocking density of 3 fish/m^2 for a period of 32 days. The experimental fish were fed twice a day (mid-morning and mid- afternoon) at 5% of their body weight. The weight of fish was measured using a digital balance (precision of 0.01) and length using a measuring board to assess growth bi-weekly. Survival was estimated by checking the nets daily for dead fish, recording the number and removing them. The final number was calculated by subtracting the number of dead fish from the initial number stocked. Survival percentage was calculated as;

% Survival = (No. of fish at termination of experiment/ Initial No. stocked)*100.

Experiment 3: Intertidal earthen ponds

Experimental ponds were constructed along the open mangrove intertidal flats and measured 10 m x 12 m (120 m^2). The intertidal earthen ponds are designed to allow free flushing at spring high tides to self-regulate water volume, salinity and quality (Mirera, 2011). Full seawater laboratory aquaria acclimatised fish with an average weight of 1.8 – 2.6 g were stocked at densities of 3 fish/m^2 for a period of 123 culture days. The fish were fed twice a day (mid-morning and mid-afternoon) at 5% of their body weight. The growth performance of fish was monitored by measuring weight and total length using a digital balance and measuring board respectively once a month. At the end of the experiment, all fish were retrieved from pond through seining and finally draining all the water from the ponds. Fish recovery estimates were made by counting all the retrieved after emptying the pond. Survival was calculated as;

% Survival = (No. of fish retrieved/ No. of fish stocked)*100

Water quality monitoring

Experimental aquaria water management involved siphoning 80% of the dirt water and replacing with clean filtered water of same salinity level. Water quality parameters like salinity, temperature, pH and dissolved oxygen in laboratory aquaria were monitored daily, while in cages and intertidal ponds quality parameters were monitored bi-weekly using water quality meter.

Data analysis

The proportion of time taken for fish to survive at each salinity gradient without any modification was

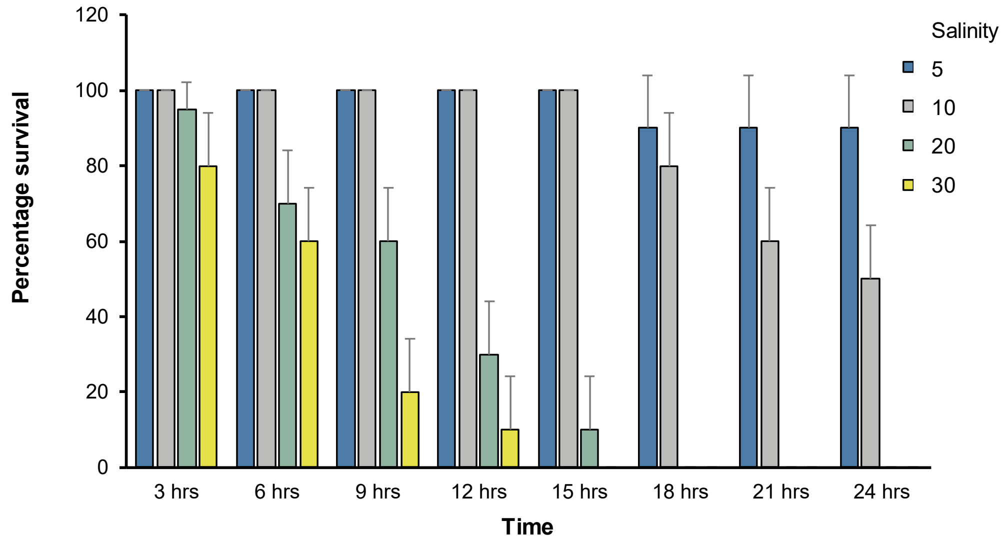


Figure 1. Survival (± Stdev) of *O. niloticus* fry to different salinity gradients over a period of 24 hours in the laboratory

estimated and averages were calculated. Fish growth rate in laboratory, cages and ponds was estimated using the formula;

Growth rate = (FW – IW)/T

Where FW= average final fish weight (g), IW = average initial fish weight (g), T= duration of the experiment (days).

The growth performance data of fish in the laboratory, cage and pond experiments were analysed using one-way Analysis of Variance (ANOVA). Pearson correlation analysis was done to assess the influence of salinity on survival. Statistics were performed using graph pad prism vs 9.0.

Results

Salinity tolerance

A total of 5,330 *O. niloticus* juveniles were used for the salinity tolerance experiments. The direct transfer of fish juvenile to different salinities over a period of 24 hours indicate a progressive decline in survival to 100% mortality in 18 hours for salinity levels above 20 (Figure 1). Laboratory aquaria experimental units experienced salinity fluctuations ranging between 0.16 and 0.24 per day (Table 2). Overall, during the 216 hours laboratory aquaria experimental cycle, fish survival decreased with increasing salinity levels (Figure 2a). Gradual incremental salinity modifications in the laboratory aquaria experiments attained stable fish survival rates of 78% for salinity levels above 30 (Figure 2b). Correlation analysis established a significant negative correlation between salinity and survival ($p < 0.001$, r = 0.387).

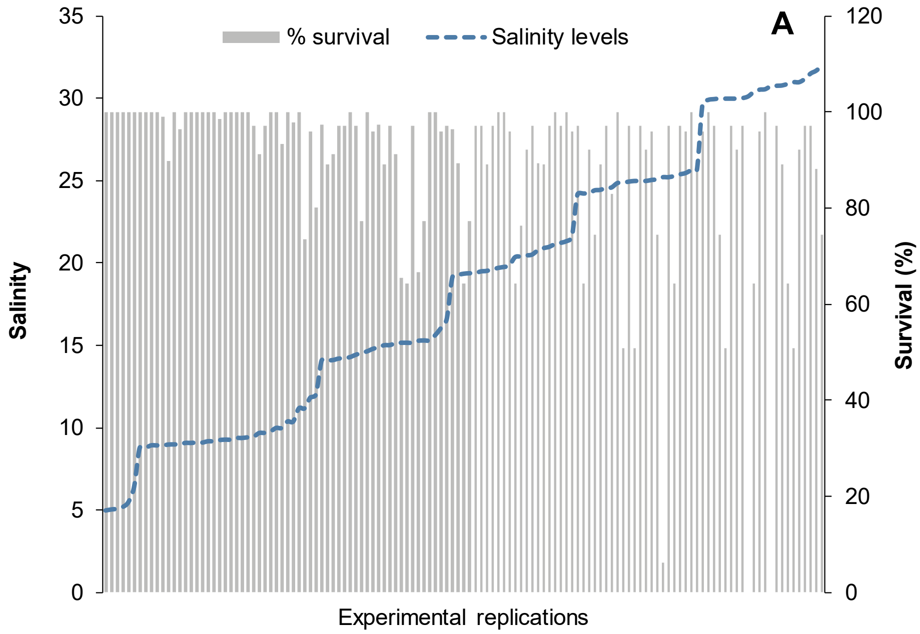
Growth performance

Experiment 1: Laboratory

Daily growth rates of 0.01 – 0.05 g/day were attained in laboratory aquaria experiments. Growth rates varied between and within the three feed treatments (Figure 3). A slower daily growth rate (0.01 g/day) was recorded for the locally formulated feed (Table 3). Fish fed on the locally formulated feed grew 33.3%

Table 2. Average daily salinity (± Stdev) dynamics in the experimental units at different salinity gradients during the *O. niloticus* laboratory modification

Salinity gradient	Salinity fluctuation (Mean ± STDEV)
5	0.20 ± 0.086
10	0.23 ± 0.092
15	0.16 ± 0.081
20	0.20 ± 0.026
25	0.24 ± 0.035
30	0.18 ± 0.044



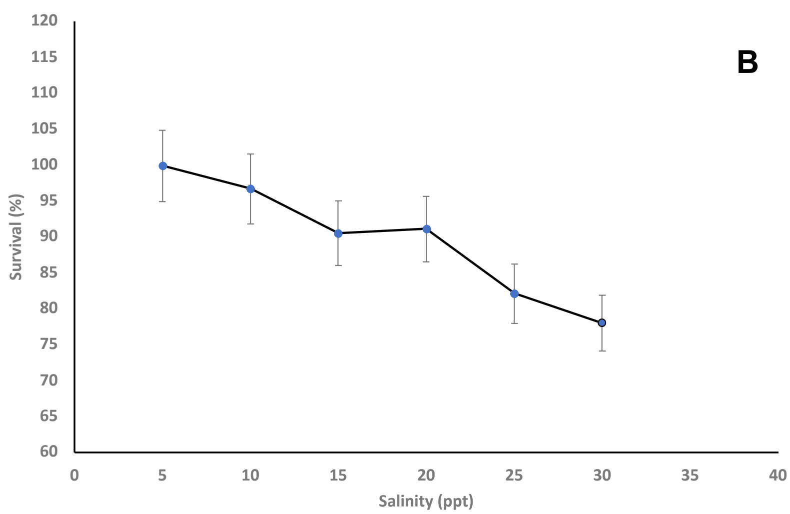


Figure 2. The relationship between survival and salinity levels for *O. niloticus* for the different experimental replicates (A) and average recorded survival at different salinity levels (B) in the laboratory modification experiments.

slower than the mean growth rate for the three feed diets. In treatments where commercial feed 2 was used fish grew 66.7 % more than the mean growth rate of the three feed diets. There was a significant difference in fish growth when all the diets were compared ($p < 0.05$) and commercial feed 2 had the highest growth rate.

Experiment 2: Cage experiments

The weight of fish in all feed experiments increased gradually during the experimental period. On average, the daily fish growth rate of 0.5 g/day, 0.6 g/day and 2.5 g/day was attained for locally formulated feed, commercial feed 1 and 2, respectively (Table 3; Figure 4). A fish survival of more than 90% was attained in all three feed treatments. Statistical analysis (one-way ANOVA) showed a significant difference ($p < 0.05$) in weight increment for the different feed diets. Commercial feed 2 had a significantly higher weight increment compared to the other two diets.

Experiment 3: Intertidal earthen ponds

There was a steady increase in weight of fish for all the feed treatments throughout the experimental period. Daily growth rates varied between treatments; 1.1 g/day for locally formulated feed, 1.5 g/day for commercial feed 1 and 2.5 g/day for commercial feed 2 (Table 3). Over the 123 days experimental period, fish

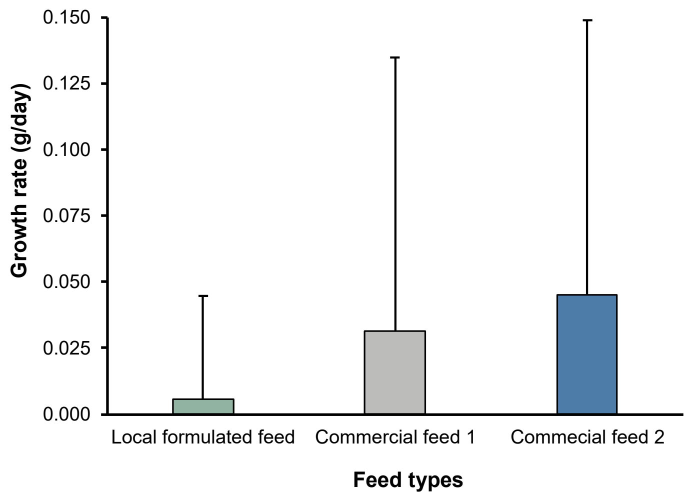


Figure 3. Growth (± Stdev) of full seawater salinity transformed *O. niloticus* subjected to different feeds under laboratory conditions over seven-day culture period

attained an average weight of 250 g for commercial feed 2, 200 g for commercial feed 1 and 150 g for the locally formulated feed (Figure 5). Fish survival in the different diet treatments ranged between 60% and 80% with no statistically significant difference. There was an observed decline in fingerling reproduction with only a few produced in the ponds. Fish colour was more clear and morphological features were well identified. The study established that the fish mucus layer was available and consistent in all treatments.

Water quality

In the laboratory growth experiments, water quality was maintained at a salinity of 30.0 ± 5.1, pH of 7.8 ± 0.2 and temperature of 26.4 ± 0.5 ^{0}C. Water quality in cage experimental facilities was documented as DO 4.85 ± 0.25, pH 7.71 ± 0.32, salinity 31.65 ± 5.52 and temperature 29.68 ± 2.85 ^{0}C . The salinity of water in experimental ponds varied between 30 and 34 (average of 32.99), pH between 7.5 and 8.6 (average of 7.9) and dissolved oxygen 2.3 – 8.7 mg/l depending on time of day and an average of 7.26 mg/l in mid-morning (Table 4).

Discussion

Effect of salinity on survival of O. niloticus

The pursuit to farm *O. niloticus* in seawater is due to its prolific reproduction, faster growth, market acceptability and simple established breeding technologies. Therefore, seawater tilapia aquaculture will maximise utilization of the ocean space to enhance food security and nutrition for the population. Studies on the salinity tolerance of tilapia have focused on single populations, comparison between varieties and genetic influences (Villegas, 1990; Kamal & Mair, 2005; Lutz *et al.*, 2010). We assessed the tolerance of *O. niloticus* to different salinity levels/gradients over

Table 3. Growth response (± Stdev) of *O. niloticus* to different feeds in aquaria, cages and intertidal earthen ponds

Experiment	Local formulated feed	Commercial feed 1	Commercial feed 2
Laboratory aquaria			
Stocking density (fish/L)	5	5	5
Average weight at stocking (g)	2.2 ± 0.4	4.2 ± 1.2	4.7 ± 0.1
Growth rate (g/day)	0.01 ± 0.03	0.03 ± 0.2	0.05 ± 0.1
Cages			
Stocking density (fish/m²)	5	5	5
Average weight at stocking (g)	5.5 ± 1.4	3.5 ± 1.1	14.0 ± 4.9
Growth rate (g/day)	0.5 ± 0.0	0.6 ± 0.1	2.5 ± 0.0
Intertidal earthen ponds			
Stocking density (fish/m²)	3	3	3
Average weight at stocking (g)	2.3 ± 0.6	2.6 ± 1.3	1.8 ± 0.0
Growth rate (g/day)	1.1 ± 0.0	1.5 ± 0.6	2.5 ± 0.6

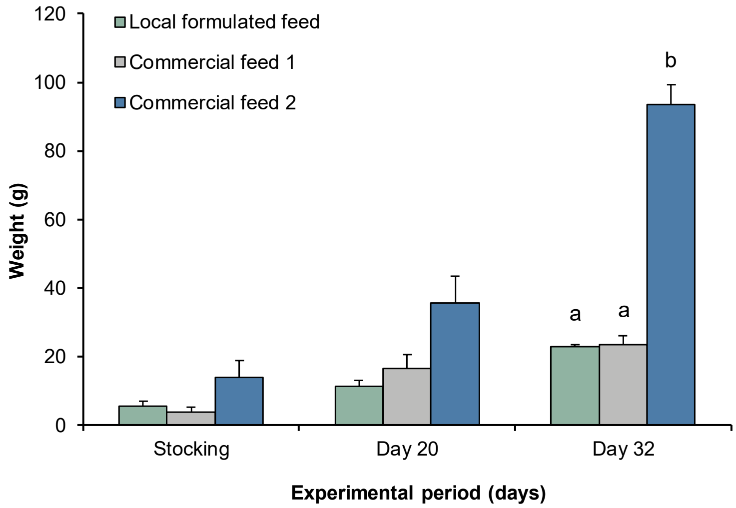


Figure 4. Growth (± Stdev) response of *O. niloticus* to different feeds in fish cages held in intertidal earthen ponds over the culture period (different super scripts indicate significant different)

time. Taking cognizance of gaps from previous studies, we employed a three prolonged approach (1) Establishment of a salinity level at which higher survival could be attained over a short time period as a modification baseline, (2) Establishment of a constant gradual salinity gradient increment and time lapse to full seawater salinity tolerance, (3) Assessing the performance of transformed tilapia in laboratory and field conditions.

In this study, laboratory experiments involved the use of juvenile/fry *O. niloticus* for the salinity trials based on previously documented studies where earlier exposure of eggs and fry to high salinity conditions helped to attain higher tolerance to salinity (Al Asgah, 1984; Watanabe *et al.*, 1985b). According to Watanabe *et al.* (1985a), *O. niloticus* fry (60 days after hatching) could withstand salinity of up to 25 when transferred directly from freshwater. Also, the method of such transformation/acclimatization has been underscored as one of the factors influencing salinity tolerance of tilapia (Suresh & Lin, 1992). We found that all fish transferred directly from a salinity of 0.63 to 30 and 25 died within 18 hours of the experiment due to inability to withstand drastic salinity change. Al-Amoudi (1987), argued that direct transfer of *Oreochromis* species to different salinity levels led to low survival compared to gradual increment of salinity thus supporting the findings of this study. Studies by Villegas (1990) and Fineman-Kalio (1988) found that

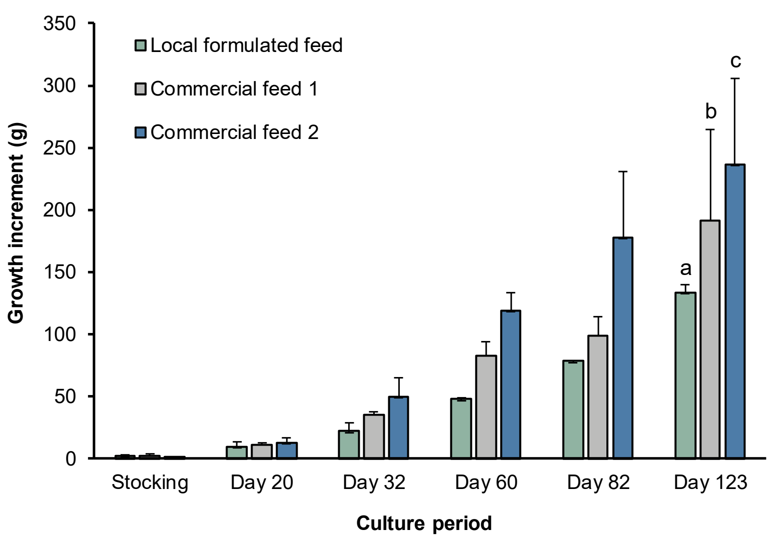


Figure 5. Growth (± Stdev) response of *O. niloticus* to different feeds in intertidal earthen ponds over the culture period (different super scripts indicate significant different)

Table 4. Average **(Mean ± STDEV)** water quality parameters in the *O. niloticus* experimental intertidal ponds and net cages

Parameter and unit	Ponds	Cages
Dissolved oxygen (mg/l)	7.26 ± 0.21	4.85 ± 0.25
pH	7.90 ± 0.90	7.71 ± 0.32
Salinity	32.99 ±2.99	31.65 ± 5.52
Total dissolved solids (mg/l)	30.33 ± 1.15	27.07 ± 0.44
Temperature (^{0}C)	25.12 ± 0.49	29.68 ± 2.85

O. niloticus survived direct salinity transfers to 15 – 17.7 by 87%, above 15 led to more than 50% mortality, and to 20 and 32 salinity resulted in complete mortality. Even for the higher salinity tolerant tilapia species like blue tilapia, direct transfer to seawater could result in almost complete mortality compared to gradual transfer (Villegas, 1990; Phillippart & Ruwet, 1982; Lotan, 1960). We attained an *O. niloticus* salinity tolerance of 78% at 30 salinity in a progressive 9-day salinity increment which is comparatively higher than previous studies (Kirk, 1972; Watanabe *et al.*, 1985a). Fineman- Kalio (1988) observed that *O. niloticus* could gradually acclimatize to salinities of 20 – 50 with an average survival of 93.8%. Similarly, we established that there was higher salinity fluctuations in the intertidal earthen ponds ranging between 30 and 40 based on tidal changes and seasonality and the transformed *O. niloticus* was resilient to the higher levels.

Higher *O. niloticus* survival attained at full seawater salinity could be associated with the prolonged transformation/acclimatization period in the laboratory running for days before scaling up to higher salinity levels and progressively advancing to full seawater salinity. According to Al-AMoudi (1987), *O. niloticus* require a longer acclimatization period (8 days) compared to other species like *O. mossambicus* which required less periods (4 days). The current study findings correlated positively to the fact that gradual acclimatization is sufficient to transform salt tolerant tilapia successfully (Villegas, 1990; Phillippart & Ruwet, 1982; Lotan, 1960). Some studies have used a shorter acclimatization period for *O. niloticus* (5 salinity per 45 hrs) and experienced mortalities of all fish before reaching 28 salinity (Villegas, 1990; Lotan, 1960). However, other studies have used prolonged acclimatization periods running to even weeks and obtained minimal survival above 28 salinity (Al Asgah, 1984). Gradual salinity acclimatization is preferred because it takes advantage of the previous level adaptation to facilitate the subsequent adaptation in the next level with less energy cost.

Increased survival at higher salinities can be associated with natural selection due to long-term population adaptation to saline waters (Watanabe *et al.*, 1989). Furthermore, genetic selection was observed to improve the salinity tolerance of *O. niloticus* to survival rate of 75.3 – 91.9% when cultured (1-2 fish/m^2) in earthen ponds with salinities of 15 – 20 (Ninh *et al.*, 2014). We did not use genetic selection in the current study but it's an indication of a potential research gap required to enhance the performance of full seawater acclimatised *O. niloticus*.

Growth performance of *O. niloticus* in different culture systems

Throughout the experimental period, dissolved oxygen, temperatures, pH and other physicochemical parameters in the pond, cage and laboratory conditions were within levels suitable for the growth of tilapia. Growth rates were assessed at a salinity range of 30– 34. In laboratory aquaria experiments, commercial feed 2 had a higher growth than the other two diet formulations. Fish fed on the locally formulated diet grew 4.8 times lower than commercial feed 2 in cages and 2.3 times lower than commercial feed 2 in earthen ponds. Growth variations in cage and pond results for the same feed treatment could be associated with restricted movement in cages that does not allow access to planktonic and benthic feed communities that were available in intertidal earthen ponds (Yi *et al.*, 1996; 2002).

The growth results obtained in the current study for *O. niloticus* are not comparable to any in literature due to the previous inability to acclimatize and stabilize the species to full seawater salinity (Watanabe *et al.*, 1985a; Woessner *et al.*, 1991). However, the current growth results are comparable to those of hybrid tilapia grown in freshwater and full seawater with growth rates of 1.4 g/day and 0.73 g/day respectively. The hybrid were cultured in a circulatory system for 180 days at stocking densities of 150 fish/m^3 and fed on sea bream feed pellets (Ridha, 2014). We also got results that resonate well with findings of Thai red tilapia grown in cages placed in earthen ponds and Florida tilapia grown in marine cages with growth rates of 1.17 g/day and 1.82 g/day respectively (Clark *et al.*, 1990; Yi *et al.*, 2002). Also, Basiao *et al.* (2005) observed that *O. niloticus* hybrids mixed with *O. mossambicus* attained a higher daily growth rate (1.58 g/day) compared to other hybrids (1.2 g/day) due to tolerance to saline environments (Liao & Chang, 1983).

A consistent trend of fish growth rate was observed for commercial feed 2, commercial feed 1 and locally formulated feed in all culture systems. This implies that feed formulations will to a larger extent influence the growth rate of fish irrespective of the farming system. The current results support the findings by Simon *et al.* (2019) where Gift tilapia fed on commercial feed 2 increased weight with the inclusion of the marine microbial biomass. In the study, a 10% inclusion of the microbial biomass led to 19.5% weight gain in fish compared to 5% weight gain when fish meal was used in the feed. Unlike in other previous studies where hybrids have attained smaller terminal size or slow growth rate (Lutz, 2001), performance of gift tilapia (Simon *et al.* 2019) supports the significance of feed formulisations in enhancing production of *O. niloticus* in full seawater salinity. Therefore, the need for research to establish a suitable feed formulation for full seawater *O. niloticus*.

Conclusions

The findings elucidate the viability of optimal salinity acclimatization of *O. niloticus* to full seawater using gradual salinity increment. The seawater salinity transformed tilapia was able to withstand environmental variabilities in intertidal earthen ponds and attain competitive growth rates thus providing hope for aquaculture investors along the coastal areas. Full seawater transformed *O. niloticus* responded well to different feed formulations. However, varied growth rates were attained for different feed formulations weighing unto the need for quality affordable feeds for the farmers.

This study is the first to demonstrate survival and growth of *O. niloticus* in full seawater and forms a baseline for research on the species to enhance food and nutritional security in Sub-Saharan Africa. Research is needed to assess breeding and reproduction potential of *O. niloticus* in seawater, diseases resistance, and selective breeding to inform farming of the species. Also, there is need for research to assess the ecological impact of *O. niloticus* in the ocean to guide management of coastal farms.

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Original Article

Diet and trophic interactions between catadromous eels and sympatric fish in Kenyan east flowing river systems

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Abstract

Biotic interactions such as competition and predation are important ecological drivers of population structure. Interactions among higher trophic level fish can contribute to further population declines in species, such as eels, made vulnerable by overexploitation or environmental change. Furthermore, trophic interactions may further predispose eel populations to collapse, but this is poorly understood, particularly along the Western Indian Ocean (WIO) rivers. This study evaluated stomach contents of fish captured with glass and commercial fyke nets in the Athi and Ramisi Rivers, which discharge into the WIO. Stomach contents were examined using dissecting microscope to establish diet composition. Eels primarily consumed assorted fish (43 %), and crustaceans (36 %); such as penaeid shrimp (14%) and prawns (13%) and crab (9%), thus belonged to a higher trophic level (TL) of 3.47 than native (2.98) or introduced (2.8) sympatric fish species. Diet breadth of eels was significantly lower (0.20) than for sympatric fish species (0.27), attributed to higher diet specialization. The TL of carnivorous fish (3.19) and their diet compared well with those of eels, even though diet preference differed significantly among fish types. Consequently, eels ranked as vulnerable by the IUCN are further threatened by previously undescribed competition from carnivorous fish.

Keywords: biotic interactions, niche breadth, diet overlap, feeding guilds, trophic levels

Introduction

Globally, freshwater fish with a life-history involving long-distance inter-ecosystem migration, are driven by a quest for quality breeding and feeding grounds (McIntyre *et al.*, 2016). In tropical systems, these strategies are particularly exemplified by diadromous eels, migrating between freshwater and saline oceanic habitats (Lin *et al.*, 2018). However, global declines in wild eel populations have been observed in both temperate and subtropical regions, and are largely blamed on anthropogenic stressors, such as climate induced changes in oceanic circulation, habitat degradation, overexploitation (Jellyman *et al.*, 2000; Revenga, 2003; Strayer and Dudgeon, 2010), in addition to biotic stressors, notably associated with the introduction of alien and exotic fish species (Jacoby *et al.*, 2015). Nonetheless, other biotic interactions, for instance between eels and predatory introduced and indigenous fish, are also of particular concern, not only due to dietary overlap, but also predation on vulnerable stages and species. Biotic interactions such as intra- and inter-specific competition, predation, mutualism, facilitation, and commensalism, are among the powerful ecological drivers, influencing species occurrence, community structure and functioning in terrestrial and aquatic ecosystems (Ben-Natan *et al.*, 2004; Tadesse, 2018).

Despite the western Indian Ocean (WIO) being regarded as an eel biodiversity hotspot by hosting 25 % (4/16) of global panmictic eel biodiversity (Schabetsberger *et al*., 2016), inter- and intra-specific biotic interactions and associated pressures remain poorly documented. Furthermore, recent upgrading of three (*Anguilla mossambica, A. bengalensis,* and *A. bicolor)* of the four WIO eel taxa to near threatened (Hanzen *et al*., 2019), is largely attributed to prevailing anthropogenic stressors such as river modification, pollution (Jellyman, 2021), but also exotic introduction which needs evaluation.

Sympatric fish interacting through predation and competition have been shown to impact piscivorous freshwater fishes in the tropical (Hickley *et al*., 2008; Okwiri *et al*., 2019), as well as temperate habitats (Jonsson and Jonsson, 2004), but are even more critical to trans-habitat migratory species, such as Atlantic salmon (*Salmo salar*) (Jonsson and Jonsson, 2004). Both predation and competition results in loss of fitness among interacting species, acting through direct mortality and/or reduction in performance (Tadesse, 2018). James *et al*. (2003) attributed declines in native Australian riverine fish including predatory and migratory eels, to increased competition for food and space with the introduced predatory trout and carp species. In view of the documented introduction of similar species into African rivers, similar interactions are suspected with regards to WIO eels, but this has rarely been explored.

In most temperate and subtropical locales, eels are monospecific, and consequently intraspecific competition among eel species has only been demonstrated with the introduction of *Anguilla japonica* into European rivers which was partially blamed for declines in native *A. anguilla* (Hulme *et al*., 2010). In the WIO, although differences in habitat use among eel species is reported, with *A. bengalensis* and *A. bicolor* occurring exclusively at upstream and downstream reaches, respectively, and *A. marmorata* and *A. mossambica* being less selective (Van Someren and Whitehead, 1959; Okeyo, 1998), whether such patterns are linked to biotic interactions, requires validation.

In Kenya, the larger east flowing rivers, such as the Athi and Tana, apart from experiencing greater anthropogenic stressors, such as damming, pollution and overexploitation, have in the past seen multiple introductions of exotic fish such as trout, carps, local tilapiines and catfish (Okeyo, 1998; Seegers *et al*., 2003; Wanja, 2013). Subsequently, this has led to possible competition with indigenous species which has not been well documented. In contrast, the smaller east flowing rivers such as Ramisi and others, not only experience lower hydrological modification and pollution, but also have fewer documented fish introductions. It is thus unclear whether the documented eel declines in the WIO region are associated with trophic interactions resulting from diet overlaps of species co-existence within these systems. Hence the current study was designed to further understand the potential causes for the decline in eel populations in the WIO region.

Materials and methods

Study Rivers

The study focused on two Kenyan east flowing rivers; Athi-Galana-Sabaki and Ramisi, both draining into the Indian Ocean (Fig. 1). Both river catchments receive bimodal seasonal rainfall, during the long (March–May) and short (October–December) rains. The average temperature in both catchments is about 26 °C, with an annual precipitation of 400 mm at the downstream coastal locations and 800 mm annually at upstream highland locations. In this paper, the name Athi will be used interchangeably to designate the Athi-Galana-Sabaki River.

The Athi-Galana-Sabaki River

The Athi-Galana-Sabaki River is the second largest eastward flowing river in Kenya. The river headwaters are on the southern slopes of the Aberdare range, the Ngong hills and the eastern flank of Mount Kilimanjaro, draining the Kapiti plains and parts of the Yatta plateau, with a catchment of over 70,000 km^2 (Okeyo, 1998). The major tributaries of the Athi River include the Nairobi, Kiboko, and Tsavo Rivers. The Tsavo River that is fed by the Mzima Springs, is the only permanent inflow in the middle reaches of the drainage. The river in the upstream reaches including the headwaters and associated tributaries, is commonly referred to as Athi River.

The midstream reaches of the river occur below Lugard's Falls (after the Tsavo River confluence), where the river name changes to the Galana River. In the downstream reaches, the river is commonly called the Sabaki, which flows into the Indian Ocean 11.3 km north of Malindi town. Two sampling locations were selected for sampling: one each in the upstream (Kiaoni) and downstream (Sabaki Bridge) reaches of the Athi-Galan-Sabaki River. The upstream location was located 200 kms from the estuary, while the downstream location was 3.3 kms inland from the ocean. Previous studies such as those of Okeyo (1998), Kimakwa (2004) and Wanja (2013) have reported on fish diversity especially for sympatric species. These are fish populations that exist in the same geographic area, frequently encountering one another, and supposedly coexist with eels. In this context, sympatric fish were composed of both indigenous and introduced fish species. Seeger *et al.* (2003) have reported the presence of exotic fish species along the Athi River. 2020). The Ramisi catchment also transverses the 600 ha Buda evergreen tropical dry savannah forest, which is a remnant of the once more extensive East African coastal forest (Wekesa *et al.*, 2019). The catchment harbours a relatively low human population density of 105 persons. km^{-2}, dominated by smallholder subsistence farmers (KCIDP, 2018). Similarly, two sampling locations were selected in the Ramisi River; in the upstream (Eshu) and downstream (Taliani) reaches. The upstream location was 35 km from

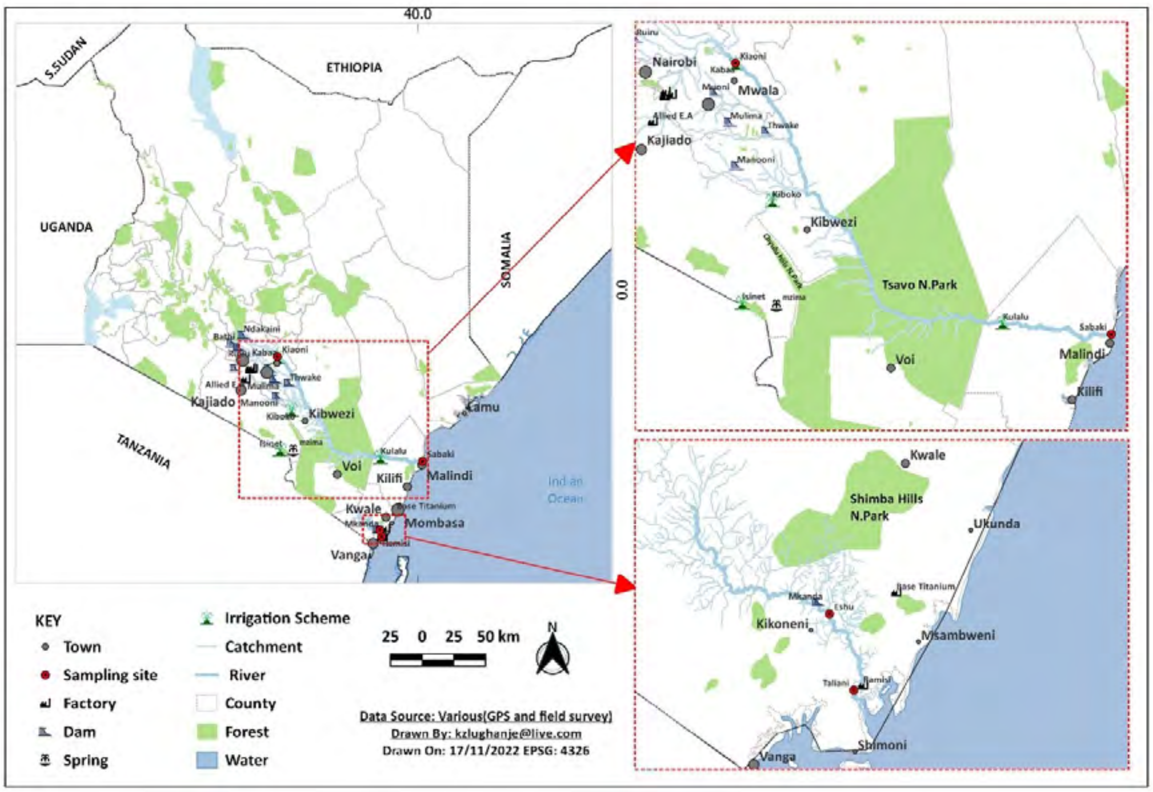

Figure 1. A map of Kenya highlighting the two east flowing rivers and a detailed sketch of the upstream and downstream sampling locations on the Athi-Galana-Sabaki (Kiaoni and Sabaki) and Ramisi (Eshu and Taliani) Rivers, Kenya.

The Ramisi River

The Ramisi River is located within Kwale County on the southern coast of Kenya (Fig. 1). The river rises from the Shimba hills, and flows over 60 km to discharge into the Indian Ocean through the Kiwamba mangrove forest at Shimoni, with a catchment of 1800 km^2 (Kiteresi *et al.*, 2012. The Ramisi catchment receives average annual rainfall of about 1200 mm and has an average temperature of around 26 °C (KCIPD, 2018). The main vegetation in the area is drought resistant savannah woodlands and coastal dryland forests, noted for endemic flora and fauna (KWTA, the estuary, whereas the downstream location was 4 km upstream of the ocean. Unlike at Athi River, information on fish species diversity and the presence of exotic species is scant.

Fish sampling

Fish sampling was undertaken monthly at the upstream and downstream locations of both the Athi and Ramisi Rivers. At both locations along the rivers, fish were sampled from freshwater and estuarine habitat types such as riffles, vegetation and pools. Fish were captured using double and glass eel fyke nets deployed fortnightly in the different habitats types overnight from April 2021 to March 2022. At each sampling location, six different sampling sites were randomly selected and the fyke nets deployed in each. Landed fish and eels were temporarily incapacitated using clove oil diluted with river water to ease handling. Landed fish were identified in the field using Wanja (2013) and Okeyo and Ojwang (2015), pictures taken, counted and a representative sample (~30 %) separated for dissection and subsequent gut content analysis. Reference specimens of each species encountered were preserved in 5 % formalin for species confirmation, and the remaining live fish released into the river, whenever appropriate. Reference specimens of fish collected are lodged at the Department of Biological Sciences laboratory at Egerton University. Fish species identification and information on distribution were obtained from Eccles (1992), Skelton (1993), and FishBase (Froese and Pauly, 2019).

Selected fish were first dissected in the field prior to gut content removal. Each gut removed was preserved in 5 % formalin for subsequent laboratory gut content evaluation.

Fish gut content evaluation

Prior to removal of gut contents in the laboratory, the relative fullness for each stomach was assessed and fullness index scores allocated using the modified point method as in Hyslop (1980): empty stomach (0), quarter (5), half (10), three quarter (15) and completely full (20) stomachs. Stomach contents were then emptied into a petri dish, washed with distilled water and constituent food items separated and identified under a dissecting microscope to the lowest taxonomic level possible. Guides for invertebrate (Gerber and Gabriel, 2002) and vertebrates (Keppeler *et al*, 2020) were used for taxonomic identification of dietary items.

Food importance index

The contribution of each identified food item to the gut content was estimated and recorded. The data was subsequently used to compute the Hyslop (1980) food importance index (FI) scores using the following equation:

$$\%FI = \frac{\text{Total points for each food item}}{\text{Total number of points for all food types}} \quad (1)$$

Dietary composition and FI were compared between locations using analysis of similarity (ANOSIM).

Table 1. Diet importance in stomach of fish from the Athi and Ramisi Rivers, Kenya.

Food items	Occurrence (n)	Food index Scores (FI) (%)	Athi (%)	Ramisi (%)
Annelid worm	1	0.2	0.2	0.0
Polychaeta worms	2	0.3	0.4	0.0
Beetle	21	2.4	3.5	1.6
Bivalve	1	0.2	0.0	0.8
Caddisflies	37	5.6	6.8	0.0
Chironomidae	5	0.8	0.9	0.0
Damselfly	3	0.5	0.6	0.0
Mayflies	11	1.7	2.0	0.0
Pond snails	4	0.6	0.7	0.0
Stoneflies	1	0.2	0.2	0.0
Unidentified Insect	26	3.3	4.2	2.5
Animal detritus (AOM)	60	9.0	10.5	2.5
Plant organic matter (POM)	66	9.9	11.8	1.6
Unidentified detritus (DOM)	32	4.8	3.5	10.7
Vegetation	62	9.3	9.8	7.4
Plant seeds	1	0.2	0.0	0.8
Crab	43	6.5	6.1	8.0
Penaeid Shrimps	128	19.0	22.3	6.0
Prawns	36	5.4	0.2	28.7
Fish	122	18.4	16.0	30.0
Birds	2	0.3	0.4	0

AOM-animal organic matter detritus, POM-plant detritus origin, and DOM-unidentified dead organic matter detritus

Diet breadth

Data on frequency of occurrence (F) and relative abundance (Pi) of each food item were used to compute the Levin (1968) standardized diet breadth index (B) for both eel and sympatric fish species as follows:

$$\text{B (breadth)} = 1/\sum(P_{ij})^2 \quad (2)$$

Where B is Levin's standardized niche breadth, p_i is the proportion/ relative abundance of each food item i in the gut content of fish species j.

The B values obtained were compared between rivers, reaches and fish types (eels and sympatric resident and introduced fish) using one way-ANOVA.

Diet overlap

Dietary item frequency of occurrence data (F) were also used in computing the Pianka dietary overlap index (O) for each fish type using the following equation as in Pianka (1981):

$$\text{)ij} = \sum(P_{ij}P_{ik})/\sqrt{\sum(Pij)^2\sum(Pik)^2} \quad (3)$$

Where O_{ij} is Pianka's niche overlap between fish species j and species k, P_{ij} is the proportion of the food type i in the gut of fish type j, while P_{ik} is the proportion of food type i in the gut of fish type k.

Pianka's index values commonly range from 0 (total diet separation) to 1 (total overlap). Data on diet overlaps were subsequently applied to pairwise One-way Analysis of Similarity (ANOSIM) correlation to detect diet overlaps among fish types, rivers and locations.

Fish trophic levels (TL)

Each food item encountered in the gut was allocated a food trophic level (TL/Tis). The food trophic levels for each dietary items were obtained from Kihia *et al.* (2015), and Keppeler *et al.* (2020) among others. Food trophic level values obtained ranged from 0-1.2 for vegetation, seeds and plant detritus; 1.2-1.5 was allocated for herbivorous fauna such as snails (1.3), coleopteran, dipteran, trichopteran and ephemeropterans (1.5). Animal detritus was allocated a level of 1.5, while unidentified detritus (DOM) (1.2) and plant detritus (POM) (1.4). Filter feeding annelids and bivalves were allocated an intermediate value of (1.5); documented carnivorous invertebrates such as prawns and penaeid shrimps (2.1), crab (2.2), while carnivorous vertebrates such as birds and finfish (3.0).

Data on the relative contribution of each food item (FI) calculated and respective food item trophic level (Tis) were subsequently used to compute fish trophic levels (TL) as in Choi *et al.* (2008) and Kihia *et al.* (2015) using the following equation:

$$TL_f = 1.0 + (\textstyle\sum_i^s FI_{is} \times T_{is}) \quad (4)$$

Where TL_f is trophic level of fish species f, FI_{is} is relative importance of diet item i to s, T_{is} is trophic level of diet item i to s.

The trophic levels obtained were then used to categorize the sympatric fish species into three feeding guilds: Carnivorous (>2.8); omnivorous (2.5-2.8); and herbivorous (<2.5). Subsequently, the trophic levels of eels, native and introduced fish were compared among rivers reaches using the Mann-Whitney test.

Results

Diet composition and preference among eels and sympatric fish

Stomachs contents of 350 (283, 67) sympatric fish and 75 (31, 44) eels from the Athi and Ramisi Rivers, respectively were examined. Thirty-eight fish specimens (5, 33) including eels and sympatric fish, respectively had empty stomachs and were excluded from subsequent diet evaluations. At the Athi River, 30 (13, 17 eels) and 254 (83, 171) sympatric fish were evaluated at the upstream and downstream locations. At Ramisi, 40 (36, 4 for upstream and downstream, respectively) eels and 63 (38, 25 for upstream and downstream, respectively) sympatric fish were evaluated.

A total of 21 food types were identified among which penaeid shrimps (19 %) and fish (18%) were most common (Table 1). Vegetation, caddisflies, crabs, detritus, prawns, beetles, unidentified insect and mayflies, were consumed by between 2 and 10 % of fish, while birds, annelid worms, bivalves, seeds, flies and stoneflies were the least consumed (Table 1).

The diet contribution between the rivers differed significantly (One-way analysis of similarity (ANOSIM), Global R=0.46, $p<0.05$), as well as by location (R=0.403, $p<0.05$) (Appendix 1). Fish in the Athi River consumed 19 food items, dominated mainly by penaeid shrimps (22 %), fish (16 %) and vegetation (10 %). Caddisflies (7 %) and crabs (6 %) were of intermediate importance (Table 1). Fish in the Ramisi River consumed 12 food items dominated by fish (30 %), prawns

Table 2. Dietary resource and their importance in the upstream and downstream reaches of Athi River among eels and sympatric native and exotic fish.

Focal river	Athi-Galana-Sabaki Food index (FI)							
Reaches	Upstream/Kiaoni (%)				Downstream/Sabaki (%)			
Food items	Eels	Native	Exotic	All	Eels	Native	Exotic	All
Annelid worms			0.63	0.5	-	-	-	-
Polychaetae				-	2.5	-	0.61	0.6
Beetles		-	10.75	9.0	-	0.72	0.61	0.6
Pond snails	7.14	3.57	0.63	2.0	-	-	0.61	0.3
Caddisflies		10.71	21.52	19.0	-	-	-	-
Damselflies		-	-	-	-	0.72	1.22	0.9
Mayflies		14.29	4.4	5.5	-	-	0.61	0.3
Stoneflies				-	-	-	0.61	0.3
Chironomidae			3.16	3.2	-	-	-	-
Unidentified Insects			7.5	6.0	2.5	2.88	3.66	3.2
AOM		21.43	13.30	13.5	7.5	10.1	7.93	8.75
POM		28.57	18.35	18.5		8.0	9.76	7.87
DOM		10.71	2.53	3.5	2.5	5.76	1.83	3.4
Vegetation	7.14	10.71	14.0	13.0	7.5	5.76	9.76	8.0
Crabs		-	-	-	20	10.80	6.10	9.6
Penaeid Shrimps		-	-	-	35	37.0	34.0	35
Prawns		-	0.63	1.0	-	-	-	-
Fish	78.57	-	2.53	8.0	22.5	18.71	22.0	21.0
Bird	7.14	-	-	0.5	-	-	0.61	0.3

AOM-animal organic matter detritus, POM-plant detritus origin, and DOM-unidentified dead organic matter detritus

(29 %) and unidentified detritus (11 %), while crabs (8 %), vegetation (7.4 %) and penaeid shrimps (6 %) were of intermediately importance (Table 1). Fish in the Athi consumed a higher variety of invertebrate (12) than at the Ramisi River (5) (Table 1).

Fish at the upstream location (Kiaoni) in the Athi River consumed 14 dietary items dominated by detritus (36 %), mainly composed of plant organic matter (18.5 %), and followed by caddisflies (19 %) and vegetation (13 %), while beetle (7.5 %) fish (8 %) and mayflies (5 %) were of intermediate importance. In contrast, fish at the downstream location of the Athi River also consumed 14 items but were dominated by penaeid shrimps (35 %) and fish (21 %), while crabs (10 %) and vegetation (8 %) were of intermediate importance (Table 2). Although fish at both locations in the Athi consumed a similar number of items (14), beetles, caddisflies, chironomids and prawn were only encountered upstream while penaeid, crab, damselfly and stoneflies were encountered at the downstream location. Exotic fish at both reaches consumed the highest number of food items (13); at the upstream location (Kiaoni) dominated by caddisflies (22 %), and (15) at the downstream location (Sabaki) dominated by penaeid shrimps (33 %) and fish (22 %).

At the upstream location of the Ramisi River, fish consumed 10 items dominated by prawns (37 %) and fish (35 %) while crabs (7 %), dead organic matter (DOM) and vegetation (6 %) were of intermediate importance. In contrast, at the downstream location, fish consumed 7 items dominated by DOM and penaeid shrimps (27 %), and fish and crabs (12 %). Prawns, bivalves and seeds were only consumed at the upstream location in the Ramisi, while penaeid shrimps were only encountered at the downstream location (Table 3). Similarly, exotic fish consumed the highest number of food items at both upstream (8) dominated by prawns (27 %) followed by fish (23 %) and downstream (6) largely composed of penaeid shrimps (33 %) and plant detritus (POM) (22 %) (Table 3).

Fish (29 %) and prawns (28 %) were the most important for dissimilarity between both locations in the Ramisi contributing to 57 % of the dissimilarity. On the other hand, penaeid shrimps contributed to the dissimilarity at both locations in the Athi (upstream and downstream) as well as between downstream locations of the Athi and Ramisi (Appendix 2). Prawns (18.62 %) and fish (17.48 %) contributed to the dissimilarities between the upstream locations of the Athi and Ramisi Rivers respectively (Appendix 2).

Table 3. Dietary resource and their importance in the upstream and downstream reaches of Ramisi River among eels and sympatric native/residents and exotic/introduced fish.

Focal river	Ramisi Food index (FI)							
Reaches	Upstream/Eshu (%)				Downstream/Taliani (%)			
Food items	Eels	Native	Exotic	All	Eels	Native	Exotic	All
Beetles	-	-	4.55	1.0	-	-	11.11	4.0
Bivalves	2.13	-	-	1.1	-	-	-	-
Unidentified insects	4.26	-	4.45	3.1	-	-	-	-
AOM	-	7.41	4.55	3.13	-	-	-	-
POM	-	-	-	-	-	-	22.22	7.69
DOM	-	3.70	22.73	6.3	33.33	45.46	-	27.0
Vegetation	6.40	7.41	4.55	6.3	17.00	9.10	11.11	12.0
Plant seeds	2.13	-	-	1.1	-	-	-	-
Crabs	4.25	11.0	9.1	7.3	-	18.18	11.11	12.0
Penaeid Shrimps	-	-	-	-	17.00	27.27	33.33	27.0
Prawns	30.0	55.56	27.3	36.5	-	-	-	-
Fish	51.1	14.82	23.0	35	33.33	-	11.11	12.0

AOM-animal organic matter detritus, POM-plant detritus origin, and DOM-unidentified dead organic matter detritus

The anguillids encountered consumed 13 out of the 21 food items identified dominated by fish (43 %), and crustaceans (37 %) composed of penaeid shrimps (14 %) and prawns (13 %), while crabs (10 %) were of intermediate value. Pond snails, birds, bivalves, polychaete worms, and seeds were the least consumed (Fig. 2). Among the eels, *A. bengalensis* was purely carnivorous, feeding on fish (55 %), prawn (23 %), crab (5 %), and even birds (2 %). *A. mossambica* was mainly carnivores on fish (32 %), penaeid shrimp (21 %), and crabs (16 %), but also consumed detritus (11 %), particularly in the Athi River. Both *A. bicolor* and *A. marmorata* were omnivorous consuming fish, prawns, penaeid shrimps, insects, vegetation and detritus.

The sympatric fish consumed 19 dietary items dominated by penaeid shrimps (20 %), fish (14 %). Vegetation (10 %) was of intermediate importance while caddisflies (7 %) and crab (6 %) were less often consumed (Fig. 2). Both eels and sympatric fish shared crabs, fish, penaeid shrimps, prawns and vegetation.

Diet preferences of the fish types evaluated differed significantly (ANOSIM; $p<0.05$) among the sampling locations. Sympatric fish at the upstream location of the Athi River primarily consumed plant detritus (POM) and caddisflies (20 %) followed by vegetation (14 %). At the downstream location, penaeid shrimps (35 %) and fish (21 %) were the most important, with (animal

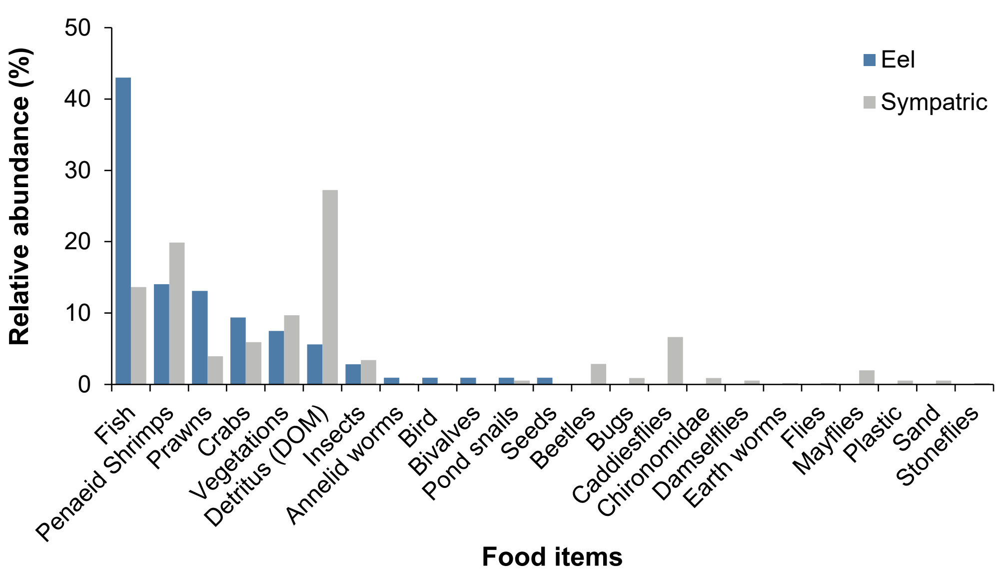

Figure 2. Diet preferences between sympatric species and eels in the two east flowing rivers, Kenya.

detritus) AOM and (plant detritus) POM (9 %) followed by crab and vegetation (8.0 %) being intermediately consumed. On the other hand, eels at the upstream location primarily consumed fish (79 %) but also birds (7.2 %). In contract, penaeid shrimps (35 %), followed by fish (23 %) and crabs (20 %) were more consumed at the downstream location, comparable to those of sympatric fish (Fig. 3). Unlike at the upstream location, fish at the downstream location of the Athi consumed birds (0.33 %), especially exotic fish species. At the upstream location of the Ramisi River, sympatric fish mainly consumed prawns (43 %), fish (18 %), plant detritus (12 %) and crabs (10 %), while at the downstream location, sympatric species largely consumed detritus (35 %), penaeid shrimps (30 %), detritus (DOM) (25 %) and crabs (15 %). Fish and beetles (5 %) were least consumed (Fig. 3). Eels at the upstream location of the Ramisi consumed fish (51 %) and prawns (30 %) while at the downstream location detritus (DOM), fish, penaeid shrimps and vegetation were comparably consumed (Fig. 3).

At the upstream locations of both rivers, eels mainly consumed fish, while at downstream locations penaeid shrimps, fish and crabs were commonly encountered. Prawns were only consumed at the upstream location of Ramisi while penaeid shrimps were consumed at downstream locations.

Introduced sympatric predatory carnivorous fish especially *Bagrus docmak* primarily consumed 15 items dominated by penaeid shrimps (37 %), fish (24 %) and vegetation (10 %), while animal detritus (AOM) (8 %) and crabs (7 %) were intermediately consumed. Resident predatory carnivorous fish which were composed of *Glossogobius giuris*, *Eleotris fusca*, *Oligolepis acutipennis* and *Pisodonophis cancrivorus* consumed nine (9) food items dominated by penaeid shrimps (35 %), fish (19 %) and crabs (14 %), while prawn (11 %) and animal detritus (AOM) (10 %) were intermediately consumed (Appendix 3). Among the resident predatory carnivorous fish, *Oligolepis acutipennis* (70 %), followed by *Glossogobius giuris* (47 %) and *Pisodonophis cancrivorus* (39 %),

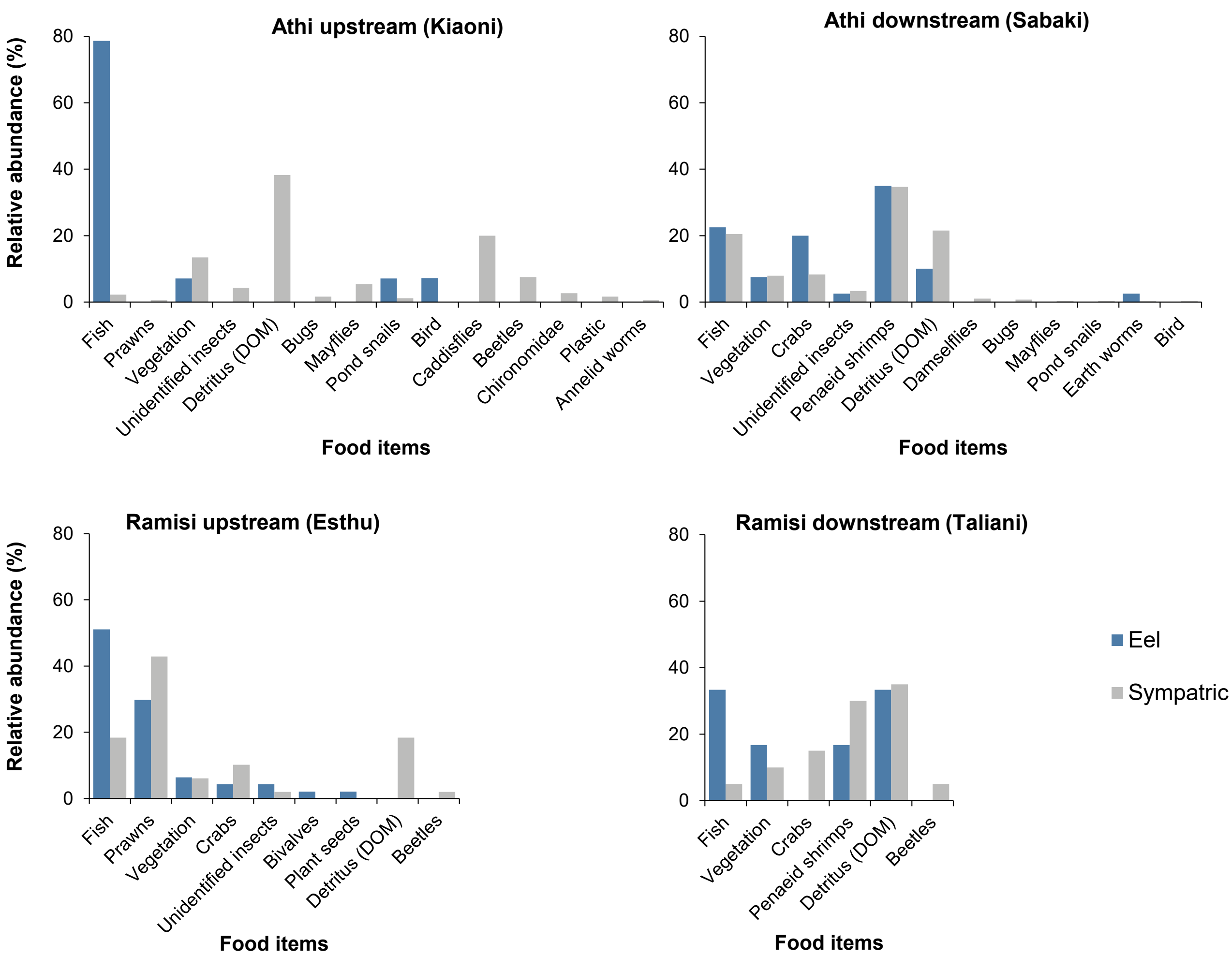

Figure 3. Diet preferences between sympatric fish and eels fish from the Athi and Ramisi Rivers.

Table 4. Summary statistics of One-way ANOSIM pairwise correlation between fish type and food item preferences (P values in bold with an asterisk are significant at p<0.05).

Fish types	Eel	Carnivorous	Herbivorous	Omnivorous	Native	Introduced
Eel	1					
Carnivorous	**0.083***	1				
Herbivorous	0.0001	0.008	1			
Omnivorous	0.007	**0.19***	**0.082***	1		
Native	0.008	0.11	0.044	0.034	1	
Introduced	**0.011***	0.11	0.092	0.098	0.77	1

consumed penaeid shrimps, while *Eleotris fusca* (56 %) consumed prawns. 50 % of *Otolithes ruber* followed by *O. acutipennis* (30 %) and *G. giuris* (29 %) consumed fish.

Introduced omnivorous fish (*Clarias gariepinus*) consumed 15 items but mostly preferred caddisflies (17 %), animal detritus (AOM) and vegetation (15 %) while fish (9 %), were of intermediate value. In contrast, resident omnivorous fish consumed seven (7) items dominated by penaeid shrimps (33 %) and fish (27 %) (Appendix 3). On the other hand, introduced sympatric herbivorous fish such as *O. niloticus* consumed 10 items, with preference for plant detritus (43 %) and caddisflies (15 %) while unidentified detritus (DOM) (11 %) and beetles (8%) were of moderate importance (Appendix 3).

Subsequently, Analysis of variance revealed a significant difference between the diets of fish types (eels and sympatric fish) (Global R=0.09, p<0.05). Although, similarity in diet preference between sympatric carnivorous guild and eels was observed (p=0.08) (Table 4), especially for resident predatory carnivorous (ANOSIM; p=0.1) (Appendix 4). This was attributed to their consumption on fish and penaeid shrimps.

Sympatric fish species trophic interactions, diet overlaps and feeding guilds in the Athi and Ramisi Rivers

Sympatric fish in the Ramisi River belonged to significantly (t=6, df=682, p<0.05) higher trophic levels (3.11±0.1) than those of the Athi River (2.94±0.03). The fish species examined for gut content in the Ramisi were composed of five species, dominated by *Eleotris fusca* and *Clarias gariepinus* while in the Athi there were 13 species dominated by *Bagrus docmak* and *Clarias gariepinus*. Among the fish examined, there were a total of 10 sympatric native fish species dominated by *Pisodonophis cancrivorus*, followed by *Otolithes ruber, Glossogobius giuris* and *Eleotris fusca*. On the other hand, introduced fish were dominated by *Bagrus docmak*, *Clarias gariepinus* and *O. niloticus*, encountered from the two rivers (Table 5). The highest TL was recorded on *Oligolepis acutipennis* (3.66±0.18).

In the Athi River, among the 10 native fish species, 5 species (*Glossogobius giuris*, *Oligolepis acutipennis*, *Otolithes ruber*, *Terapon jarbua*, and *Pisodonophis cancrivorus*) had the highest TL of above 3.0, while *Mugil cephalus* and *Macolor niger* had TLs of less than 2.4. Among the three introduced species in Athi River, two (*Bagrus docmak*, and *Clarias gariepinus*) had the highest TL, while *O. niloticus* had the lowest (>2.4). In the Ramisi River, two out of three of the native species, *Eleotris fusca* and *Pisodonophis cancrivorus* had the highest TL with *Ambassis gymnocephalua,* having the lowest (Table 5).

Mean diet breadth of sympatric fish examined was (1.49±0.08) for both the Athi and Ramisi Rivers, but there were significant differences among rivers (t=3.4, df=85, p=0.01) and residency (t=6, df=292, p<0.05). The diet breadth of sympatric fish from Athi River was higher (1.65±0.05) than Ramisi (1.32±0.1) (Table 5). Among all sympatric fish species examined, the widest diet breadth was recorded in introduced omnivorous *Clarias gariepinus* in both rivers (Table 5). Among the native fish from the Athi River, the widest diet breadth was recorded for the carnivorous *Arius africanus* and herbivorous *Labeobarbus oxyrhynchus* and *O. spilurus spilurus*, with the lowest recorded on herbivorous *Labeo cylindricus* and *Mugil cephalus*. Among the introduced sympatric species in the Athi, the widest diet breadth found in the omnivorous *Clarias gariepinus* and the carnivorous *Bagrus docmak* (Table 5).

At the Ramisi, among the native fish examined, predatory carnivorous *Eleotris fusca* (2.80±0.14) and *Pisodonophis cancrivorus* (2.25±0.47) had the widest diet breadth while carnivorous *A. gymnocephalua* (1.00±0.67) had the narrowest. Among the introduced species in the Ramisi, omnivorous *Clarias gariepinus* (4.37±0.20) had a wider breadth than *O. niloticus* (2.20±0.25), which was higher compared to all the species.

Table 5. Trophic levels (TL) and diet breadth of sympatric fish species from the Athi and Ramisi Rivers. The values in bold with an asterisk represent higher species TL and diet breadth (B).

Rivers	Species	Ecological status	Feeding guilds	N	Trophic level (TL)	Diet breadth (B)
Athi	*Arius africanus*	Native	Carnivores	5	**2.95±0.22***	3.34±0.3
	Glossogobius giuris	Native	Carnivores	23	**3.30±0.10***	2.47±0.14
	Oligolepis acutipennis	Native	Carnivores	8	**3.66±0.18***	1.697±0.22
	Otolithes ruber	Native	Carnivores	3	**3.46±0.27***	1.92 ±0.39
	Pisodonophis cancrivorus	Native	Carnivores	24	3.13±0.10	2.53±0.14
	Terapon jarbua	Native	Omnivores	4	3.06±0.24	2.56±0.34
	Labeo cylindricus	Native	Herbivores	1	2.4±0.47	1.00±0.67
	Labeobarbus oxyrhynchus	Native	Herbivores	7	2.49±0.18	4.90±0.25
	Mugil cephalus	Native	Herbivores	3	2.27±0.27	1.00±0.39
	Oreochromis spilurus niger	Native	Herbivores	11	2.49±0.14	3.03±0.20
	Oreochromis spilurus spilurus	Native	Herbivores	13	2.44±0.13	2.98±0.19
	Bagrus docmak	Introduced	Carnivores	77	**3.12±0.06***	3.65±0.08
	Clarias gariepinus	Introduced	Omnivores	39	2.60±0.08	**6.65±0.11***
	Oreochromis niloticus	Introduced	Herbivores	35	2.44±0.08	2.48±0.12
Ramisi	*Ambassis gymnocephalua*	Native	Carnivores	5	2.3±0.15	1.00±0.67
	Eleotris fusca	Native	Carnivores	22	3.24±0.1	2.80±0.14
	Pisodonophis cancrivorus	Native	Carnivores	7	3.1±0.2	2.25±0.47
	Clarias gariepinus	Introduced	Omnivores	11	**3.36±0.15***	**4.37± 0.20***
	O. niloticus	Introduced	Herbivores	7	2.29±0.9	2.20±0.25

Diet and niche breadth (B) and trophic levels between eel species, feeding guilds and residency

Eels belonged to significantly (F=113, p<0.05) higher trophic levels (TL) (3.47±0.69), especially for *A. bengalensis* (3.61±0.07) at all sites, followed by *A. bicolar* (3.20±0.15), compared to (2.90±0.03) for either native (2.98±0.6) or introduced (2.8±0.04) sympatric fish. The trophic level of *A. bicolor* (3.67± 0.34) increased in the Ramisi compared to the Athi (3.09±0.16). *Anguilla marmorata* had the lowest TL (2.45±0.49) at all sites (Table 6). The sympatric native fish (3.00±0.02) had a higher trophic level compared to introduced fish (2.88±0.02) but did not differ significantly (Mann-Whitney U=24987, p>0.05). The TL recorded for the Athi River was higher for native (3.0±0.02) than introduced fish (2.86±0.02) though significantly (F=146, p<0.05) lower compared to Ramisi River for either introduced fish (3.01±0.06) or native (2.99±0.05). Sympatric carnivorous fishes recorded a higher trophic level (3.19±0.04) in the Athi, but in the Ramisi the TL was comparable with omnivorous species, especially for introduced fish (Table 6).

The lower TL recorded for sympatric fishes, subsequently corresponded to a wider diet breadth compared to eels. The narrow diet breadth for eels was accounted for by their active diet selection. The sympatric herbivorous species had the least TL (2.40±0.05), at all sites especially in the Ramisi. Native sympatric species in the Athi had a higher TL (3.0±0.02) while introduced species (3.01±0.05) recorded the highest in the Ramisi (Table 6); although significantly lower (F=4.0, p=0.03) than eels at all sites. Sympatric species diet breadth (B) (0.27±0.05) was always significantly higher (t=3.15, df=132, p<0.05) compared to eels (0.20±0.1) in both rivers. Native sympatric fish had lower diet breadth (0.43±0.04) than introduced fish (0.57±0.06), attributed to dietary specialization. Similarly, at both locations native species (0.23±0.15, 0.20±0.30 for Athi and Ramisi respectively) had lower diet breadth than corresponding introduced fishes (0.32±0.13, 0.26±0.43 for Athi and Ramisi, respectively).

Omnivorous fish recorded a higher diet breadth (0.43±0.3) followed by carnivorous species (0.30±0.4) which corresponded to an intermediate diet breadth at all sites. The least diet breadth was encountered among herbivores (0.27±0.3) at all sites largely due to their specialized feeding habit on dead organic matter (DOM). Among the rivers, omnivorous fish at both Athi (0.53±0.1) and Ramisi (0.33±0.2) corresponded to the widest breadth; significantly higher (p<0.05) compared to eels, except for introduced fishes in the Ramisi River (Table 6). Introduced sympatric species always recorded the widest diet breadth in the Athi (0.40±0.2) and Ramisi (0.39±0.4) compared to resident sympatric species and eels, which did not differ

Table 6. Levin's diet breadth indices and trophic levels among sympatric species feeding guilds and eels from the Athi and Ramisi Rivers. The values in bold with an asterisk represent higher TL and diet breadth (B) for eel species and sympatric feeding guilds.

Rivers	Fish categories	Fish type	N	Trophic level (TL)	Diet breadth (B)
Athi	Eels	*A. bengalensis*	15	**3.79±0.13***	0.10±0.18
		A. bicolor	9	3.09±0.16	0.16±0.23
		A. mossambica	7	3.34±0.19	**0.27±0.26***
	Sympatric	Carnivores	243	**3.19±0.04***	0.22±0.06
		Omnivores	115	2.65± 0.07	**0.53±0.10***
		Herbivores	106	2.44±0.06	0.22±0.08
		Introduced	322	2.86±0.02	0.32±0.13
		Native	167	3.0±0.02	0.23±0.15
		Eel	31	3.42±0.04	0.31±0.5
Ramisi	Eels	*A. bengalensis*	34	**3.53± 0.08***	0.17±0.12
		A. bicolor	2	**3.67± 0.34***	0.11±0.49
		A. marmorata	1	2.45±0.47	**0.19±0.69***
		A. mossambica	3	2.8±0.27	0.12±0.40
	Sympatric	Carnivores	29	**3.21± 0.10***	0.23±0.14
		Omnivores	23	**3.28±0.14***	**0.33± 0.20***
		Herbivores	14	2.26±0.14	0.11±0.21
		Introduced	31	3.01±0.06	0.26±0.43
		Native	38	2.99±0.05	0.20±0.30
		Eel	40	3.36±0.04	0.31±0.3

significantly (F=0.1, p=0.91). Among the eels, highest breadth was encountered in *A. mossambica* (0.27±0.3) from the Athi and *A. marmorata* (0.19±0.69) from the Ramisi, demonstrating unselective feeding habits.

Diet overlap between eels and sympatric fish

Among the sympatric fish evaluated in the Athi, the greatest overlap was observed between omnivores and herbivores (0.50±0.1), but also in predatory carnivores (0.24±0.1). In the Ramisi, the greatest overlap was between carnivores and omnivores (0.35±0.2) (Table 7).

Among the eel species evaluated in the Athi, the greatest overlap was between *A. bengalensis* and *A. mossambica* (0.65±0.1), especially in fish diet items. The least overlap was encountered between *A. bicolor* and *A. mossambica* (0.29±0.1). Highest diet overlap was observed between *A. bengalensis* and *A. bicolar* (0.92±0.6) in the Ramisi, while the lowest was observed between *A. marmorata* and *A. mossambica* (0.08±0.1) (Table 8).

The greatest dietary overlap for resource portioning were observed between sympatric carnivorous species and *A. bicolar* (0.81±0.01) in the Athi, followed by *A. bengalensis* (0.48±0.1), and lower in *A. mossambica* (0.18±0.1), respectively (Table 9). The sympatric carnivorous fishes responsible for the overlaps included *G. giuris*, *Arius africanus* and *Oligolepis acutipennis*, particularly in the along the estuarine areas. *Anguilla mossambica* had a higher overlap (0.29±0.2) with sympatric omnivorous species (Table 9) contributed by *Clarias gariepinus*. *Anguilla bicolor* (0.07±0.1) recorded the least diet overlap with sympatric herbivorous species. On the other hand, in the Ramisi River, diets of *A. bicolar*

Table 7. Dietary overlap among sympatric feeding guilds from Athi and Ramisi Rivers. The values in bold with an asterisk represent higher diet overlaps between feeding guilds.

Rivers	Feeding guilds	Carnivores	Omnivores	Herbivores
Athi	Carnivores	-		
	Omnivores	**0.24±0.1***	-	
	Herbivore	0.17±0.6	**0.50±0.1***	-
Ramisi	Carnivores	-		
	Omnivores	**0.35±0.2***	-	
	Herbivores	0.08±0.1	0.26±0.2	-

Table 8. Pianka symmetrical niche overlaps among eel taxa from Athi and Ramisi Rivers. The values in bold with an asterisk represent higher overlaps between eel species.

Rivers	Eel species	*A. bengalensis*	*A. bicolor*	*A. marmorata*	*A. mossambica*
Athi	*A. bengalensis*	-			
	A. bicolor	0.43±0.4	-		
	A. marmorata	-	-	-	
	A. mossambica	**0.65±0.1***	0.29±0.1	-	-
Ramisi	*A. bengalensis*	-			
	A. bicolor	**0.92±0.6***	-		
	A. marmorata	0.20±0.01	0.20±0.01	-	
	A. mossambica	0.41±0.2	0.45±0.16	0.08±0.1	-

(0.74±0.11) overlapped with those of omnivorous fish such as *C. gariepinus*, while *A. bengalensis* (0.52±0.1) overlapped with those of carnivorous fish (Table 9) such as *Ambassis gymnocephalua* and *Eleotris fusca*. The diet of *A. mossambica* occasionally overlapped with those of herbivorous (0.89±0.3) and omnivorous species (0.46±0.4). Consequently, the Athi River recorded the highest overlap (0.33±0.18) as compared to the Ramisi River (0.31±0.15), demonstrating greater relative amounts of inter and intraspecific competition on consumer-resource interaction between eels and sympatric fishes. No significant differences were however ($p>0.05$) observed on both niche and dietary overlap among the fish taxa and rivers evaluated.

Discussion

Diet composition and preference among eels and sympatric fish

The majority of the fish species encountered throughout the two rivers largely selected foods high in protein, such as penaeid shrimps and fish (Table 1). This demonstrates a prevalence of high trophic level fishes in the rivers, especially in the Ramisi. In particular, for the Athi River, the upstream locations showed more varied diet compositions, indicating unselective feeding patterns among upstream river fishes (Gerking, 2014). These fishes primarily consumed a wide range of prey items, especially for sympatric fish species.

The upstream location in the Athi River harbored unique food item strictly associated with freshwater taxa, and of lower trophic level such as vegetation, detritus and macroinvertebrates as previously described by Kihia *et al.* (2015) and Keppeler *et al.* (2020), associated with urban polluted rivers (Kobingi *et al.*, 2009). Additionally, the majority of the fishes encountered belonged to lower trophic levels, including tilapiines and *Clarias sp*, which are primarily herbivores and omnivorous respectively. These results are in line with those of Tófoli *et al.* (2013) who noted *Clarias sp*. predominantly consumed chironomidae and trichopteran (Table 5), recognized as being extremely resistant to extreme pollution conditions (Walsh *et al.*, 2005).

On the other hand, the downstream estuarine locations revealed a lower diet composition attributed to higher diet specialization, with food items available only in brackish waters, such as shrimp and crabs, predominating (Itakura *et al.*, 2015). These findings are consistent with those of Maitra *et al.* (2018), who reported higher specialization among estuary fishes, accredited to greater food availability in brackish environments than freshwater (Kaifu *et al.*, 2013). The downstream location of the Athi River was mainly dominated by high protein rich diets as compared to the upstream location, which was linked to the presence of higher

Table 9. Overlap between sympatric species and eels from the Athi and Ramisi Rivers. The values in bold with an asterisk represent higher diet overlaps between eel species and sympatric feeding guilds.

Rivers	Guilds	*A. bengalensis*	*A. bicolor*	*A. marmorata*	*A. mossambica*
Athi	Carnivores	**0.48±0.1***	**0.81±0.01***	-	0.18±0.1
	Omnivores	0.10±0.13	0.33±0.06	-	0.29±0.2*
	Herbivores	0.04±0.3	0.07±0.07	-	0.17±0.2
Ramisi	Carnivores	**0.52±0.1***	0.22±0.01	0.08±0.01	0.29±0.1
	Omnivores	0.45±0.1	**0.74±0.11***	0.13±0.01	0.46±0.4
	Herbivores	0.01±0.4	0.005±0.1	0.03±0.01	**0.89±0.3***

trophic level fish (Pasquaud *et al.*, 2010) with inclusion of marine fish species (Kimakwa, 2004).

Eels demonstrated a preference for higher protein rich diets over sympatric fish among the fish taxa evaluated at the Athi River upstream location, attributed to their higher trophic level (Jellyman and Sykes, 2003; Schulze *et al.*, 2004). However, at the downstream location, both eels and sympatric fish had comparable diets, indicating a larger interspecific interaction along the food web (Manko, 2016). Similarly, in the Ramisi River, eel fish species preferred high-protein diets such as fish and crustaceans (Itakura *et al.*, 2015). Previously, Sinha and Jones (1967) reported similar results, however sympatric fish were reported for the first time in this study, revealing incidences of inter- and intra-specific interactions among species (Zacharia, 2017). According to Simpfendorfer *et al.* (2011) and Manly *et al.* (2002), such information is critical in efforts to preserve endangered species and manage exploited populations, especially for eels, which have been reported to continuously decline (Hanzen *et al.*, 2019; Jellyman, 2021).

The current study further found out that eels belonged to higher trophic levels as a result of exclusively consuming fish and crustaceans, in addition to bivalves (Itakura *et al.*, 2015). Furthermore, sympatric carnivorous fishes had a substantial feeding relationship with eels, indicating probable diet similarities and overlaps (Guzzo *et al.*, 2015). Omnivorous fish also consumed a diet similar to those of eels. Similar findings have been observed in salmon and trout feeding on eel-preferred diets (Sinha and Jones, 1967; Moorhouse-Gann *et al.*, 2020).

Furthermore, some of the eel species encountered, demonstrated unselective feeding behavior, feeding even on detritus and vegetation. As such, displaying an ontogenic feeding patterns (Sagar *et al.*, 2005), hence sometimes described as important opportunistic predators and scavengers preying on a wide variety of food items (Jellyman, 1989; Jellyman, 2021; Itakura *et al.*, 2020). This partly suggests that eels serve as indicator species for freshwater biodiversity conservation linked to their feeding habits (Itakura *et al.*, 2020). The results of this study also revealed that, in addition to preying on sympatric fishes, eels prayed on birds, particularly at the upstream location in the Athi River (Fig. 3). Other studies have reported eels to be an important diet in a number of predators including birds, affecting eel populations (Leukona, 2002). Furthermore, predatory exotic fish also included birds in their diets, Sabaki, classified as an Important Bird Areas (IBA) (Okuku *et al.*, 2022). Other studies, such as those of Ovegård *et al.* (2017) reported cormorant birds (*Phalacrocorax spp.*) predating on Percidae and Cyprinidae fish populations. Predation, along with other biotic interactions is thus demonstrated as a key component of ecological food webs (Hart and Pitcher, 2012), regulating community populations (Abrahams *et al.*, 2007).

Sympatric fish species feeding guilds, trophic levels (TL) and diet breadth

The highest trophic level of sympatric fish species recorded for the Ramisi River (Table 5) is related to the prevalence of high trophic guilds encountered among sampling locations (Froese and Pauly, 2019), mainly contributed by resident sympatric fishes. The higher trophic-level fish included omnivorous *C. gariepinus*, while predatory carnivorous *E. fusca*, *P. cancrivorus*, and *A. gymnocephalua* were among the higher trophic level fish (Froese and Pauly, 2019). Unlike at Athi River, omnivorous *C. gariepinus* had the highest trophic level in Ramisi River, owing to its active diet selection, proliferated by a wider diet breadth. As such, the Ramisi River is associated with intrinsic ecosystem values earning a higher conservation credibility (Duffy, 2002; Barbier *et al.*, 2009).

The lower trophic level recorded for Athi River was primarily due to the presence of lower trophic level fish species, despite the fact that the estuarine location contributed more to the trophic level due to high trophic level diets (Maitra *et al.*, 2018; Keppeler *et al.*, 2020). The findings of this study are consistent with those of Romanuk *et al.* (2006), who demonstrated that the structures of a food web are known to shift between river systems from mountains to lowland areas.

Diet and niche breadth (B) trophic interactions

Due to their specialized feeding habit on high trophic level diets (Drouineau *et al.*, 2018) eels belonged to significantly higher trophic levels than sympatric fish. This subsequently corresponds to a narrower diet breadth (Belpaire *et al.*, 2011). As a result, *A. bengalensis* had the highest trophic level, placed higher on the food web pyramid, while *A. marmorata* had the lowest TL and a wider breadth (Table 6), and linked to unselective feeding habits. The unselective feeding habits of *A. marmorata*, supposedly give credence to its least concern classification by IUCN. Sympatric fishes, on the other hand, had a broader diet breadth, indicating the presence of numerous nutritional dietary options and unselective feeding habits. Predominantly, this feeding behavior was most noticeable in exotic fishes. Although, sympatric fish had the lowest trophic level, carnivorous fish had the highest trophic level, indicating quantified trophic overlaps with eels (Hecnar and M'Closkey, 1997; González-Bergonzoni *et al*., 2020) compounded with lower diet breadth, indicating diet specialization. Omnivorous fish, on the other hand, recorded a wider diet breadth due to the consumption of a wide range of dietary items from the environment (Sánchez-Hernández *et al*., 2011; Gerking, 2014). As a result, because they compete on identical diets, both feeding guilds may be harmful to eels, displaying overlapped niche breadth. Similar findings have been reported in European catfish (*Silurus glanis*) which potentially compete with freshwater eels due to niche breadth and overlaps (Bevacqua *et al*., 2011).

Niche and diet overlap

In the Athi river, carnivorous and omnivorous dish diets overlapped with those of eels, particularly *A. bicolar* and *A. bengalensis*, which were more prominent on carnivorous guilds. On the other hand, omnivorous guilds partially overlapped with *A. mossambica* diets, indicating a possibility of unselective feeding behavior and ontogenic shifts in diet. Furthermore, the observed food resource partitioning between carnivorous *A. bicolar* and *A. bengalensis* render them vulnerable to competition pressure (Bevacqua *et al*., 2011). In addition, the diet overlaps observed between the eel species such *A. bengalensis* and *A. mossambica* (Table 8), demonstrates their coexistence throughout their range, as a result of their needs to meet energy and nutritional requirements (Sih *et al*., 1998). Subsequently, this may result in interspecific competition as described by Arai, (2016). These findings agree with those of Laffaille *et al*. (2004), who resported minimal intraspecies competition for food among different eel growth stages.

Conversely, at Ramisi River, omnivorous species diets largely overlapped with those of *A. bicolar*, whereas carnivorous fish diets overlapped with those of *A. bengalensis* (Table 9), demonstrating that omnivorous fishes share their diets habitually with eels. However, *A. mossambica* diets primarily overlapped with those of herbivorous followed by omnivorous species, indicating that eels can also be regarded as generalists (Jellyman, 2021). *Anguilla bengalensis* exhibited the largest food resource portioning with *A. bicolar* among the eel diets evaluated. Following that, Athi River displayed larger relative amounts of inter and intraspecific competition for consumer-resource interaction between eels and sympatric fish species than the Ramisi River, ascribed to higher diet overlaps.

Conclusions

Competition and predation are important ecological drivers that allow species to coexist in biotic communities where resources are limited in quantity and/or quality. The findings of this study revealed that species interactions were influenced by competition, and it is apparent that the diets of *A. bengalensis* and *A. bicolar* not only overlapped but also shared food items with sympatric carnivorous and omnivorous guilds. Furthermore, due to the greater overlap, eel taxa found in the Athi are more susceptible to competition with prominent interacting sympatric fishes. As such, there is more inter- and intraspecific competition between eels and sympatric fish species, as well as similar ecological specialization. This implies that these species are possibly vulnerable to previously undescribed competition from carnivorous fish. Therefore, diet overlap information is important for inferring trophic interactions and to enable a better understanding of ecological aspects determining fish community structure.

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Supplementary material

Table S.1. One-way ANOSIM pairwise correlation on diet composition among sampling locations on the Athi and Ramisi Rivers. Significant differences are indicated in bold.

Sampling locations	Eshu	Kiaoni	Sabaki	Taliani	Athi	Ramisi
Eshu	1					
Kiaoni	0.003	1				
Sabaki	0.0007	0.002	1			
Taliani	0.004	0.006	0.003	1		
Athi	0.001	0.026	**0.70**	0.001	1	
Ramisi	**0.92**	0.004	0.006	0.005	**0.006**	1

Tabel S.2. One-way SIMPER analysis of diet contribution and composition among the sampled locations in the Athi-Galana-Sabaki and Ramisi Rivers, Kenya. Significant contributions to dissimilarities are in bold.

Reaches	Upstream		Downstream		Upstream vs Downstream				Focal rivers	
Sampling locations	Kiaoni vs Eshu		Sabaki vs Taliani		Kiaoni vs Sabaki		Eshu vs Taliani		Athi Vs Ramisi	
Taxon	Av. dissim	Contrib. %	Av. dissim	Contrib. %	Av. dissim	Contrib. %	Av. dissim	Contrib. %	Av. dissim	Contrib. %
Penaeid Shrimp	0.00	0.00	34.13	**38.58**	26.79	**33.78**	5.90	6.43	19.24	**24.44**
POM	10.34	12.57	7.77	**8.79**	10.18	**12.83**	2.55	2.72	8.58	**10.89**
AOM	7.95	9.66	6.11	**6.92**	5.24	**6.60**	4.64	4.95	6.34	**8.049**
DOM	7.25	8.82	9.07	**10.26**	5.24	**6.60**	10.22	10.89	7.66	**9.73**
Fish	14.40	**17.48**	12.62	**14.26**	9.60	**12.1**	27.46	**29.27**	10.14	**12.88**
Prawns	15.34	**18.62**	0.00	0.00	0.04	0.05	26.11	**27.83**	7.81	10.00
Crabs	2.61	3.17	9.84	11.12	6.65	8.3	4.52	4.82	4.42	5.61
Vegetations	7.27	8.83	4.18	4.72	3.12	3.94	4.29	4.60	5.00	6.32
Unidentified insects	2.59	3.15	3.28	3.71	2.75	3.47	4.96	5.29	2.86	3.65
Damselflies	0.00	0.00	0.41	0.48	0.35	0.47	0.00	0.00	0.23	0.30
Mayflies	1.35	1.64	0.23	0.28	1.01	1.27	0.00	0.00	0.88	1.13
Polychaete worms	0.00		0.18	0.21	0.12	0.16	0.00	0.00	0.10	0.13
Pond snails	0.53	0.65	0.13	0.15	0.33	0.42	0.00	0.00	0.28	0.36
Beetles	3.15	3.83	0.40	0.45	2.10	2.64	0.34	0.36	1.3	1.68
Stoneflies	0.00	0.00	0.07	0.08	0.06	0.08	0.00	0.00	0.04	0.06
Bird	0.84	1.01	0.04	0.05	0.52	0.65	0.00	0.00	0.35	0.46
Annelid worms	0.08	0.10	0.00	0	0.05	0.07	0.00	0.00	0.03	0.04
Bivalves	0.47	0.60	0.00	0.00	0.00	0.00	0.65	0.70	0.26	0.34
Caddisflies	6.60	8.01	0.00	0.00	4.51	6.60	0.00	0.00	2.67	3.40
Chironomidae	1.11	1.34	0.00	0.00	0.68	0.85	0.00	0.00	0.37	0.48
							0.00			
Plant seeds	0.45	0.54	0.00	0.00	0.00	0.00	2.17	2.37	0.14	0.18

Table S.3. Diet composition and preferences among eels and feeding guild residency in the Athi-Galana-Sabaki and Ramisi Rivers.

Food items	Eel	Introduced carnivorous	Introduced herbivorous	Introduced Omnivorous	Native carnivorous	Native herbivorous	Native omnivorous
Annelid worm	0.0	0.0	0.0	0.8	0.0	0.0	0.0
Polychaeta worms	0.9	0.7	0.0	0.0	0.0	0.0	0.0
Beetle	0.0	0.7	8.3	9.8	0.0	0.0	6.7
Bivalve	0.9	0.0	0.0	0.0	0.0	0.0	0.0
Caddisflies	0.0	0.0	15.3	17.3	0.0	5.9	0.0
Chironomidae	0.0	0.0	2.8	2.3	0.0	0.0	0.0
Damselfly	0.0	1.4	0.0	0.0	0.0	0.0	6.7
Mayflies	0.0	0.7	0.0	5.3	0.0	7.8	0.0
Pond snails	0.9	0.7	0.0	0.8	0.0	2.0	0.0
Stoneflies	0.0	0.7	0.0	0.0	0.0	0.0	0.0
Unidentified Insect	2.8	4.1	5.6	6.8	0.0	3.9	6.7
AOM	2.8	8.1	4.2	15.0	10.1	13.7	6.7
POM	0.0	3.4	43.1	8.3	2.2	31.4	0.0
DOM	2.8	2.0	11.1	0.8	0.7	27.5	13.3
Vegetation	7.5	10.1	6.9	15.0	7.9	5.9	0.0
Plant seeds	0.9	0.0	0.0	0.0	0.0	0.0	0.0
Crab	9.3	6.8	0.0	2.3	14.4	0.0	0.0
Penaeid Shrimps	14.0	36.5	1.4	3.0	34.5	2.0	33.3
Prawns	13.1	0.0	1.4	4.5	10.8	0.0	0.0
Fish	43.0	23.6	0.0	9.3	18.7	0.0	26.7
Birds	0.9	0.7	0.0	0.0	0.0	0.0	0.0

Tabel S.4. One-way ANOSIM pairwise correlation between eel and different sympatric feeding guilds belonging to different ecological status and food item preferences (P values in bold are significant at p<0.05).

Residency guilds	Eel	Introduced carnivorous	Introduced Omnivorous	Introduced herbivorous	Native carnivorous	Native omnivorous	Native herbivorous
Eel	1						
Introduced carnivorous	0.003	1					
Introduced Omnivorous	0.016	**0.193**	1				
Introduced herbivorous	0.001	0.011	0.072	1			
Native carnivorous	**0.095**	0.025	0.070	0.007	1		
Native omnivorous	0.001	0.220	0.018	0.001	0.0003	1	
Native herbivorous	0.003	0.030	**0.120**	**0.973**	0.01	0.003	1

Original Article

Phthalates in marine sediment, water and the cockle *Anadara antiquata* on the coast of Tanzania

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Abstract

Phthalates are a group of chemicals used as plasticisers, and are easily released into the environment, where they degrade over time. We investigated the concentrations of phthalates in sediments, seawater, and the cockle *Anadara antiquata* from beaches at Dar es Salaam, Mtwara, Tanga and Zanzibar in Tanzania. A dispersive liquid-liquid microextraction method was used to extract analytes from samples, whereafter they were analysed with a gas chromatograph coupled to a mass spectrophotometer. Concentrations of diisobutyl phthalate (DiBP), dibutyl phthalate (DBP) and Bis(2-ethylhexyl) phthalate (DEHP) were determined. DiBP concentrations were highest at Dar es Salaam (11.5 - 12.4 ng/mL in seawater; 11.5 - 13.6 ng/g dry weight in sediments), compared to the other three sites, where minimum and maximum concentrations in sediments were 3.5 ng/g dw (Mtwara) and 10.7 ng/g dw (Tanga). DBP concentrations were also highest at Dar es Salaam (12.4 - 20.6 ng/mL in seawater; 12.1 - 18.7 ng/g dw in sediments) compared to 2.7 (minimum, Mtwara) and 11.2 ng/g dw (maximum, Tanga). DEHP at Dar es Salaam ranged from un-detected to 12.6 ng/mL in seawater and to 12.6 ng/g dw in sediments. It was further revealed that *A. antiquata* from Kawe Beach (Dar es Salaam) had higher concentrations of DiBP, DBP, and DEHP compared to other sites. Monitoring of phthalate concentrations will indicate pollution hotspots and trends in the region.

Keywords: dibutyl phthalate, Bis (2-ethylhexyl) phthalate, diisobutyl phthalate, seawater, sediment, cockles, Tanzania

Introduction

Marine ecosystems in the Western Indian Ocean (WIO) region, similar to other coastal areas in the world, are vulnerable to synthetic organic pollutants from anthropogenic sources (Vered *et al*., 2019). Among the most widely used synthesised chemicals, phthalates have many applications in industrial products, such as plastic-based packaging material, adhesives, printing inks, canned food containers, cosmetics, paints, medical products, ammunition, and pesticides (Paluselli *et al*., 2018). They are used with polymer-making materials such as polyvinyl chloride, polyethene terephthalate, polyethene, and polyvinyl acetate, making up to 60 % of the weight of the product (Bi *et al*., 2021). In 2019, it was estimated that the global phthalate output ranged between 6 and 8 million metric tonnes per annual (Seyoum and Pradhan, 2019). China has been identified as the largest consumer, accounting for about 45 % of global phthalate output, whereas, Europe and the United State together have been estimated to consume 25 % (Holland, 2018; Zhang *et al*., 2021). Due to the low production costs and lack of ideal alternatives, the demand for phthalates is constantly growing at an estimated rate of 1.3 % per year, which raises environmental concerns (De-la-Torre *et al*., 2022).

Phthalates unavoidably contaminate numerous environmental systems as they are likely to escape from the plastic matrix by volatilization, leaching, or abrasion (Paluselli *et al.,* 2018). Phthalates can infiltrate marine systems through atmospheric deposition, direct discharge and river runoff (Arslan *et al.,* 2021; Cao *et al.,* 2022). Coastal sediment is a major pollutant sink, carrier, and potential secondary pollution source of phthalates since most, particularly those with a higher molecular weight, possess high octanol-water partition coefficients and are primarily carried and sequestered in solid-phase matrices in aquatic environments (Paluselli *et al.,* 2018; Jebara *et al.,* 2021).

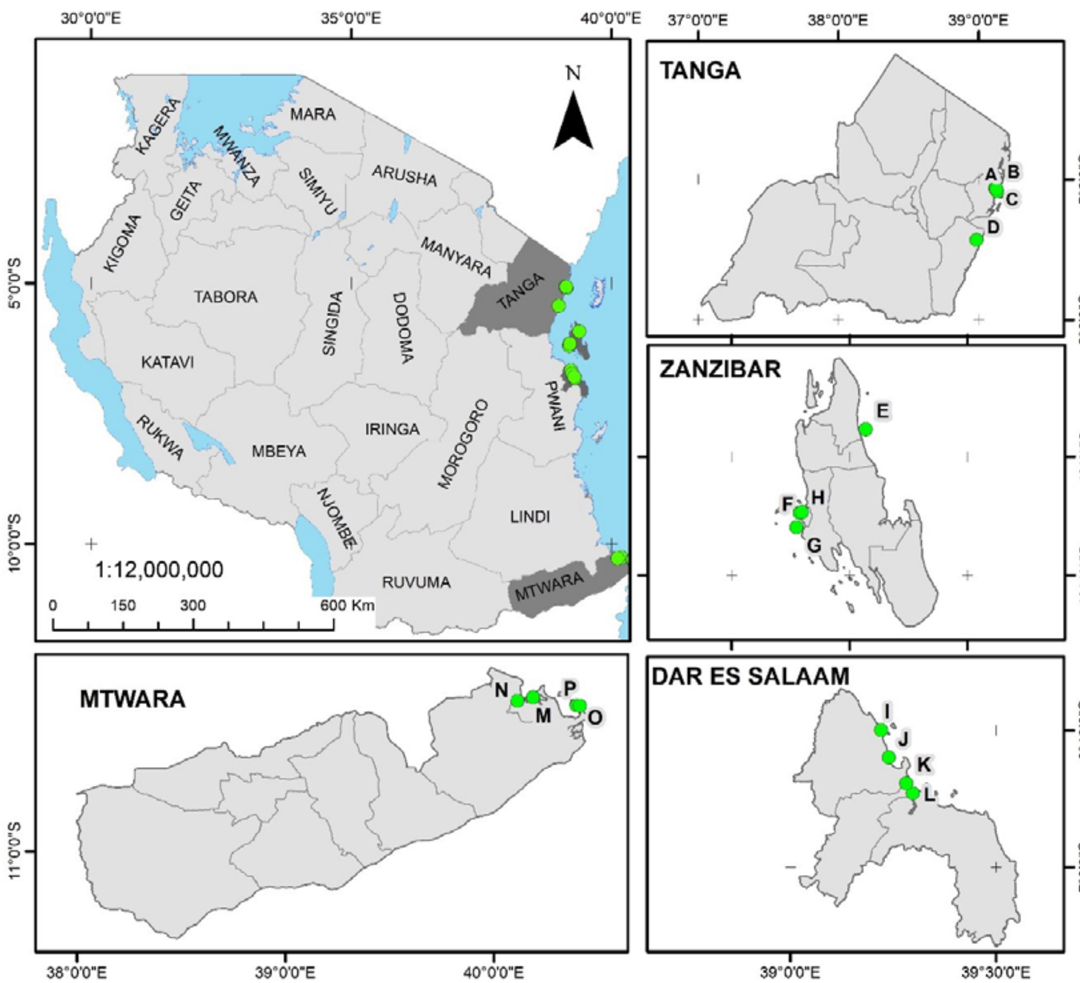

Figure 1. Map showing the locations of sampling sites. **A**: Tanga Sahare Fish Market Beach Beach, **B**: Tanga Raskazone Beach, **C**: Tanga Mkongeni Beach **D**: Pangani Fish Market Beach, E: Pwani Mchangani, **F**: Zanzibar Ferry Beach **G**: Zanzibar Mazizini Fish Market, **H**: Zanzibar Bwawani Komba, **I**: Kunduchi Beach, **J**: Kawe Beach, Selander Bridge, **L**: Posta Ferry Beach, **M**: Mtwara Ferry Fish Market Beach, **N**: Mikindani, **O**: Ruvula, **P**: Msimbati.

Phthalates have long been considered pervasive and entrenched organic pollutants of major environmental concern (Zhang *et al.*, 2018). These chemicals are well known for their adverse impact on organisms, including humans. Phthalates have endocrine-disrupting effects on marine organisms, impacting their development and the reproductive systems of amphibians, crabs, annelids, molluscs, fish, and insects (Godswill and Godspel, 2019). They have been linked to the development of genetic abnormalities in amphibians and crustaceans (Oehlmann *et al*., 2009). They have been associated with a reduction in the diversity and abundance of marine organisms in highly contaminated areas, by halting reproduction (Chaudhry, 2018).

Studies have revealed that swimming, fishing, and consuming marine biota contaminated by phthalates pose a risk to humans (Savoca *et al*., 2018; Cheng *et al*., 2018; Heo *et al.,* 2019; Kim *et al*., 2020). It has been reported that exposure to various types of phthalates can cause health issues, such as premature puberty and short anogenital distance, endocrine disruption, altered semen quality and quantity, endometriosis, hyperactivity, mental impairment in children, metabolic syndrome, allergies, and breast cancer (Savoca *et al*., 2018; Cheng *et al*., 2018; Heo *et al*., 2019; Kim *et al*., 2020).

The presence of phthalates in the marine environment has been reported in various studies (Paluselli *et al.,* 2018; Mi *et al.,* 2019; He *et al.,* 2020; Ai *et al*., 2021; Jebara *et al.,* 2021). However, no study reported on the occurrence of phthalates in the marine environment along the Tanzanian coast. Furthermore, no study has been performed to assess the level of bioconcentration of plasticizers and their associated metabolites in biota along the Tanzanian coast. Effective environmental management and remediation need an understanding of the existing situation, pollutant sources, and ecological risk posed by phthalates along Tanzania's coast. The current study, therefore, investigated the levels of phthalates in beach sediment, seawater, and the cockle, *Anadara antiquata*.

Materials and methods

Study area and sample collection

The sampling locations were chosen to reflect a spectrum of anthropogenic activities, from marine protected areas and park reserves (Ruvula and Msimbati in Tanga) to heavily industrialized areas (Kunduchi Beach, Kawe Beach, Selander Bridge and Posta Ferry Beach in Dar es Salaam) (Table 1 and Fig. 1). Most of the sampling sites were characterized by fishing and/or recreational activities. Sampling was performed during the Northern Monsoon period, between November 2020 and February 2021. This period corresponds to summer in temperate regions of the southern hemisphere, and to the transition from the dry to wet season. At each site a hand-held metal shovel was used to collect triplicate sediment samples of about 500 g by scraping about 5 cm off the surface at three designated points spaced about 300 m apart. The sediment samples were placed into aluminium bags, which were sealed tightly and stored in a cooler box containing ice

Table 1. The locations and descriptions of anthropogenic activities at the sampling sites.

S/NO	Sampling site	Coastal Region	Location sample corrected	Main Anthropogenic Activities
1	Tanga Sahare Fish Market Beach (TSB)	Tanga	(-5.087628, 39.130000)	The sandy beach is mostly used for recreational and fishing activities.
2	Pangani Fish Market Beach (PFM)		(-5.430754, 38.982405)	Recreational activities and fishing are predominant along the sandy beach.
3	Tanga Mkongeni Beach (TMB)		(-5.061770, 39.115607)	Recreational activities and fishing are predominant along the sandy beach.
4	Tanga Raskazone Beach (TRB)		(-5.068851, 39.125562)	The sandy beach is mostly used for recreational activities.
5	Mtwara Ferry Fish Market Beach (MTF)	Mtwara	-10.262807, 40.187560	Sandy beach that is primarily dominated with ferry transportation landings and fish commerce.
6	Mikindani (MK)		-10.278588, 40.112321	A beach dominated mostly by ferry transportation, fishing, small-scale trade, and boat building.
7	Ruvula (RU)		-10.301849, 40.396824	A sandy beach situated within a marine park reserve, with restricted fishing and recreational pursuits.
8	Msimbati (MS)		-10.304109, 40.411538	A sandy beach situated within a marine park reserve, with restricted fishing and recreational pursuits.
9	Zanzibar Ferry Beach (ZF)	Unguja (Zanzibar)	-6.157824, 39.191915	Marine transportation and small businesses.
10	Zanzibar Mazizini Fish Market (ZMF)		-6.199110, 39.182703	Dominated by fishing activities and small businesses.
11	Pwani Mchangani (PM)		-5.922915, 39.378741	Recreational activities.
12	Zanzibar Bwawani Komba (ZBK)		-6.155921, 39.197996	Recreational activities.
13	Kunduchi Beach (KU)	Dar es Salaam	-6.666713, 39.220493	Fishing, and small businesses.
14	Kawe Beach (K)		-6.733608, 39.239545	Recreational activities, fishing and small businesses.
15	Selander Bridge (S)		-6.733785, 39.239609	Mouth of Msimbazi river receiving water from industries and domestic wastes.
16	Posta Ferry Beach (PF)		-6.820087, 39.297296	Transportation, fishing and small businesses.

bags. For seawater sampling, a boat was used to collect samples (1 L each) offshore using a Niskin bottle and transferred to amber bottles precleaned with absolute acetone and dichloromethane. The samples were collected from three sampling points situated about 100 m from the shore and about 300 m apart at each site. The cockle, *A. antiquata*, was purchased from fishermen at each site. Three different fishermen were randomly chosen at each site to obtain different *A. antiquata*. When only one or two fishermen were available at a site, the *A. antiquata* specimens were randomly separated by eye. A total of 48 seawater, 48 sediments, and 15 *A. antiquata* samples were collected. Physical parameters including temperature, pH, total dissolved solids (TDS) and electrical conductivity (EC) were measured using a low-range Combo® pH/EC/TDS meter (Model HI 98129, HANNA Instruments Inc., USA).

Sample preparation

In the laboratory, sediment samples were sieved to remove organic shells, plants, and any other non-sediment material. They were dried at room temperature (25 °C) overnight in a laminar flow cabinet (Model: EC6VF) using an airflow of 0.5 m/s to facilitate the drying process. The samples were subsequently crushed using a mortar and pestle to ensure homogeneity and reduce particle size. This step was crucial for increasing the surface area to volume ratio of the sediments to enhance the efficiency of the extracting solvent. After homogenization, 10 mL of analytical-grade ethanol (99.9 %) was added to 1 g of sediment and sonicated for 30 minutes at 30 ± 3 °C. The mixture was centrifuged for 5 min at 1500 X g (Hettich Zetrifugen Model: Universal 320R, Andreas Hettich GmbH & Co. KG, 785332 Tuttlingen, Germany). The supernatant was transferred to screw-capped test tubes.

The tissue of *A. antiquata* was dissected from the shell and homogenised using a blender. After homogenization, 10 mL of analytical-grade ethanol (99.9) was added to 1 g of tissue sample, and the mixture was sonicated for 60 minutes at 30 ± 3 °C. The sample was then centrifuged (Hettich Zetrifugen Model: Universal 320R, Andreas Hettich GmbH & Co. KG, 785332 Tuttlingen, Germany) for 5 min at 1500 X g, and the supernatant transferred to screw-capped test tubes. Seawater was filtered using clean and sterilised cloth gauze.

Extraction of analytes

Phthalates were extracted using a dispersive liquid-liquid microextraction method, adapted from Liang *et al.* (2008). Twenty aliquots, each containing 5 mL of the sample solution, were added to separate conical-bottomed glass test tubes from each sample. A 1 mL glass syringe (Pressure-Lok, VICI Precision Sampling Inc., Baton Rouge, LA, USA) was used to inject 1 mL of acetonitrile (CAS No. 75-05-8, Sigma Aldrich Japan KK) into the sample solution as the dispersive solvent, followed by 100 µL of carbon tetrachloride (CCl_4) (CAS No. 56-23-5, VWR International BVBA, Leuven, UK) as the extraction solvent. The mixture was vortexed using a Scientific Vortex-2 Genie (Model: G-560E, Scientific Industries, Inc., Bohemia, NY, 11716, USA) for 5 minutes and then centrifuged (see model above) for 5 minutes at 3000 X g to create a cloudy solution of very small droplets of CCL_4. Due to its high density, sedimented CCl_4 was collected using a 100 µL glass syringe into a single vial and allowed to dry overnight, before being dissolved in 1 mL dichloromethane (99.5%, AR/ACS, CAS: 75-092 ADR/PG, LOBA Chemie., Jehangir Villa, 107 Wonderhouse, Mumbai, India).

Determination of phthalates

An analytical standard phthalate mixture of 1000 µg/mL was diluted by methanol (Brand: Supelco: CRM48805, Sigma-Aldrich Chemie GmbH) and used for the preparation of external calibration curves for quantification of analytes in the samples. The standard mixture contained Dimethyl phthalate, Diethyl phthalate, Diisobutyl phthalate, Dibutyl phthalate, Methyl glycol phthalate, Phthalic acid, di(2-methylpent-3-yl) ester, Dimethoxyethyl phthalate, Di-n-pentyl phthalate, di-n-Hexyl phthalate, Benzyl butyl phthalate, Bis (2-butoxy ethyl) phthalate, Diisooctyl phthalate, Dicyclohexyl phthalate, 1,2-Benzenedicarboxylic acid, diphenyl ester, Di-n-octyl phthalate, Phthalic acid, and Nonyl pentadecyl ester.

Determination of phthalates was performed using Gas Chromatography-Mass Spectrometry (GC-MS) using a Shimadzu GC-MS-2010 instrument operated in Electron Ionization (EI) mode (MS) at 70 eV and Flame Ionization Detector (FID) for GC (Lo Brutto *et al.*, 2021). A Restek-5MS column (30 m x 0.25 mm x 0.25 µm) was used. The oven temperature programming was 90 °C to 280 °C, held at 90 °C for two minutes. The temperature was increased to 280 °C for 10 minutes (hold time), at a rate of 15 °C per minute. The injection temperature was 250 °C with splitless injection mode. The flow rate of carrier gas Helium was 1.21 mL min^{-1}. The ion source temperature and interface temperature in MS were 230 °C and 300 °C, respectively. The final instrumental runtime per sample was 26.48 minutes.

Phthalate bioaccumulation in *Anadara antiquata*

Bioconcentration of plasticizers in *A. antiquata* was calculated as:

$$BCF = {C_B}/{C_w} \quad \text{Equation (1)}$$

Where BCF is the bioconcentration factor, C_B is the concentration in the organism, and Cw is the concentration in seawater.

Biota sediment accumulation factor was calculated as:

$$BSAF = {C_B}/{C_S} \quad \text{Equation (2)}$$

Where BSAF is the bioconcentration factor in sediment, C_B is the concentration in the organism, and Cs is the concentration in sediment.

Quality control and assurance

All solvents were measured for phthalates before analysis. Plastic experimental tools were avoided whenever deemed necessary. Sampling and procedural blanks were used to check for background contamination of target contaminants. Trace levels of phthalates detected in procedural blanks were subtracted from the real samples. Percentage recovery was determined by spiking a known concentration of the analytical standard solution into sediment, seawater, and *A. antiquata* tissue. The spiked samples were subsequently subjected to liquid-liquid microextraction and the percentage recovery was determined using Equation 3. The limit of detection (LOD) and limit of quantification (LOQ) were determined by applying Equations 4 and 5, respectively (Table 2). Samples that fell below the detection limit were statistically treated as half of the detection limit. Triplicate samples were taken and treated as separate samples; the average concentration of the triplicate samples was determined, and the results are presented as the mean and standard deviation.

$$\%Recovery = \frac{C_o - C_e}{C_s} x100 \quad \text{Equation (3)}$$

Where C_o is the observed Concentration, C_e is the endogenous concentration, Cs is the spiked concentration of the standard (Burns *et al.*, 2002).

LOD = mean of limit of blank + 3 SD Equation (4)

LOQ = Limit of blank (mean value) +10 SD Equation (5)

Where, LOD is the limit of detection, LOQ is the limit of quantification, SD is the standard deviation of the low-concentration sample (Taleuzzaman 2018).

Statistical analysis

Statistical tests were performed using nonparametric or parametric tests, chosen based on the data distribution determined using the F-test. ANOVA was used for parametric data, while Mann-Whitney and Kruskal-Wallis tests were used for non-parametric data. In all cases, a p-value of < 0.05 was used to identify statistically significant differences between phthalate concentrations amongst groups. Pearson's correlation test was used to evaluate the correlation among and between phthalates and physico-chemical parameters (temperature, pH, EC, TDS). The Paleontological Statistics Software Package for Education and Data

Table 2. Analytical recovery, limit of detection (LOD), and limit of quantification (LOQ).

Analyte Name	%Recovery			LOD	LOQ
	Sediment	Seawater	A. antiquata	ng/mL	
Dimethyl phthalate	92.81	97.23	86.68	0.03	0.11
Diethyl phthalate	87.02	96.06	81.42	0.04	0.13
Diisobutyl phthalate	100.75	91.32	78.44	0.05	0.13
Dibutyl phthalate	103.04	118.04	81.60	0.06	0.21
Methyl glycol phthalate	86.97	93.25	75.02	0.08	0.29
Phthalic acid, di(2-methylpent-3-yl) ester	94.01	94.76	80.76	0.07	0.23
Diethoxyethyl phthalate	86.78	90.50	83.50	0.04	0.15
Di-n-pentyl phthalate	86.92	89.02	76.02	0.07	0.24
di-n-Hexyl phthalate	87.07	90.25	90.25	0.06	0.20
Benzyl butyl phthalate	78.70	80.44	74.06	0.05	0.16
Bis(2-butoxyethyl) phthalate	86.24	91.22	81.00	0.05	0.18
Bis(2-ethyhexyl) phthalate	89.48	78.20	78.20	0.17	0.58
Dicyclohexyl phthalate	79.02	86.10	77.78	0.06	0.22
1,2-Benzenedicarboxylic acid, diphenyl ester	86.23	93.09	76.44	0.09	0.33
Di-n-octyl phthalate	87.61	89.73	79.06	0.08	0.27
Phthalic acid, nonyl pentadecyl ester	80.56	86.00	73.56	0.22	0.72

Analysis (PAST), version 4.09 (Hammer *et al.*, 2001), was used to conduct the statistical analyses. Graphs were generated using Microsoft® Excel Version 16.52.

Results

Quality control and assurance

The percentage recovery, LOD, and LOQ are provided in Table 2. Recovery ranged from 73.56 to 118.04 %, which is within the acceptable range of 70 to 120 % (Shabeer *et al.*, 2018). A test for instrument sensitivity under the set of machine measurement acquisition revealed that the LOD ranged from 0.03 to 0.22 ng/mL, while the LOQ was from 0.11 to 0.72 ng/mL.

Phthalates in Dar es Salaam samples

Figure 2 presents the presence of three phthalates (DBP, DiBP, and DEHP) in sediment, seawater, and *A. antiquata* samples from four sampling sites in Dar es Salaam. The levels of DiBP varied from 11.53 ± 0.41 ng/mL to 13.35 ± 1.41 ng/g dw in seawater and sediment samples, respectively, meanwhile, the concentration in *A. antiquata* was 11.82 ± 4.21 ng/g fw. DBP levels ranged from 12.09 ± 0.28 ng/g dw to 20.63 ± 0.99 ng/g dw in sediments and seawater, respectively, whereas in *A. antiquata* samples it was 12.19 ± 1.81 ng/g fw. DEHP was detected at Kawe Beach and Selander Bridge, which levels ranged from 6.04 ± 2.52 ng/mL to 12.57±2.52 ng/mL in seawater and 7.57 ± 1.02 ng/g dw to 12.52 ng/g dw in sediments, and 5.87 ± 2.47 ng/g fw in *A. antiquata*. One-Way ANOVA revealed no significant differences in phthalate levels between seawater and sediment amongst the sampling locations ($p > 0.05$) (Table 3). However, the distribution of phthalates in sediment showed significant differences, with DBP having the highest mean concentration, followed by DiBP and DEHP ($p > 0.05$) (Table 3).

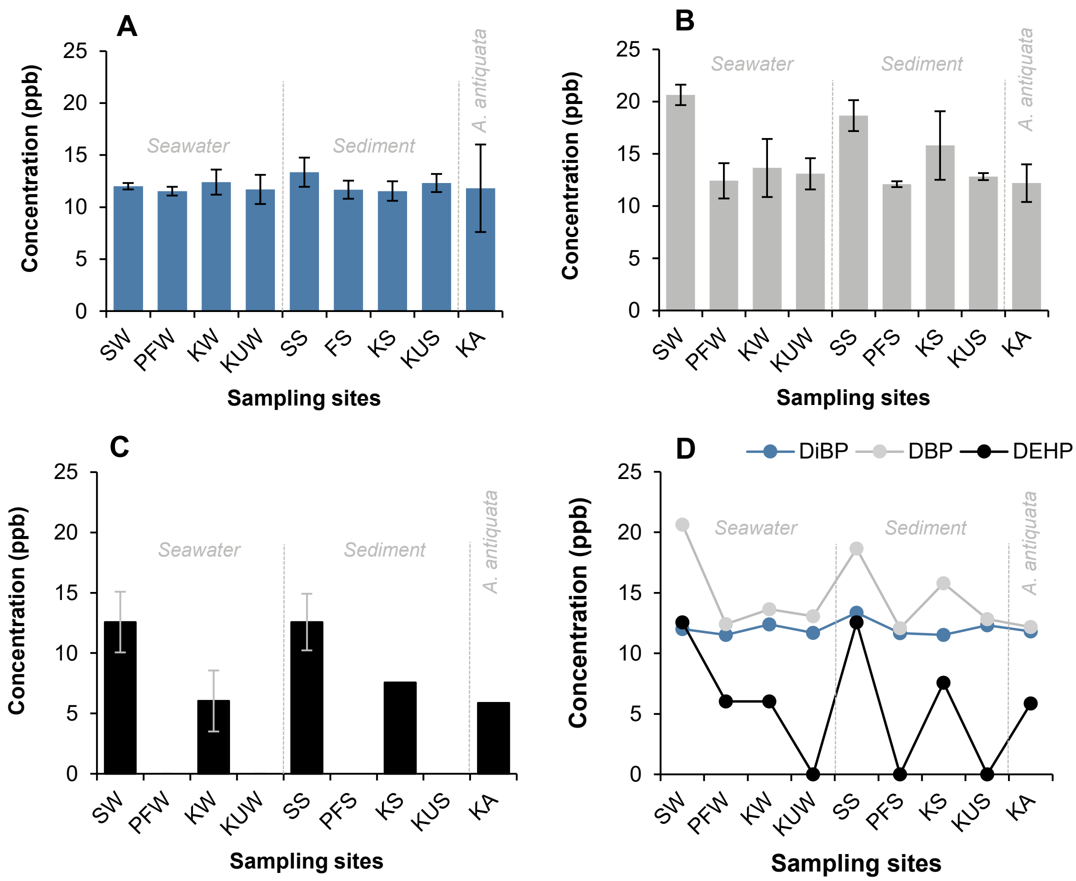

Figure 2. Concentrations of phthalates along the coast of Dar es Salaam. **A**: Diisobutyl phthalate (DiBP) **B**: Dibutyl phthalate (DBP), **C**: Bis(2-ethyhexyl) phthalate (DEHP), **D**: DiBP, DBP and DEHP concentration comparison. SW: Selander Bridge-Seawater, SS: Selander Bridge-Sediment sample, PFW: Posta Ferry Beach-Seawater, FS: Posta Ferry-Sediment sample, KW: Kawe Beach-Seawater, KS: Kawe Beach-Sediment, KUW: Kunduchi Beach-Seawater and KUS: Kunduchi Beach-Sediment. Error Bar= Standard deviation (SD, n=3). Part per billion (ppb)= ng/mL for seawater, ng/g dw (dry weight) for sediment), ng/g fw (fresh weight) for *A. antiquata*.

Table 3. Concentration of DiBP, DBP and DEHP along the coast of Tanzania.

Statistical comparison	Sample type	Sampling sites	Phthalates (Concentration Mean ± SD)		
Dar es Salaam (D)			**D_DiBP**	**D_DBP**	**D_DEHP**
(W_DiBP Vs W_DBP VsW_DEHP)** (S_DiBP Vs S_DBP Vs S_DEHP)* (W_DiBP Vs S_DiBP) * (W_DBP Vs S_DBP)* (W_DEHP Vs S_DEHP)*	Seawater (W) (ng/mL)	SW	12.00 ± 0.31	20.63 ± 0.99	12.57 ± 2.52
		FW	11.53 ± 0.41	12.41 ± 1.69	nd
		KW	12.4 ± 1.20	13.64 ± 2.78	6.04 ± 2.52
		KUW	11.70 ± 1.40	13.08 ± 1.49	nd
	Sediment (S) (ng/g dw)	SS	13.35 ± 1.41	18.65± 1.49	12.57 ± 2.35
		FS	11.67 ± 0.86	12.09 ± 0.28	nd
		KS	11.54 ± 0.94	15.83 ± 3.28	7.57 ± 1.02
		KUS	12.32 ± 0.86	12.82 ± 0.33	nd
	A. antiquata (A) (ng/g fw)	KA	11.82 ± 4.21	12.19±1.81	5.87 ± 2.47
Mtwara (M)			**M_DiBP**	**M_DBP**	**M_DEHP**
(M_DiBPVs M_DBP Vs M_DEHP)* *(W_DiBP Vs W_DBP Vs W_DEHP)** *(S_DiBP Vs S_DBP Vs S_DEHP)** *(W_DiBP Vs S_DiBP)** (W_DBP Vs S_DBP)* (W_DEHP Vs S_DEHP)*	Seawater (W) (ng/mL)	MTFW	14.35 ±1.12	11.15 ± 0.76	nd
		MKW	6.17 ± 1.34	7.07 ± 1.04	nd
		RUW	3.71 ± 0.58	5.82 ±1.02	nd
		MSW	5.54 ± 1.43	6.31 ± 1.61	nd
	Sediment (S) (ng/g dw)	MTFS	10.42 ± 0.89	9.71 ± 0.14	nd
		MKS	7.81 ± 1.43	8.40 ± 0.09	nd
		RUS	6.30 ± 1.04	4.3 ± 0.60	nd
		MSS	4.56 ± 1.21	5.26 ± 0.37	nd
	A. antiquata (A) (ng/g fw)	MTFA	2.60 ± 1.12	4.43 ± 0.95	nd
		MKA	2.72 ± 0.66	3.53 ± 0.62	nd
Tanga (T)			**T_DiBP**	**T_DBP**	**T_DEHP**
(T_DiBP Vs T_DBP Vs T_DEHP)*** (W_DiBP Vs W_DBP Vs W_DEHP)* (S_DiBP Vs S_DBP Vs S_DEHP)* (W_DiBP Vs S_DiBP)* (W_DBP Vs S_DBP)* (W_DEHP Vs S_DEHP)*	Seawater (W) (ng/mL)	TSBW	8.23 ± 0.94	9.32 ± 1.16	nd
		PFMW	9.23 ± 0.94	4.86 ± 0.71	nd
		TRZBW	9.56 ± 1.65	5.36 ± 1.34	nd
		MBW	4.56 ± 1.71	5.96 ± 1.60	nd
	Sediment (S) (ng/g dw)	TSBS	10.16 ± 0.82	11.23 ± 0.93	3.14 ± 1.32
		PFMS	10.72 ± 1.27	7.87 ± 1.37	4.61 ± 1.17
		TRZBS	7.91 ± 2.13	5.67 ± 0.98	0.57± 0.64
		MBS	5.12 ± 2.05	6.97 ± 2.13	nd
	A. antiquata (A) (ng/g fw)	TSBA	2.61 ± 0.56	3.17 ± 0.97	1.37 ± 0.65
		PFMA	1.69 ± 0.65	1.48 ± 0.67	0.87 ± 0.56
Zanzibar(Z)			Z_DiBP	**Z_DBP**	**Z_DEHP**
(Z_DiBP^{+++} Vs Z_DBP^{++} Vs Z_DEHP^{+})*** ((W_DiBP Vs W_DBP VsW_DEHP)* (S_DiBP Vs S_DBP Vs S_DEHP)* (W_DiBP Vs S_DiBP)* (W_DBP Vs S_DBP)* (W_DEHP Vs S_DEHP)*	Seawater (W) (ng/mL)	PMW	3.67 ± 0.93	5.23 ± 0.93	nd
		ZFAW	9.87 ± 2.02	6.78 ± 1.13	3.31 ± 1.24
		ZBKW	3.07 ± 0.32	6.67 ± 0.56	nd
		ZFMW	8.48 ± 0.27	5.56 ± 1.46	nd
	Sediment (S) (ng/g dw)	PMS	4.81 ± 2.54	4.44 ± 2.54	nd
		ZFAS	12.87 ± 1.56	9.54 ± 2.45	4.67 ± 0.84
		ZBKS	5.78 ± 1.04	5.32 ± 0.63	1.04 ± 0.21
		ZFMS	4.72 ± 0.21	5.72 ± 0.51	2.17 ± 0.32
	A. antiquata (A) (ng/g fw)	ZFMA	2.97 ± 0.93	3.31 ± 1.09	0.86 ± 0.27

(xxi)(D_DiBP vs. M_ DiBP)***, (xxii) (D_DiBP vs. T DiBP***, (xxiii)(Da_DiBP vs. Z_DiBP)***, (xxiv)(M_DiBP vs. T_DiBP)*, (xxv) (M_DiBP vs. Z_DiBP)*, (xxvi)(T_DiBP vs. Z_DiBP)*. (xxvii)(D_DBP vs. M_DBP)*,(xxviii)(D_DBP vs. T_DBP)***, (xxix)(D_DBP vs. Z_DBP)***, (xxx)(M_DBP vs. T_DBP)*, (xxxi)(M_DBP vs. Z_DBP)*, (xxxii)(T_DBP vs. Z_DBP)*.

Key:
***$p < 0.01$ (highly significant difference)
** $p < 0.05$ (significant difference)
*p (no significant difference)
Post Hoc
$^{+++}p<0.01$
$^{++}p<0.05$
$^{+}$p (no significant difference)

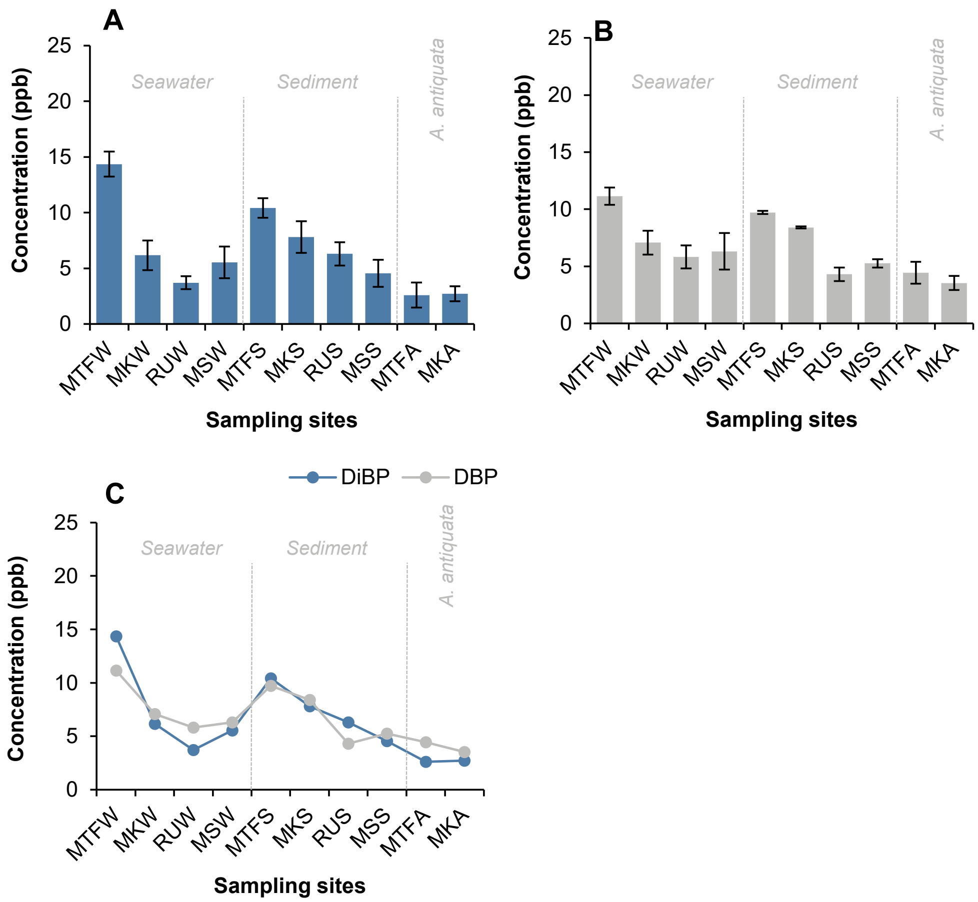

Figure 3. Concentrations of phthalates along the coast of Mtwara. **A**: Diisobutyl phthalate (DiBP) **B**: Dibutyl phthalate (DBP), **C**: DiBP, DBP and DEHP concentration comparison. MTFW (Mtwara Ferry Fish Market Beach Beach-Seawater), MTFS (Mtwara Ferry Fish Market Beach-Sediment), MTFA (Mtwara Ferry Fish Market Beach-A. antiquata), MKW (Mikindani-Seawater Sample), MKS (Mikindani-Sediment), MKA (Mikindani-A. antiquata), RUW (Ruvula-Seawater), RUS (Ruvula-Sediment), MSW (Msimbati-Seawater) and MSS (Msimbati-Sediment). Error Bar= Standard deviation (SD, n=3). Part per billion (ppb)= ng/mL for seawater, ng/g dw (dry weight) for sediment), ng/g fw (fresh weight) for *A. antiquata*.

Phthalates in Mtwara samples

Figure 3 compares the presence of DiBP and DBP in sediment, seawater, and *A. antiquata* samples collected at four Mtwara sites (Mtwara Ferry Fish Market Beach, Mikindani, Ruvula, and Msimbati). DiBP concentrations in sediments ranged from 4.30 ± 0.60 to 9.71 ± 0.14 ng/g dw, with the highest concentration observed at Mtwara Ferry Fish Market Beach. Seawater samples had DiBP concentrations from 5.82 ± 1.02 to 11.15 ± 0.76 ng/mL, with the highest concentration at Mtwara Ferry Fish Market Beach. *A. antiquata* from Mtwara Ferry Fish Market Beach had a higher DBP concentration (4.43 ± 0.95 ng/g fw) compared to Mikindani (3.53 ± 0.62 ng/g fw). DBP concentrations in sediments ranged from 4.56 ± 1.21 to 10.42 ± 0.89 ng/g dw, with the highest concentration observed at Mtwara Ferry Fish Market Beach. Seawater samples had DBP concentrations from 3.71 ± 0.58 to 14.35 ± 1.21 ng/mL. Statistical analysis revealed no significant differences in DiBP and DBP concentrations between seawater and sediments (Table 3).

Phthalates in Tanga samples

Figure 4 compares the results obtained from the Tanga coast, which indicated the presence of phthalates (DiBP, DBP, and DEHP) in sediment, seawater and *A. antiquata* samples. The concentration of DiBP in sediments varied between 5.12 ± 2.05 and 10.72 ± 1.27 ng/g dw, with the highest level observed at Pangani Fish Market. In seawater, DiBP concentrations ranged from 4.76 ± 1.71 to 9.56 ± 1.65 ng/mL, with the highest level found at Tanga Raskazone Beach. *A. antiquata* samples had DiBP levels of 2.61 ± 0.56 ng/g fw for Tanga Sahare Fish Market Beach and 1.69 ± 0.65 ng/g fw for Pangani Fish Market Beach. DBP concentrations in sediments ranged from 5.67 ± 0.98 to 11.23 ± 0.93 ng/g dw, with the highest concentration observed at Tanga Sahare

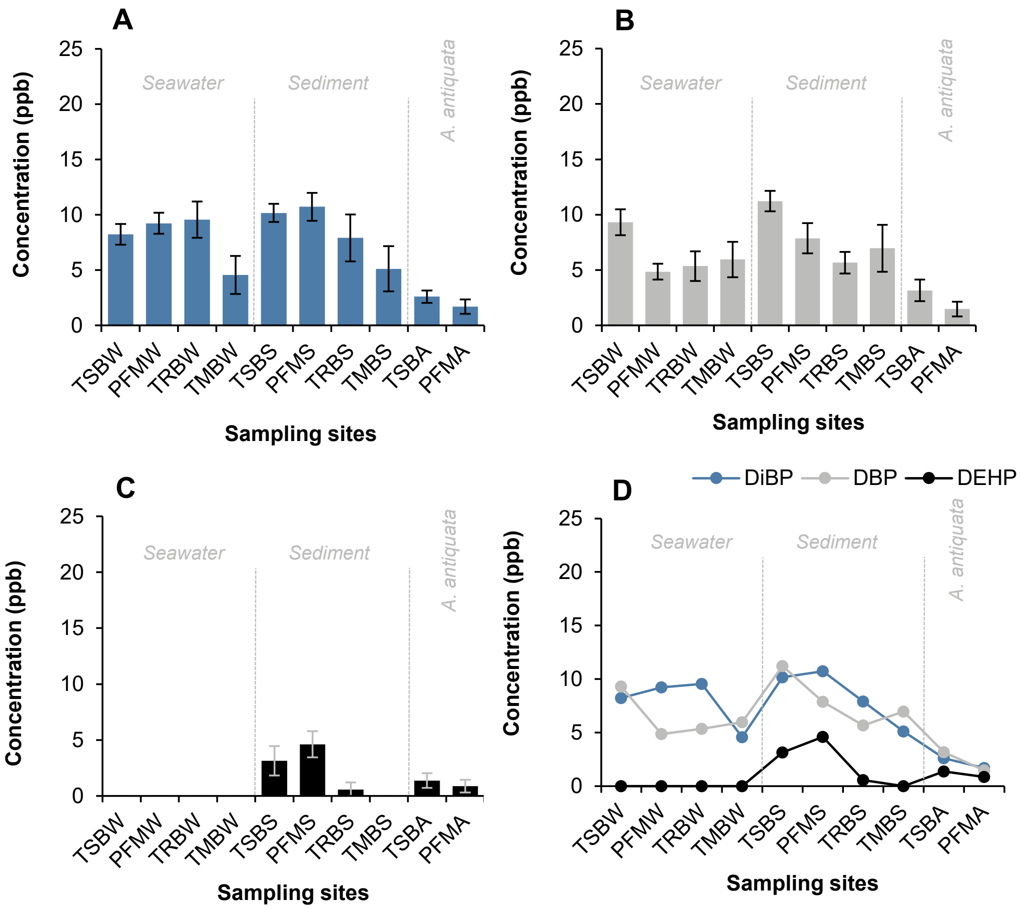

Figure 4. Concentrations of phthalates along the coast of Tanga. A: Diisobutyl phthalate (DiBP) B: Dibutyl phthalate (DBP), C: Bis(2-ethyhexyl) phthalate (DEHP), D: DiBP, DBP and DEHP concentration comparison. TSBW: Tanga Sahare Fish Market Beach -Water, TSBS: Tanga Sahare Fish Market Beach - Sediment, TSBA: Tanga Sahare Fish Market Beach-*A. antiquata*, PFMW: Pangani Fish Market Beach-Seawater, PFMS: Pangani Fish Market Beach - Sediment, PFMA: Pangani Fish Market Beach-*A. antiquata*, TRBW: Tanga Raskazone Beach-Seawater, TRBS: Tanga Raskazone Beach-Sediment, TMBW: Tanga Mkongeni Beach-Seawater, TMBS: Tanga Mkongeni Beach-Sediment. Error Bar= Standard deviation (SD, n=3). Part per billion (ppb)= ng/mL for seawater, ng/g dw (dry weight) for sediment), ng/g fw (fresh weight) for *A. antiquata.*

Fish Market Beach. In seawater, DBP concentrations ranged from 4.86 ± 0.71 to 9.32 ± 1.16 ng/mL, with the highest level found at Tanga Sahare Fish Market Beach. *A. antiquata* from Tanga Sahare Fish Market Beach also exhibited a higher DBP concentration (3.17 ± 0.97 ng/g fw) compared to those from Pangani Fish Market Beach (1.48 ± 0.67 ng/g fw). Figure 4D shows that DBP had the highest concentrations, followed by DiBP, while DEHP had the lowest levels. Statistical analysis confirmed significant differences in mean concentrations amongst the sampling sites in Tanga ($p<0.05$) (Table 3), with DiBP showing significantly higher levels compared to DBP and DEHP.

Phthalates in Zanzibar samples

Figure 5 compares the concentrations of phthalates in sediments and seawater from four sites in Zanzibar (Pwani Mchangani, Zanzibar Ferry Beach, Zanzibar Bwawani Komba, and Zanzibar Mazizini Fish Market). The results showed varying concentrations of DiBP, DBP, and DEHP across the sampling locations (Table 3). DiBP concentrations ranged from 4.72 ± 0.51 to 12.87 ± 2.45 ng/g dw in sediments, with the highest concentration observed at the Zanzibar Ferry Beach. In seawater, DiBP concentrations ranged from 3.07 ± 1.46 to 9.87 ± 2.02 ng/mL, with the highest concentration again found at Zanzibar Ferry Beach. The concentration of DiBP in *A. antiquata* from Zanzibar Mazizini Fish Market was 2.97 ± 0.93 ng/g fw. For DBP, sediment concentrations ranged from 4.44 ± 2.54 to 9.54 ± 2.45 ng/g dw, while seawater concentrations ranged from 5.23 ± 0.93 to 6.78 ± 1.13 ng/mL. DEHP concentrations in sediments and seawater were quantifiable at various sites. DiBP had the highest concentrations among the phthalates analysed (Fig. 5D). Statistical analysis indicated no significant differences in phthalate

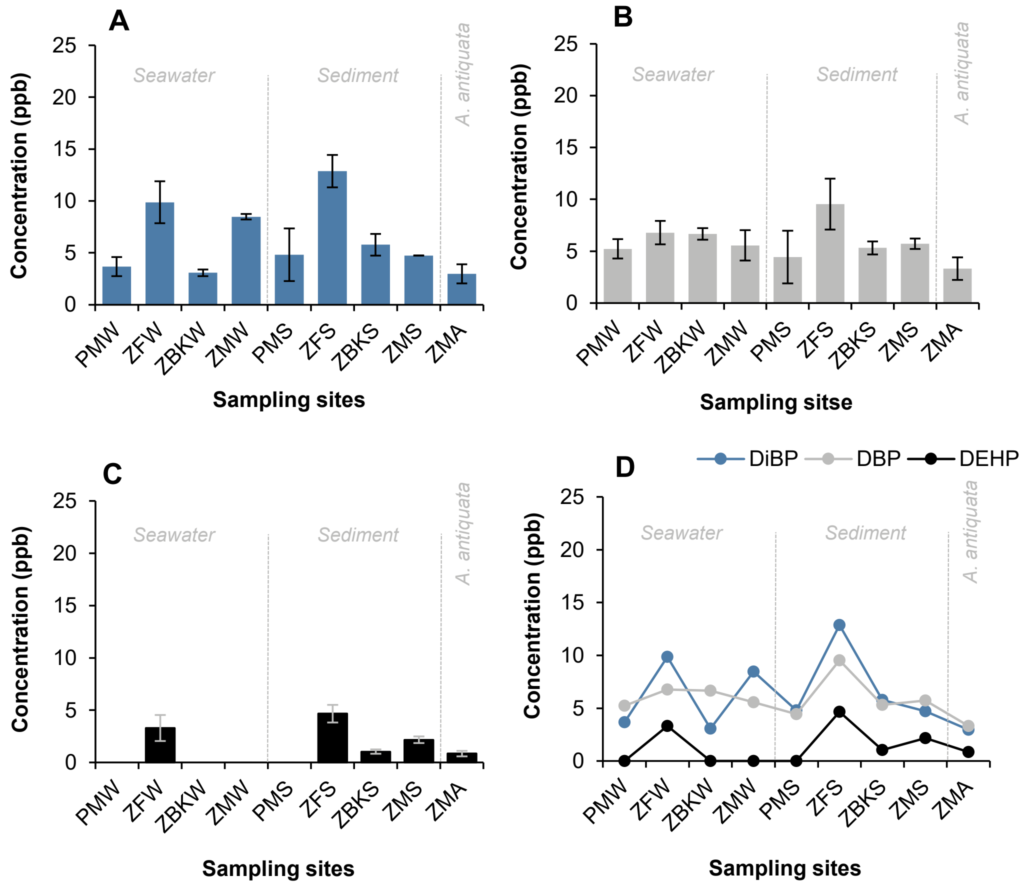

Figure 5: Concentrations of phthalates in Zanzibar. A: Diisobutyl phthalate (DiBP) B: Dibutyl phthalate (DBP), C: Bis(2-ethyhexyl) phthalate (DEHP), D: DiBP, DBP and DEHP concentration comparison. PMW: Pwani Mchangani-Seawater, PMS: Pwani Mchangani-Sediment, ZFW: Zanzibar Ferry Beach-Seawater, ZFS: Zanzibar Ferry Beach-Seawater, ZBKS: Zanzibar Bwawani Komba-Sediment, ZBKW: Zanzibar Bwawani Komba-Seawater, ZMW: Zanzibar Mazizini Fish Market-Seawater, ZMS: Zanzibar Mazizini Fish Market-Sediment, ZMA- Zanzibar Mazizini Fish Market-*A. antiquata*. Error Bar= Standard deviation (SD, n=3). Part per billion (ppb)= ng/mL for seawater, ng/g dw (dry weight) for sediment), ng/g fw (fresh weight) for *A. antiquata*.

concentrations between sediments and seawater ($p > 0.05$), but there were significant differences observed amongst the phthalates in seawater ($p < 0.05$) (Table 3).

Cumulative concentration of phthalate in sediment, seawater and Anadara antiquata

Due to their similar mode of toxicity, it has been recommended that the cumulative concentration of phthalates in the environment should also be considered (Araki *et al.*, 2020, Chen *et al.*, 2020 and Sumner *et al.*, 2019). Higher concentrations of phthalates were evident in samples collected from Dar es Salaam sites, particularly at Selander Bridge (45.20 and 44.57 ng/mL in seawater and sediment, respectively). Generally, seawater, sediment and *A. antiquata* samples from Dar es Salaam sites exhibited higher cumulative concentrations than samples from other sites (Figure 6). However, statistically, there was no significant difference in the concentrations of phthalates between seawater and sediment matrices ($p > 0.05$).

Bioconcentration of phthalates in the cockle Anadara antiquata

Table 4 presents the bioconcentration factor (BCF) and biota sediment accumulation factor (BSAF) values of phthalates (DiBP, DBP, and DEHP) in *A. antiquata* at various sampling sites. The BCF values ranged from 0.18 at Pangani Fish Market Beach to 0.95 at Kawe Beach. Similarly, the BSAF values vary, with the lowest value of 0.16 at Pangani Fish Market Beach and the highest of 1.02 at Kawe Beach. These findings indicate variations in the accumulation potential of phthalates in *A. antiquata* across different sampling sites.

Correlation analysis

Table 5 shows Pearson's correlation coefficients of phthalates (DiBP, DBP, DEHP) and physico-chemical parameters in seawater and sediment samples, respectively. The finding depicts the extent and direction of associations among DiBP, DBP and DEHP and temperature, pH, EC and TDS. The findings show

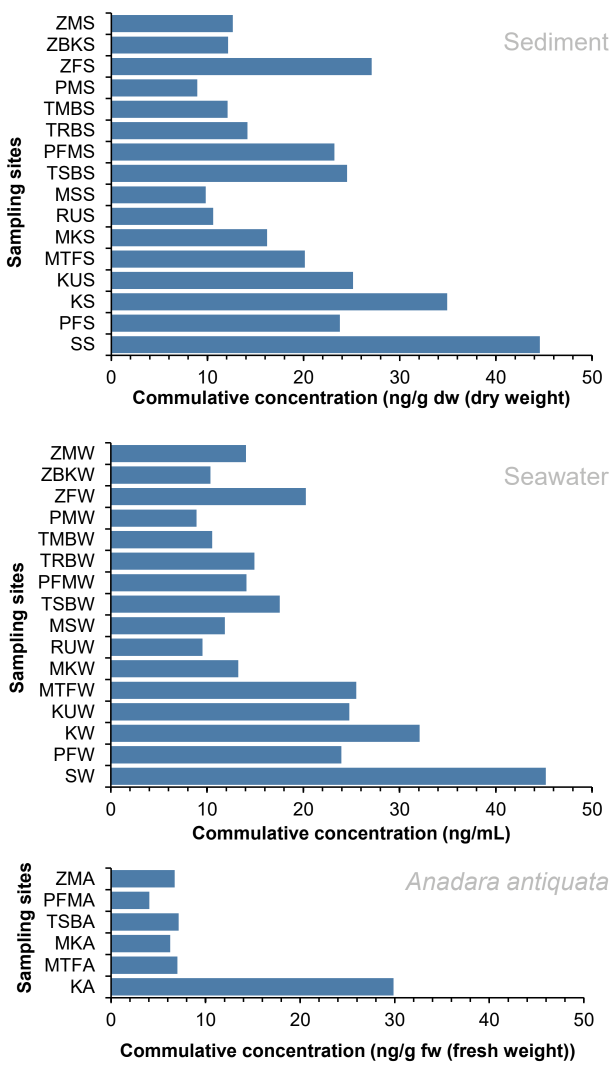

Figure 6. Cumulative concentration of Diisobutyl phthalate (DiBP), dibutyl phthalate (DBP) and Bis (2-ethylhexyl) phthalate) in marine sediment, seawater and *A. antiquata* along the Indian Ocean Coast. **A**: Diisobutyl phthalate (DiBP) **B**: Dibutyl phthalate (DBP), **C**: Bis(2-ethyhexyl) phthalate (DEHP), **D**: DiBP, DBP and DEHP concentration comparison. SW: Selander Bridge-Seawater, SS: Selander Bridge-Sediment, PFW: Posta Ferry Beach-Seawater, PFS: Posta Ferry Beach-Sediment, KW: Kawe Beach-Seawater, KS: Kawe Beach-Sediment, KUW: Kunduchi Beach-Seawater and KUS: Kunduchi Beach-Sediment. MTFW (Mtwara Ferry Fish Market Beach -Seawater), MTFS (Mtwara Ferry Fish Market Beach-Sediment), MTFA (Mtwara Ferry Fish Market Beach -*A. antiquata*), MKW (Mikindani-Seawater Sample), MKS (Mikindani-Sediment), MKA (Mikindani-*A. antiquata*), RUW (Ruvula-Seawater), RUS (Ruvula-Sediment), MSW (Msimbati-Seawater) and MSS (Msimbati-Sediment). TSBW: Tanga Sahare Fish Market Beach-Seawater, TSBS: Tanga Sahare Fish Market Beach-Sediment, TSBA: Tanga Sahare Fish Market Beach-*A. antiquata*, PFMW: Pangani Fish Market Beach-Seawater, PFMS: Pangani Fish Market Beach-Sediment, PFMA: Pangani Fish Market Beach-*A. antiquata*, TRBW: Tanga Raskazone Beach-Seawater, TRBS: Tanga Raskazone Beach-Sediment, TMBW: Tanga Mkongeni Beach-Seawater, TMBS: Tanga Mkongeni Beach-Sediment. PMW: Pwani Mchangani-Seawater, PMS: Pwani Mchangani-Sediment, ZFW: Zanzibar Ferry Beach-Seawater, ZFS: Zanzibar Ferry Beach-Seawater, ZBKS: Zanzibar Bwawani Komba-Sediment, ZBKW: Zanzibar Bwawani Komba-Seawater, ZMW: Zanzibar Mazizini Fish Market -Seawater, ZMS: Zanzibar Mazizini Fish Market-Sediment, ZMA-Zanzibar Mazizini Fish Market-*A. antiquata*.

that DiBP in seawater had a slightly positive correlation with DBP (r = 0.66) and a weak positive correlation with DEHP (r = 0.40), while DBP demonstrated a strong positive correlation with DEHP (r = 0.77). Correlations between phthalates and physical-chemical parameters are generally weak in both seawater and sediments, with some negative correlations noted between pH and phthalates, and weak positive correlations between EC and DEHP (r = 0.42). In sediment samples (Table 5), DiBP exhibited a strong positive correlation with DBP (r = 0.84) and a moderate positive correlation with DEHP (r = 0.58). On the other hand, a strong positive correlation between the concentrations of DBP and DEHP was evident (r = 0.73).

Discussion

Occurrences of phthalates on the coast of Tanzania

Three of the 16 targeted phthalates, namely DiBP, DBP, and DEHP, were detected and quantified in seawater and sediments from sampling sites in two regions of the Tanzanian mainland (Dar es Salaam and Tanga) and at Zanzibar Island, whereas only DiBP and DBP were detected in samples from the Mtwara area. Statistical analysis using One Way ANOVA revealed that the cumulative concentrations of DiBP, DBP, and DEHP were generally higher in sediments and seawater at Dar es Salaam beaches (Selander Bridge, Kawe Beach, Posta Ferry Beach and Kunduchi Beach) than at Mtwara, Tanga, and Zanzibar.

The high prevalence of phthalates at the Dar es Salaam sites can be explained by the highest level of anthropogenic activities in the region, which include 532 industries and 5,383,728 inhabitants that account for 5.4 % of the population in Tanzania (NBS, 2022). The Msimbazi River, which runs for 35 km through Dar es Salaam has been identified as the main channel for the flow of organic pollutants to the city's coast. Domestic wastes and wastewater from nearby factories in Tabata and Ubungo, landfill sites, and horticultural activities in the river basin contribute to the pollution (Nchimbi *et al.*, 2022). The Dar es Salaam coast also receives water from the Zinga and Kizinga rivers flowing through the industrial suburbs of Kurasini, Mbagala, and Kigamboni. Industrial effluents, garage waste, pesticides from nearby horticulture sites, and domestic plastic waste in these river basins are potential sources of phthalate contamination (Nchimbi *et al.*, 2022). Phthalate contamination may also come from recreational and fishing activities on Dar es Salaam's popular beaches, where swimwear and plastic fishing nets are common.

Table 4. Bioconcetration factor (BCF) and biota sediment accumulation factor (BSAF) of individual phthalates in *A. antiquata*. X – could not be calculated.

Sampling site	Concentration factor	DiBP	DBP	DEHP
Kawe Beach (K)	BCF	0.95	0.89	0.97
	BSAF	1.02	0.77	0.78
Mtwara Ferry Fish Market Beach (MTF	BCF	0.4	0.18	X
	BSAF	0.30	0.46	X
Mikindani (MK)	BCF	0.5	0.38	X
	BSAF	0.35	0.42	X
Tanga Sahare Fish Market Beach (TSB)	BCF	0.32	0.34	X
	BSAF	0.26	0.28	X
Pangani Fish Market Beach (PFM)	BCF	0.18	0.3	X
	BSAF	0.16	0.89	X
Zanzibar Ferry Beach (ZF)	BCF	0.35	0.45	X
	BSAF	0.62	0.58	X

The presence of phthalates in the protected mangrove forests of Ruvula and Msimbati, which are 43 and 36 kilometres from Mtwara town, respectively, can find support in a study by Mayoma *et al.* (2020) along the Tanzanian coastline, which reported the presence of microplastics. The microplastics could potentially be a source of phthalate contamination in these protected coastal areas (Weideman *et al.*, 2013; Kida and Koszelnik, 2021). The findings indicate that phthalate pollution is a widespread problem along Tanzania's coast and indicates the need for control and monitoring efforts.

The findings of the current study indicate significant associations between phthalates in both seawater and sediment samples, as revealed by Pearson's correlation coefficients (Table 5). The positive correlations between DiBP, DBP, and DEHP suggest that these phthalates originate from similar pollution sources. Notably, the strength of these relationships is stronger in sediment samples (Table 5), suggesting similar adsorption properties of these chemicals in sediments. These observations agree with the literature on phthalate sorption behaviour (Staples *et al.*, 1997). It is commonly recognised that the sorption of phthalate esters (PAEs) to soil, sediment, or suspended solids is influenced by their relative hydrophobicity (Staples *et al.*, 1997). Furthermore, a study in JiangHan Plain reported that DiBP, DBP and DEHP coexisted in soil, sediments, and groundwater (Liu et *al.*, 2013).

Table 5. Person correlation coefficients for diisobutyl phthalate (DiBP), butyl phthalate (DBP), and bis(2-ethylhexyl phthalate) (DEHP) and temperature (TEMP), pH, electrical conductivity (EC), and total dissolved solid (TDS) in seawater and sediment samples. Perfect positive correlation: r = 1, Strong positive correlation: 0.7 ≤ r ≤ 0.99, Slightly positive correlation: 0.4 ≤ r ≤ 0.69, Weak positive correlation: 0.1 ≤ r ≤ 0.39, No correlation: -0.1 ≤ r ≤ 0.1, Weak negative correlation: -0.1 ≥ r ≥ -0.39, Slightly negative correlation: -0.4 ≥ r ≥ -0.69, Strong negative correlation: -0.7 ≥ r ≥ -0.99, Perfect negative correlation: r = -1.

	Parameters	DiBP	DBP	DEHP	TEMP	pH	EC	TDS
Seawater	DiBP							
	DBP	0.66						
	DEHP	0.41	0.77					
	TEMP	0.47	0.53	0.39				
	pH	-0.31	-0.23	-0.16	-0.59			
	EC	-0.14	0.11	0.42	0.12	0.13		
	TDS	-0.34	-0.23	-0.16	-0.59	0.99	0.13	
Sediment	DiBP							
	DBP	0.84						
	DEHP	0.58	0.73					
	TEMP	0.153	0.19	0.17				
	pH	-0.09	0.16	-0.20	-0.01			
	EC	0.16	0.31	0.35	0.48	0.29		
	TDS	-0.199	-0.28	-0.18	-0.03	-0.51	-0.25	

Moreover, it has been shown that dispersion and partition coefficients increase with the carbon chain length of phthalates (Liu *et al.,* 2013). Specifically, the sorption rate of DiBP and DBP was found to be approximately 10 %, compared to 1 % for DEHP (Liu *et al.,* 2013). The findings reported by Liu *et al.* (2013) agree with the strong correlation observed between DiBP and DBP in the present study, as compared to DEHP. By considering the collective evidence from the literature, the findings from this study contribute to the understanding of the fate and behaviour of phthalate contaminants in coastal areas, particularly along the coast of Tanzania.

Comparison with other studies

Table 6 provides a comparison between phthalate concentrations recorded in the current study and other relevant studies from the marine environment in different regions of the world. The table specifically highlights the concentrations of DiBP, DBP, and DEHP in water, sediments and biota. It can be observed in Table 6 that the present study reveals contrasting concentration ranges of phthalates in seawater compared to findings from other studies. Mackintosh *et al.* (2006) found lower concentrations of these phthalates in water from False Creek Harbor, Vancouver. Similarly, Jebara *et al.* (2021) reported relatively lower concentrations along the north-eastern coastline of Tunisia. Sánchez-Avila *et al.* (2012), who investigated the Bay of Biscay in Spain and the Port Sea in the Mediterranean Sea, also observed lower concentrations of these phthalates. Additionally, Fossi *et al.* (2012) who examined the Mediterranean Sea in Italy, reported lower concentrations of these phthalates in studied areas.

Table 6. Comparison of DiBP, DBP, and DEHP concentrations with other studies.

Locations	DiBP	DBP	DEHP	References
Seawater (ng/mL)				
Dar es Salaam	11.53-12.4	13.08-20.63	nd-12.57	This study
Mtawara	3.71-14.35	5.82-11.70	nd	This study
Tanga	4.56-9.56	4.86-9.32	nd	This study
Zanzibar	3.07-9.87	5.23-6.78	nd-3.31	This study
False Creek Harbor, Vancouver	0.005	0.11	0.275	Mackintosh *et al.* (2006)
North-Eastern coastline-Tunisia	0.075	0.017	0.071	Jebara *et al.* (2021)
Bay of Biscay, Spain	-	8.3×10^{-5}	64×10^{-4}	Sa'nchez-Avila *et al.* (2012)
Port sea, Mediterranean Sea, Spain	-	-	0.6×10^{-4}–0.006	Sa'nchez-Avila *et al.* (2012)
Sardinian Sea, Mediterranean Sea, Italy	-	-	0.023	Fossi *et al.* (2012)
Ligurian Sea, Mediterranean Sea, Italy	-	-	0.018	Fossi *et al.* (2012)
Sediment (ng/g dw)				
Dar es Salaam	11.54-13.35	12.09-18.65	nd-12.57	This study
Mtawara	4.56-10.42	4.30-9.71	nd	This study
Tanga	5.12-10.72	5.67-7.87	nd-4.61	This study
Zanzibar	4.72-12.87	4.44.9.54	nd-4.67	This study
Kaohsiung Harbor-Taiwan	21.9 - 69.5	37.3 - 259	259-21,559	Chen *et al.* (2017)
North-Eastern coastline-Tunisia	0.219	0.055	4.594	Jebara *et al.* (2021)
Korean bays	0.011	0.003	0.46	Kim *et al.* (2020)
Korean coast	0.009	0.001	0.38	Lee *et al.* (2020)
False Creek Harbor,Vancouver	0.004	0.103	2.9	Mackintosh *et al.* (2006)
Tropical Western Pacific Ocean	1.87 –14.43	2.24 –12.97	2.01–9.19	Zhang *et al.* (2019)
Biota (ng/g fw)				
A. antiquata, Dar es Salaam	11.82	12.19	5.87	This study
A. antiquata, Mtawara	2.6-2.72	3.53-4.43	nd	This study
A. antiquata, Tanga	1.69-2.61	1.48-3.17	0.87-1.37	This study
A. antiquata, Zanzibar	2.97	3.31	0.86	This study
North-Eastern coastline-Tunisia (ng/g))	0.817	1.771	0.921	Jebara *et al.* (2021)
S. aurata, Mahdia coast (fw basis)		<0.01	<0.0125	Beltifa *et al.* (2017)

A similar trend can be observed in the sediment samples. Chen *et al.* (2017) investigated phthalates in Kaohsiung Harbor in Taiwan, where the concentrations were higher than those reported in this study. Jebara *et al.* (2021) examined phthalates in the north-eastern coastline of Tunisia, while Kim *et al.* (2020) and Lee *et al.* (2020) studied Korean bays and the Korean coast, respectively, showing lower concentrations of phthalates compared to the results obtained in this study. A similar comparison can be observed when results obtained from the present study are compared to those reported by Mackintosh *et al.* (2006) who observed lower levels in the False Creek Harbor, Vancouver. Furthermore, Zhang *et al.* (2019) revealed the presence of different concentrations of these phthalates relative to the present study in the Tropical Western Pacific Ocean.

The potential risk of phthalates in the marine ecosystem

Phthalate esters, like other organic pollutants, undergo alkaline hydrolysis and biodegradation in marine ecosystems. The resulting metabolites from alkaline hydrolysis and biodegradation can have potentially harmful ecological impacts on marine ecosystems (Prasad, 2021; Gao and Chi, 2015). These compounds have the ability to acquire estrogenic activity when exposed to light, leading to the production of 4-hydroxy phthalates. Exposure to phthalates, as well as their metabolites, has been found to reduce fertilization rates in marine organisms, primarily due to their endocrine-disrupting properties (Hu *et al.,* 2020; Miller *et al.*, 2020; Gobas *et al.*, 2003; Burgos-Aceves *et al.*, 2021).

The findings of this study on the bioconcentration of phthalates in *A. antiquata* are consistent with studies that have reported significantly varying concentrations of phthalates amongst different marine biota (Miller *et al.*, 2020; Sun *et al.*, 2021; Rios-Fuster *et al.*, 2022) (Table 6). As a filter feeder, *A. antiquata* can accumulate phthalates in their tissues from the water they filter (Miller *et al.*, 2020). *A. antiquata*, similar to other bivalves, can also ingest sediment particles along with the associated phthalates, leading to bioconcentration (Miller *et al.*, 2020). The bioconcentration of phthalates in marine ecosystems has implications for human health and the environment as they potentially affect the health of the animals and the wider food web (Gobas *et al.*, 2003).

The bioconcentration of phthalates in marine ecosystems could also have broader ecological implications such as disruption of marine diversity and abundance of marine organisms as a result of their impact on the endocrine system and on reproduction and development of organisms (Gobas *et al.*, 2003; Burgos-Aceves *et al.*, 2021). Furthermore, with regards to biota contamination, Jebara *et al.* (2021) investigated the north-eastern coastline of Tunisia and reported lower concentrations of phthalates in fish when compared to the concentration in *A. antiquata* obtained in the present study. Beltifa *et al.* (2017) examined *S. aurata* along the Mahdia coast and found lower concentrations of these phthalates. The current findings underscore the importance of taking measures to reduce the use and release of phthalates into the environment to safeguard the health of both marine and human life.

Environmental and policy implications of the results

The differences in phthalate concentrations observed between the current study and other studies indicate the impact of regional and local factors on contamination levels. Factors such as industrial activities, waste disposal practices, and proximity to pollution sources can contribute to the differences in phthalate levels.

The correlation analysis conducted on marine sediment and seawater samples along the Tanzanian coastline revealed no strong correlation between phthalates. The interpretation of correlation coefficients alone does not provide definitive evidence of pollution sources. However, the coefficients indicate potential associations between phthalates (DBP and DEHP) and their occurrence in the analysed samples. To gain an understanding of the pollution sources of phthalates, further investigations that extend beyond the scope and limitations of the current study are needed. Source identification studies, including source apportionment modelling (Giglioli *et al.*, 2021) and chemical fingerprinting (Lorgeoux *et al.*, 2016), can offer valuable insights into pinpointing specific pollution sources of phthalates in the environment. These additional approaches would contribute to a more accurate assessment of the origins and factors influencing phthalate contamination.

Despite no universally acceptable worldwide guideline for all phthalates, the concentrations of DBP, DiBP, and DEHP in sediments and seawater revealed in this study are a cause for concern as they exceed the minimum allowable concentrations established by various independent environmental regulatory authorities. For example, in China, DBP and DEHP in drinking water should not exceed 3 and 8 ng/mL, respectively (Ministry of Health of the People's Republic of China, 2006). On the other hand, the National Environment Management Council (NEMC) and Tanzania Bureau of Standards (TBS) have not set limits for Tanzania. It is crucial to note that phthalates are harmful to both the environment and human health, and can be detrimental even at low exposure levels. High concentrations of phthalates can have severe effects on human health and the environment, such as harming aquatic life, disrupting the endocrine system, and impacting reproduction and development (Chen *et al.*, 2020).

It is critical to consider the possible danger posed by phthalates and to reduce their concentrations in the environment. The marine ecology of the WIO is a vital component of the biodiversity of our planet, and any negative impacts on it could have repercussions on the larger ecosystem and ultimately on human populations that depend on the resources the ocean provides. In this regard, it is essential that environmental stakeholders and pertinent authorities in the WIO region work together to address this issue. Relevant government agencies in Tanzania may create suitable guidelines to regulate the use and disposal of phthalate-containing materials/products to protect community health and the environment. Furthermore, close monitoring and enforcement of these guidelines, and collaboration with other stakeholders to create public awareness about the potential health risks of phthalate exposure are required.

Conclusions

This study revealed that three phthalates, DiBP, DBP, and DEHP, were prevalent in seawater, sediments and *A. antiquata* collected from the sampling sites in Dar es Salaam, Tanga, and Zanzibar, while DiBP and DBP were prevalent in Mtwara. The Dar es Salaam coast had a significantly higher prevalence of phthalates compared to the other sites. The concentrations of DiBP, DBP, and DEHP exceed the maximum allowable levels established by environmental regulatory authorities in some parts of the world, raising concerns about their potential harm to the environment and human health. The high levels of phthalates in the studied WIO region can be linked to the high density of anthropogenic activities, including industries, agricultural activities, and other waste-producing domestic activities. Therefore, it is crucial for appropriate stakeholders and relevant regulatory authorities to work collectively towards reducing the concentrations of phthalates in the environment by developing and enforcing appropriate regulations and creating public awareness.

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Original Article

Seasonal variation in mineral concentrations of four marine fish species retained by fishers in Vanga and Msambweni, Kenya

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Abstract

Marine fish is a rich source of minerals in the diet of humans, but seasonal variation in fish mineral concentrations is relatively unstudied. We investigated seasonal mineral concentrations among four marine fish species retained by small scale fishers in Msambweni and Vanga fishing villages in Kenya. The fish species were *Siganus sutor* (rabbitfish) in Msambweni and *Decapterus macarellus* (mackerel scad), *Sphraena forsteri* (bigeye barracuda) and *Sphyraena obtusata* (obtuse barracuda) in Vanga. Mineral concentrations were quantified in 120 fish specimens (60/season) and their mineral supplementation potential evaluated. The concentrations of Potassium (K), Magnesium (Mg), Zinc (Zn), Iron (Fe) and Iodine (I) were determined using Inductively Coupled Plasma Optical Emission Spectrometry. K, Mg, Zn and I levels in fish samples varied between seasons with higher concentrations during the wet and cool southeast monsoon (SEM) season (April to October). However, Fe concentration was significantly higher during the dry and warm northeast monsoon (NEM) (November to March). *S. fosteri* recorded the highest concentrations of Mg (72.29 mg/100g in SEM) and Fe (3.63 mg/100g in NEM). *S. sutor* was the richest source of K (410.21 mg/100g in SEM). These two species also recorded the highest concentration of I (57.6 µg/100g in SEM) while *D. macarellus* had the highest Zn concentration (5.84 mg/100g in SEM). Mineral concentrations were dependent on fish species as well as season, influencing the mineral intake in Msambweni and Vanga villages.

Keywords: fish minerals, seasonal variation, small-scale fisheries, south coast of Kenya

Introduction

Micronutrients refer to minerals and vitamins required by the body in trace amounts but their impact on overall body health is critical (Awuchi *et al*., 2020). Micronutrient deficiency is a universal subject with specifically higher prevalence rates in underdeveloped nations (Abeywickrama *et al*., 2018) with wide spread impacts exhibited in vulnerable groups such as children, women, the middle and old aged (Tulchinsky, 2010). Nutritional deficiency has been observed to be most regular in underdeveloped regions of sub-Saharan Africa and South Asia (Black *et al*., 2013). An estimated two billion people worldwide and one out of three people in developing countries are affected by vitamin and mineral deficiencies, particularly Zinc, Iron and Iodine making them susceptible to diseases such as anaemia and goitre (Abeywickrama *et al*., 2018; Borwankar *et al*., 2007).

Available data shows high prevalence rates for specified micronutrient deficiency for Potassium, Magnesium, Iron, Zinc and Iodine in a large portion of the population especially in developing countries, which are key elements for normal body functioning (Abeywickrama *et al.*, 2018; Fiorentini *et al.*, 2021; Kumssa *et al.*, 2021). Potassium regulates blood pressure, muscle contraction and stimulates effective transmission of nerve impulses which is necessary for effective functioning of nerves within the human body (Mogobe *et al.*, 2015; Kumssa *et al.*, 2021). Iron is key for the synthesis of haemoglobin in red blood cells which increases the efficiency of oxygen transport to all body parts (Alas *et al.*, 2014). Zinc plays an important role in enzyme reactions as well as cell growth and division (Alas *et al.*, 2014; Mohanty and Singh, 2018). Iodine from marine fish is necessary for thyroxine hormones which regulate body metabolism, shields against goitre, and in children it is a requirement for normal growth and mental development (Pal *et al.*, 2018). Magnesium plays a crucial role in various physiological functions such as protein synthesis, membrane integrity, hormone secretion, nerve function, blood pressure regulation, and various metabolic processes (Schwalfenberg and Genuis, 2017). Marine fish are rich sources of these essential mineral elements when consumed in adequate amounts (Zaman *et al.*, 2014).

Fish is an essential nutrient dense animal food source for numerous households in the world (Ajayi, 2016; Reksten *et al.*, 2020b). The nutritional composition of fish plays a role in promoting the health of consumers in both developed and third world countries (Béné *et al.*, 2015). Fish supplies crucial micronutrients including minerals, fatty acids and vitamins which are imperative to prevent malnutrition (Bennet *et al.*, 2018; Chan *et al.*, 2019). Fish is an essential source of minerals such as Calcium, Phosphorus, Potassium, Magnesium, Zinc, Iron, Fluorine, Selenium and Iodine (Ahmad *et al.*, 2018). These mineral elements contribute to stimulation of metabolic and physiological activities, subsequent growth and development and maintaining proper health of living organisms (Abdulkarim *et al.*, 2015). Insufficiency of mineral elements in the human body causes mineral deficiency diseases such as anaemia, goitre, genetic disorders, poor growth and development (Bhandari and Banjara, 2014: Mogobe *et al.*, 2015).

Fish are a rich source of minerals which they absorb from water and the feed material they consume (Lall and Tibbetts, 2009). Mineral composition of marine fish is relatively higher compared to freshwater fish and can differ according to season as well as biological traits (Nurnadia *et al.*, 2013; Palanikumar *et al.*, 2014). Composition of minerals in marine fish species ranges between 0.1 to 1.5 % of individual wet weight (Nurnadia *et al.*, 2013). However, geographical locations and seasons influence feed composition, which consequently affect the biochemical composition of fish muscle including mineral concentrations (Olgunoglu *et al.* 2014; Shija *et al.*, 2019). Further, findings by Aldulkarim *et al.* (2015) show that mineral content of marine fish is influenced by climatological differences between the warm and dry northeast monsoon (NEM) and the wet and cool southeast monsoon (SEM) seasons. Fish mineral levels are largely determined by the availability of nutrients in water and the type of diet, which varies with seasons (Khitouni *et al.*, 2014). Marine fish do not supply the same level of nutrients throughout the year (Barkat *et al.*, 2022).

Artisanal fisheries form a fundamental source of food for many regions, especially developing nations (Thilsted *et al.*, 2016; Lancker *et al.*, 2019). Along the Kenya coast, these fisheries support over 13,000 small scale fishers (Fondo *et al.*, 2014: Wanyonyi *et al.*, 2017). Fish forms an integral part of the diet among local residents along the Kenyan coast (Mwakaribu *et al.*, 2022). On the south coast in particular which is an active fishing area, fish harvested by artisanal fishers are especially salient for the overall health of local inhabitants (Agembe *et al.*, 2010). Without it, natives could not afford to consume sufficient proteins, omega-3 fatty acids, or crucial micronutrients such as vitamin A, Iron, Calcium, Potassium, Magnesium, Zinc and Iodine on a regular basis. However, no information is available on mineral composition of *Siganus sutor*, *Decapterus macurellus*, *Sphyraena forsteri* and *Sphyraena obtusata* which are among the most retained fish species from the artisanal fisheries on the south coast of Kenya (Mwakaribu *et al.*, 2022). Taking into consideration the importance of fish in maintaining human health, this study determined the seasonal concentrations of K, Mg, Zn and I in fish samples, and assessed the potential of fish as a remedy for mineral deficiency. This study hypothesized that mineral concentration in fish samples is influenced by season and species type.

Materials and methods

Study area

This study was conducted in Msambweni and Vanga fishing areas on the south coast of Kenya. Msambweni is located more than 50 km from the city of Mombasa, situated at S 04046'53", E 039048'13" and Vanga further south at the border with Tanzania situated at

S 04039'37", E 039013'11" (Ogongo *et al.*, 2015; Fig. 1). Both sites started as small fishing villages but have been developing rapidly over time, characterized by improved infrastructure and increasing population. The sites are among the most active fishing areas in Kenya where the artisanal fishery is considered a major source of livelihood (Agembe *et al.*, 2010). Fishing grounds in these areas have been reported to be rich in biological diversity and provide a vital food source and boosts the economy and wellbeing of the local fishing communities (KCDP, 2016). Fishing activities mainly occur within nearshore reef lagoons characterised by artisanal multi-gear and multi-fleet operators targeting and landing multiple species (Agembe *et al.*, 2010), and are highly influenced by the NEM and SEM seasons.

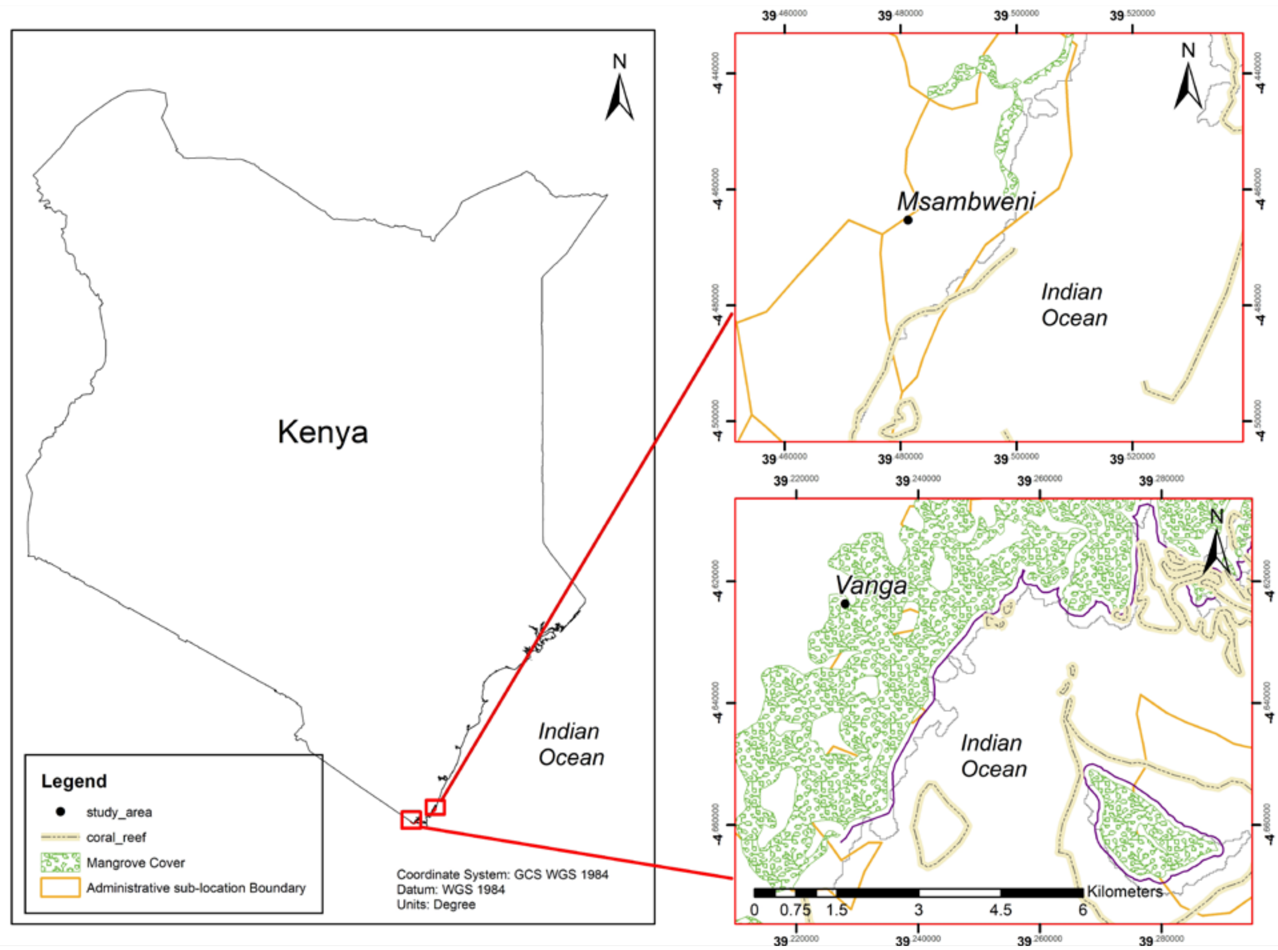

Figure 1. Location of Msambweni and Vanga fishing areas, south coast of Kenya, where retained fish for household consumption was monitored over the study period (Mwakaribu *et al.*, 2022).

Data collection

Fish sampling and preparation for mineral analysis

Following one year of shore-based catch assessments, *Siganus sutor* from Msambweni, *Decapterus macarellus*, *Sphraena forsteri* and *Sphyraena obtusata* from Vanga were identified as the most retained fish species for local home consumption (Mwakaribu *et al.*, 2022.). A total of 60 fresh specimens were randomly collected from the respective fish landing sites adding up to 120 specimens sampled in both NEM and SEM season. Sampled fish specimens were measured for individual total length (TL) (cm) and weight (g), gutted, cleaned, wrapped in plastic foil to maintain freshness, labelled, and transported in polystyrene cooler boxes topped with ice to the Kenya Marine and Fisheries Research Institute (KMFRI) for further analysis in the natural products and postharvest technology laboratory.

Seasonal mineral content composition of K, Mg, Zn, Fe and I in the sampled fish specimens was determined according to the Association of Official Analytical Chemists (AOAC) analysis method (AOAC, 2012; Kiczorowska *et al.*, 2019). Inductively Coupled

Plasma Optical Emission Spectrometry (ICP-OES) was used to quantify the mineral levels. In the laboratory, the samples were washed with deiodized water, deboned, head and fins removed, filleted (AOAC, 2000), followed by pounding fleshy portions of the fish using a porcelain crucible. During the procedure for mineral quantification of K, Mg, Zn and Fe, 2.5 g of pounded fish flesh was weighed using an analytical weighing balance, ground in porcelain crucible then dried using a hot plate. Afterwards, the samples were incinerated at 550 ^{0}C overnight using a muffle furnace and then treated with 5 ml 6 M hydrochloric acid (HCl), and 10 ml of 0.1 M nitric acid (HNO_3) (AOAC 2012: Mogobe *et al.*, 2015; Njinkoue *et al.*, 2016). For Iodine quantification, 0.2 g of fish sample was weighed and then treated with 5 ml of 6 M nitric acid and 2 ml concentrated hydrogen peroxide before being mounted on a microwave digester. The solutions were left for a duration of 2 hours before being transferred to volumetric flasks topped with 50 ml ultra-pure water and used for determination of mineral content (Mogobe *et al.*, 2015).

Data and statistical analyses

Sizes of sampled fish specimens were subjected to statistical test to determine differences in fish sizes between seasons using 1-way ANOVA for parametric data and the Kruskal-Wallis test for non-parametric data. For mineral content analysis, 1-way ANOVA was also used to test for significant differences in fish mineral concentration in sampled fish species between seasons. STATISTICA version 7 statistical software was used for the statistical tests at a significance level of $p < 0.05$, and homogeneity of variances confirmed using the Levene's test accepted at $p > 0.05$ as a requirement for using the ANOVA parametric test.

Results

Size variation of randomly sampled fish specimens

Sizes of the fish specimens varied between seasons (Table 1). *Sphyraena obtusata* and *Decapterus macarellus* were significantly larger in SEM compared to NEM season (1-way ANOVA, $p < 0.05$ in both cases). Results of 1-way ANOVA confirmed that *Siganus sutor* were larger in the NEM season than SEM season (df = 1, f = 51.340, p = 0.000). Kruskal-Wallis test indicated that *Sphyraena forsteri* were significantly larger in the NEM season than SEM season (p = 0.000).

Mineral concentration of sampled fish specimens

Results of mineral concentration varied widely among these fish species and to some extent concentrations differed between the seasons (Table 2). Seasonal variability of K, Mg, Zn, Fe and I levels in fish samples was evident.

Mineral concentration in *Sphyraena obtusata*

Results of 1-way ANOVA indicated that Fe concentration was significantly higher in the warm NEM season (2.59 ± 0.024 mg/100g) than in the wet SEM season (0.64 ± 0.016 mg/100g) (df =1, f = 4382.580, p = 0.000). The same test confirmed that K concentration was significantly higher in the SEM season (384.25 ± 3.051 mg/100g) than the NEM season (255.57 ± 2.627 mg/100g) (p = 0.000). Mg concentration was higher in SEM than NEM but not significantly different (Kruskal-Wallis test (p = 0.070). Zn concentration was significantly higher in SEM than NEM (2.69 ± 0.034; 1.45 ± 0.006 mg/100g) (Kruskal-Wallis: p = 0.000). Similar I concentration of 13.48 ± 0.807 mg/100g and 14.93 ± 0.793 mg/100g were recorded for NEM and SEM, respectively and this was not significantly different (1-way ANOVA: df = 1, f = 1.631, p = 0.210) (Table 2).

Table 1. Mean ± SE total length and weight of fish specimens sampled for mineral content analysis. The symbol * indicates a statistically significant difference at $p < 0.05$.

Species	Common name	Area	Mean Weight (g)	Mean Length (cm)	n
Siganus sutor	Rabbitfish	Msambweni	320 ± 16.7 (NEM) *vs* 172.3 ± 12.7 (SEM)	28.8 ± 0.55 (NEM) *vs* 22.8 ± 0.60 (SEM)*	30
Sphyraena forsteri	Bigeye barracuda	Vanga	34.3 ± 0.8 (NEM) *vs* 25.6 ± 1.9 (SEM)	18.7 ± 0.08 (NEM) vs 16.6 ± 0.36 (SEM)*	30
Sphyraena obtusata	Obtuse barracuda	Vanga	49.8 ± 5.1 (NEM) *vs* 132.1 ± 11.4 (SEM)	21.3 ± 0.80 (NEM) vs 31 ± 1.01 (SEM)*	30
Decapterus macarellus	Mackerel scad	Vanga	41.9 ± 0.1 (NEM) *vs* 66.2 ± 1.8 (SEM)	16.8 ± 0.14 (NEM) vs 19.0 ± 0.16 (SEM)*	30

Table 2. Results of seasonal mineral composition by fish species sampled over the study period. The symbol * indicates a statistically significant difference at $p < 0.05$.

Species	K(mg/100g)	Mg(mg/100g)	Zn(mg/100g	Fe(mg/100g)	I(µ/100g)
S. obtusata	255.57 ± 2.627 (NEM) vs 384.25 ± 3.051 (SEM)*	36.23 ± 0.807 (NEM) vs 38.30 ± 0.366 (SEM)	1.45 ± 0.006 (NEM) vs 2.69 ± 0.034 (SEM)*	2.59 ± 0.024 (NEM) vs 0.64 ± 0.016 (SEM)*	13.48 ± 0.807 (NEM) vs 14.93 ± 0.793 (SEM)
D. macarellus	242.12 ± 3.548 (NEM) vs 304.19 ± 2.759 (SEM)*	35.26 ± 0.752 (NEM) vs 47.56 ± 0.509 (SEM)*	1.49 ± 0.035 (NEM) vs 5.84 ± 0.054 (SEM)*	2.31 ± 0.029 (NEM) vs 2.06 ± 0.024 (SEM)*	13.87 ± 0.213 (NEM) vs 18.33 ± 0.412 (SEM)*
S. forsteri	246.25 ± 4.716 (NEM) ± 382.28 ± 3.802 (SEM)*	33.42 ± 0.658 (NEM) vs 72.29 ± 1.525 (SEM)*	2.69 ± 0.017 (NEM) vs 4.51 ± 0.107 (SEM)*	3.63 ± 0.021 (NEM) vs 1.52 ± 0.032 (SEM)*	14.04 ± 0.165 (NEM) vs 17.53 ± 0.240 (SEM)*
S. sutor	248.73 ± 3.109 (NEM) vs 410.21 ± 3.546 (SEM)*	26.63 ± 0.320 (NEM) vs 57.96 ± 0.926 (SEM)*	0.65 ± 0.023 (NEM) vs 3.79 ± 0.051 (SEM)*	2.75 ± 0.037 (NEM) vs 2.76 ± 0.038 (SEM)	35.40 ± 0.859 (NEM) vs 57.60 ± 1.679 (SEM)*

Mineral concentration in *Decapterus macarellus*

The concentration of Fe in *D. macarellus* was significantly higher in NEM (2.31 ± 0.029 mg/100g) than SEM season (2.06 ± 0.024 mg/100g) (1-way ANOVA: df = 1, f = 44.000, p = 0.000). K and Mg concentrations were significantly higher in SEM season than NEM season (Kruskal-wallis test: p = 0.000 for both cases). Zn concentration was significantly higher in SEM (5.84 ± 0.054 mg/100g) than NEM (1.49 ± 0.035 mg/100g) (1-way ANOVA: df = 1, f = 10.760, p = 0.000). The concentration of I was also significantly higher in SEM than NEM (1-way ANOVA: df = 1, f = 104.990, p = 0.000) (Table 2).

Mineral concentration in *Sphyraena forsteri*

The concentration of Mg in this fish species was significantly higher in SEM (72.29 ± 1.525 mg/100g) than NEM (33.42 ± 0.658 mg/100g) (1-way ANOVA: df = 1, f = 720.940, p = 0.000). For this species I concentration was also higher in SEM (17.53 ± 0.240 mg/100g) than NEM (14.04 ± 0.165 mg/100g) (1-way ANOVA: df = 1, f = 155.94, p = 0.000). The Kruskal-Wallis test confirmed that K, Fe and Zn concentrations were significantly higher in SEM than NEM season ($p < 0.05$ in all cases) (Table 2).

Mineral concentration in *Siganus sutor*

In this species Fe concentration was similar in both seasons (2.75 ± 0.037; 2.76 ± 0.038 mg/100g for NEM and SEM, respectively). The concentrations of K, Mg, Zn and I were significantly higher in SEM than NEM (1-way ANOVA: $p < 0.05$ in all cases) (Table 2).

Discussion

In reference to the recommended dietary intake for minerals (DRI, 2001; World Health Organization, 2004), this study confirmed that *S. sutor* (rabbitfish), *D. macarellus* (mackerel scad), *S. forsteri* (bigeye barracuda) and *S. obtusata* (obtuse barracuda) are an essential source of K, Mg, Zn, Fe and I. However, the concentrations of these minerals in the selected fish species was largely influenced by species type and seasons. This confirms to the work of Varljen *et al.* (2013) and Abdulkarim *et al.* (2015) who revealed that fish do not supply similar concentrations of minerals to consumers, as nutritive value of fishes differ with species and seasons. The present study therefore allows the hypothesis to be accepted that the levels of K, Mg, Zn, Fe and I are indeed significantly influenced by fish species and seasons. Varying climatological conditions between the warm northeast monsoon (NEM) and cool southeast monsoon (SEM) seasons may have caused the variation in concentration of minerals in the selected fish species. Similar variations in fish mineral concentration were also reported by Abdulkarim *et al.* (2015) who further asserted that season is an important factor that alters the mineral concentration in fish considerably. In all fish species investigated in the present study, K was the most dominant mineral followed by Mg. The lowest recorded mineral concentration in fish specimens in this study were I, Fe and Zn. Similar studies by Reksten *et al.* (2020a) and Nordhagen *et al.* (2020) also observed lower concentrations of these three minerals in fish muscles compared to Mg, K, Ca and Na concentrations. Zn concentration ranged between 0.5 and 6.13 mg/100 g which is similar to results reported by Nurnadia *et al.* (2013) and Zaman *et al.*, (2014).

Among the sampled species, Potassium concentrations ranged between 242 and 410 mg/100 g. The results agree with findings by Nordhagen *et al.* (2020) whose K concentration in fish ranged between 177 and 513 mg/100 g. Findings by Reksten *et al.* (2020a) on

Potassium content in fish were within the same range. K concentration in the four selected species was significantly higher in the SEM season compared to NEM season. Abdulkarim *et al.* (2015) reported that macro minerals such as K and Mg were higher in the wet season than the dry season. The species *S. sutor* had the highest concentration of Potassium compared to the other species with concentration ranging between 248 and 410 mg/100 g. A similar study by Wahyuningtyas *et al.* (2017) reported that *S. sutor* is a richer source of K than Mg, Fe and Zn. Adequate levels of K in *S. sutor* makes it a preferable diet for K supplementation especially for pregnant and lactating women who require levels of 4,000 mg/day and 4,400 mg/day, respectively (Strohm *et al.*, 2017). *S. forsteri*, *S. obtusata* and *D. macarellus* are also key sources for K with sufficient levels ranging between 304 to 384 mg/100 g in the wet and cool SEM season.

The Mg concentration in all the sampled species across the study sites ranged between 26.6 and 72.2 mg/100 g. Results of this study agree with the findings of Reksten *et al.* (2020a) who reported Mg concentration in fish muscles ranging between 29 and 75 mg/100 g. These results were also similar to findings of Nordhagen *et al.* (2020) who found Mg concentrations in fish muscles ranging between 18 and 57 mg/100 g. However, Mg concentrations in the present study were significantly higher during the wet and cool SEM season ranging between 38 and 72 mg/100 g. A study conducted by Abdulkarim *et al.* (2015) revealed the same results which indicated Mg concentration in *Rastrineobola argentea* to be 72.96 mg/100 g in SEM season and 54.73 mg/100 g in the warm NEM season. The species *S. forsteri* had the highest Mg concentration of 72.2 mg/100 g during the SEM season making it a suitable supplement for Mg. This species could be a suitable dietary component for active male adults who require Mg concentrations of 420 mg/day, children who require Mg concentrations ranging between 80 mg/day and 240 mg/day depending on their age, pregnant mothers who need 360 mg/day and lactating mothers who require 400 mg/day (Grober *et al.*, 2015). *S.sutor*, *S.forsteri* and *D.macarellus* are also preferable sources of Mg with concentrations of between 26 and 57 mg/100 g and are also more nutritious during the SEM season compared to NEM season.

Zn composition in all the selected fish samples ranged between 0.64 and 5.84 mg/100 g. These results were in line with those presented by Nurnadia *et al.* (2013), and Kawarazuka and Bennet (2011) where Zn content in fish species ranged between 0.15 and 20 mg/100 g. Wahyuningtyas *et al.* (2017) also reported the mean Zn concentration in *Siganus sutor* to be 1.13 mg/100 g, which matches these results where Zn in *S.sutor* ranged between 0.65 and 3.79 mg/100 g. *D.macarellus* had the highest zinc content (1.49-5.84 mg/100 g) compared to the other species making it a good meal to supplement zinc deficiency. Findings of Khalaf *et al.* (2012) also indicated that *D.macarellus* which recorded zinc levels of between 0.95 and 14.3 mg/100 g, is a better source of Zn compared to *D. macrosoma* and *D.russelli*. This makes *D.macarellus* a good choice of meal for children who require between 12 and 23 mg/day of Zn subject to their age, teenagers who need 34 mg/day and all adults including pregnant and lactating mothers who need 40 mg/day for effective normal body functioning (Institute of Medicine, Food and Nutrition Board, 2001).

Fe content among the studied fish samples ranged between 0.64 and 3.63 mg/100 g with significantly higher concentrations in the warm NEM season. Palanikumar *et al.* (2014), Zaman *et al.* (2015), Reksten *et al.* (2020a), Reksten *et al.* (2020b) and Nordhagen *et al.* (2020) reported similar results ranging from 0.2 and 7.01 mg/100 g. Palanikumar *et al.* (2014) further reported the mean Iron concentration in *S.obtusata* species to be 0.05 mg/100 g. However, *S.forsteri* recorded the highest Fe concentration of 3.63 mg/100 g thus forming a preferable part of the diet especially for lactating mothers who require 10 mg/day, pregnant mothers who require 27 mg/day and females who require between 15 and 18 mg/day to make up for the iron lost during their menstruation period (Clifford *et al.*, 2015). *S.obtusata*, *D.macarellus* and *S.sutor* are also recommended dietary items to prevent iron deficiency due to their significant concentrations of Fe ranging between 0.64 and 2.76 mg/100 g.

Iodine (I) content in selected fish specimens ranged between 13.48 and 57.60 µg/100 g. Nordhagen *et al.* (2020) reported similar results where I levels in various fish species ranged between 6.7 and 160 µg/100 g. Previous studies by Reksten *et al.* (2020a) and Reksten *et al.* (2020b) also reported similar concentrations of I in fish ranging between 22 and 280 µg/100 g. In the selected fish species for this present study, *S.sutor* showed the highest levels of I, followed by *D.macarellus*, *S.forsteri* and *S.obtusata* in that order. All these species can be used as key dietary constituents to prevent I deficiency especially in pregnant mothers who require 220 µg/day and lactating mothers who need 290 µg/day (DRI, 2001; Alvarez-Pedrerol *et al.*, 2010).

All these species were richer in I during the wet and cool SEM season than the warm NEM. Albdulkarim *et al.* (2015) also reported that fish are richer in I during the wet season compared to the dry season. *S.sutor* highly recommended for pregnant and lactating mothers due to their high concentrations of Iodine.

All the sampled fish species in this present study were found to be richer in minerals during the wet and cool SEM than warm and dry NEM season. This could be attributed to the availability of more nutrients and dietary materials as well as an increase in minerals washed into the sea from land through various freshwater inlets (Abdulkarim *et al.*, 2011; Abdulkarim *et al.*, 2015). For Vanga, long rains during the SEM season are linked to high nutrient influx from the river Umba, Mwena and Ramisi into Vanga and Jimbo fishing grounds (Opello *et al.*, 2006; Wanyonyi *et al.*, 2017). However, Fe content for *D.macarelus*, *S.obtusata* and *S.forsteri* was significantly higher in the NEM season than the SEM season but *S.sutor* content was unaffected by these seasons. According to Kessler *et al.*, 2020, dust, which is higher in the warm and dry NEM season compared to the wet and cool SEM season is a very important source of Fe to the ocean. Additionally, Fe content in fish muscles could be higher, lower or unaffected by seasons depending on the geographical conditions Abdulkarim *et al.* (2011).

Conclusions

This study reveals that fish is a rich source of K, Mg, Zn, Fe and I which has the potential to contribute to good nutrition of local fishing communities if consumed in adequate amounts. As a result, fish intake can be used to combat malnutrition and remedy various nutritive deficiencies and health problems. However, only small amounts of fish are retained for home use by artisanal fishers in both Msambweni and Vanga (Mwakaribu *et al.*, 2022). The variability in fish mineral concentration is dependent on fish species as well as the seasonal dynamics. Selected fish elemental analysis indicated that marine fish are richer in minerals during the SEM than the NEM season. Conversely, Fe content in fish is higher in NEM than SEM season. The local fishing communities on the south coast of Kenya could increase fish consumption to supplement deficiencies for K, Mg, Zn and I, especially during the SEM season, and Fe deficiency during the NEM season. This study should be extended to the entire Kenya coast focussing on a wide range of fish species in order to identify the best species to supplement particular mineral deficiencies and the best time to consume more fish.

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Original Article

River discharge, fishing effort and catch composition of prawn fisheries in coastal Tanzania

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Abstract
This study examined the relationships between river discharge, fishing effort and catch composition of prawn fisheries in coastal Tanzania. Key assumptions were that river discharge would be a good indicator of rainfall and that the number of fishing vessels would reflect fishing intensity. We investigated whether reduced river discharge or increased fishing effort caused the collapse of the industrial prawn fishery in 2007, and which of these factors delayed recovery prior to reopening the fishery in 2017. The analysis showed a positive relationship between Catch Per Unit Effort (CPUE) and river discharge, with decreased river flow resulting in reduced prawn catches. The number of fishing vessels had little impact on CPUE before 2003, but thereafter CPUE declined even when fishing effort was reduced by 50%. A shift in trawl catches from a prawn-dominated fishery to a fish-dominated fishery was observed four years before the collapse. The trend in river discharge persisted below average (22 m^3/s) between 2000 and 2007. Forewarning of low river discharge, changing trawl catch composition, and increasing effort may have led to developing proactive strategies to minimise the impact of a changing regime on fish stocks and dependent communities. We recommend establishing a monitoring system to anticipate similar events in the future.

Keywords: industrial fisheries, prawn species, overfishing, fisheries management

Introduction
Fluctuations in prawn catch are a worldwide concern (Schlenker *et al.*, 2023; Silas, 2011); recently, these have been attributed to the growing influence of anthropogenic pressures, including pollution, mangrove cover loss, reduced river flow, erratic rainfall patterns, and climate change (Cheung *et al.*, 2012; Gammelsrød, 1992; Hoguane, 2012; IPCC, 2021; Kasan *et al.*, 2023; Perry *et al.*, 2005; Schilling *et al.*, 2023; Silas *et al.*, 2023). Like many other aquatic organisms, prawns are highly sensitive to environmental changes. Their relatively short lifespan further exacerbates their vulnerability to these varying conditions (Silas, 2011). The studies by Turschwell *et al.* (2022) and Blamey *et al.* (2022) have highlighted the intricate relationship between prawns and their habitat, indicating that even slight alterations in environmental parameters can have far-reaching consequences on their populations. As such, the fluctuations in prawn catch are not solely due to natural variations but are deeply rooted in human-induced disturbances to their ecosystems.

Given the intricate relationship between prawns and their environment and the numerous anthropogenic pressures they face, managing prawn populations has become an arduous task. Balancing the economic interests of fisheries and the ecological well-being of prawn populations requires comprehensive strategies that address the root causes of fluctuations. Finding solutions to mitigate the impact of anthropogenic pressures while safeguarding sustainable growth of prawn populations present a significant challenge to fisheries management (Silas, 2011; Turschwell *et al.*, 2022). This study aimed to delve into the complexities surrounding fluctuating prawn catches in Tanzania, shedding light on the underlying causes and potential implications, and proposing avenues for effective and sustainable management in the face of such challenges.

The prawn fishery is an important economic activity supporting Tanzania's economy and the livelihood of coastal communities (Malauene *et al*., 2021; Silas, 2011; Swaleh *et al*., 2015). Despite the benefits provided, this fishery was closed in 2007 due to low catches of all prawn species common in Tanzania (Appendix 1). Before the closure however, industrial fishers had already begun to reduce their fishing vessels since 2004 (Silas, 2011; TAFIRI, 2021). In 2007, the Ministry of Livestock and Fisheries of Tanzania banned industrial prawn fishing to allow the diminished stock to recover (Mwakosya *et al*., 2010). In 2017, a decade after the ban, the prawn fishery was reopened with improved measures to ensure long-term sustainability (TAFIRI, 2021). These additional regulations included a closed fishing season between September and March for the northern fishing grounds (encompassing Bagamoyo and Pangani) and between August and April for the southern fishing grounds (including Kilwa and Kisiju) (Fig. 1). Also, fishing vessels were limited to four on each of the two major fishing grounds (MLF, 2022). Furthermore, following the reopening, previously established management measures that were in effect before the closure in 2007, including limitation on fishing operations to a 12-hour window during daylight to prevent unregulated practices at night, the imposition of a vessel capacity not exceeding 500 HP, and the strict prohibition of tickler chain usage were also reinstated for improved sustainability (MLFD, 2009; Silas, 2011).

Since prawns have a high fecundity rate, between 40 000 to 320 000 eggs (Teikwa and Mgaya, 2003), after a short period of closure, it could have been expected that the population of prawns would bounce back; however, the recovery took a decade (i.e., from 2007 to 2017) (Mwakosya *et al*., 2010; TAFIRI, 2021). Assessing other factors that might have been at play or contributed to prawn collapse and possibly a delayed recovery is vital. For Tanzania, research studies that examine factors linked to prawn catch are scarce, and the available studies are restricted to some bays (Mosha and Gallardo, 2013; Semba *et al*., 2016). Consequently, extrapolating the findings to the entire coastline is challenging. For instance, Mosha and Gallardo (2013) highlighted how salinity affects prawn availability and abundance in the Pangani estuarine environment, whilst Semba *et al*. (2016) examined the relationship between phytoplankton and prawn productivity in the Rufiji delta, both studies being confined to a local area; however, effective management requires a broader understanding of varying conditions and habitats where organisms are found (Silas *et al*., 2023).

In that regard, limited information on factors affecting prawn catches at a larger scale, for example, in coastal Tanzania, creates a challenge for managers. Without a comprehensive understanding of the factors determining prawn catches and availability at a larger scale, they have no choice but to rely solely on input control measures, including traditional effort controls. This is because other management options, such as habitat restoration and pollution control, require a better understanding of the factors involved (Farmery *et al*., 2015; Swaleh, *et al*. 2015). This article aims to fill the knowledge gap regarding the long-term trend of prawn harvests and their relationship with precipitation patterns. To achieve this, river discharge was examined as a proxy for rainfall patterns to determine whether changes in prawn catches were associated with river discharge before the closure of the prawn fishery in 2007. Doing so provides a more comprehensive understanding of the factors influencing prawn availability beyond fishing pressure. This knowledge is essential for improved prawn resource management and may help to explain the delayed recovery a decade after the moratorium in 2007.

Materials and Methods

Study area

The three main prawn-fishing zones on Tanzania's coastline are examples of the nation's abundant and diverse aquatic life, and they also provide habitat for other fisheries like sardines (Silas, 2022). Zone 1 is situated in the northern part of the coast, close to Bagamoyo and Saadani, and estuarine conditions are supported there by the Pangani, Wami and Ruvu rivers, which originate from the Kilimanjaro and Nguru mountain ranges, and the Uluguru Mountains, respectively. Zone 2 is located at the mouth of the Rufiji River which is the largest and longest river in Tanzania, originating from the Poroto and Kipengere mountain ranges in the southern highlands. Zone 3 is south of the Rufiji Delta, also influenced by the Rufiji River. Tanzania's prawn fisheries benefit from the favourable conditions created by these major rivers (see Fig. 1).

Data Sources

The data utilised in this study pertains to the period before closure in 2007 and encompasses prawn catch and effort data, as well as river discharge data between rainfall patterns and marine fish catch and migration, as highlighted by other studies (Cheung *et al*., 2012; IPCC, 2021; Perry *et al*., 2005).

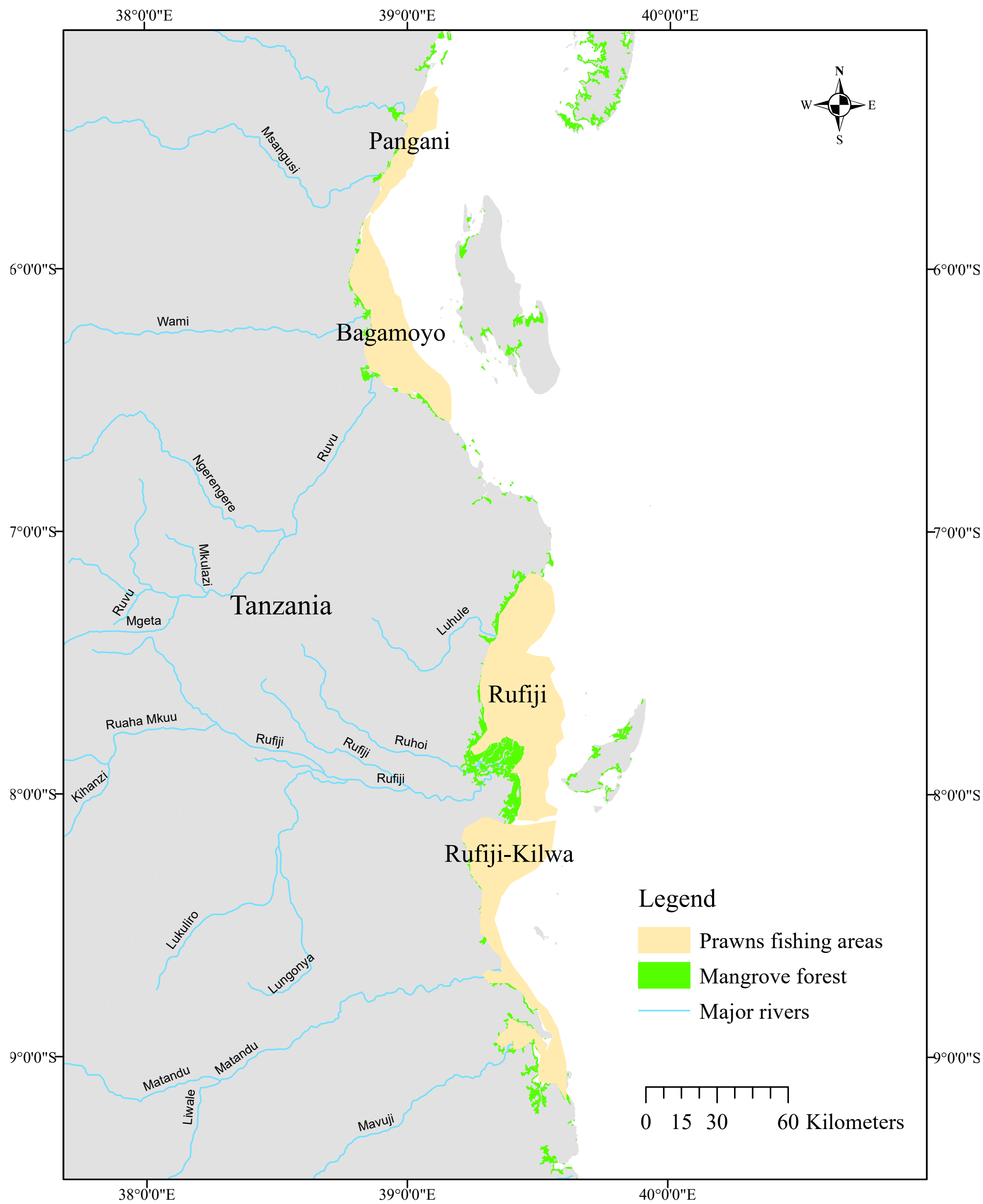

Figure 1. Map of the prawn fishing zones on the coast of Tanzania.

from 1988 to 2007. River discharge data was used to evaluate its impact on prawn catches, given its role in determining availability and catch variability in other coastal regions of the Western Indian Ocean, including neighbouring Mozambique (Malauene *et al*., 2021). This study also considered the relationship

Prawn catch data

Several data sources, including logbooks, vessel monitoring systems (VMS), at-sea inspections, port sampling, and an observer programme, were used to obtain information on industrial prawn catch and fishing effort and ensure data quality. Prawn trawlers are obliged by law to keep logbooks that record their fishing operations, including the date, time, location, time spent fishing, species of prawns caught and information on bycatch. All commercial prawn trawlers have VMS devices that communicate satellite position, speed, and direction information to the Fisheries Department. Before submitting data recorded in the logbooks to the Fisheries Department, the onboard observer checks the information logged to ensure accuracy. The Fisheries Department then digitises and includes the information in the annual statistics report books and also submits data to the Food and Agriculture Organisation of the United Nations (MLF, 2020).

River discharge data

Daily discharge data in cubic meters per second (m^3/s) was extracted from the Hydrological Year Book of Tanzania (https://www.maji.go.tz/) for the major rivers flowing into the main prawn fishing grounds in the coastal Indian Ocean. Although the Hydrological Year Book contains long-term data, this analysis was limited to data for the study period.

Data processing

Prawn relative abundance was estimated by a method described by Harley *et al*. (2001), whereby fish catch rates (CPUE) were standardised by dividing the total weight of fish landed by the number of fishing vessels involved in the fishing. Using this method, it was possible to compute an index which was employed to approximate the prawn population's relative abundance:

$$\text{Catch rate (CPUE)} = \frac{Wt}{No}$$

Where 'Wt' represents the wet weight of landed prawns and/or fish measured in kg, and 'No' is the number of fishing vessels involved when fishing.

Since the available prawn catch data were recorded on a yearly basis and lacked seasonal representation, an alternative approach had to be adopted. Therefore, the mean annual river discharge was computed as a proxy to compare with the limited prawn catch data. This allowed investigation of potential correlations or relationships between the two variables despite the low resolution of the prawn catch data.

Analysis

R version 4.2.0 was used for all statistical analyses and ggplot2 for plotting (R Core Team 2013, 2021). To investigate whether fishing effort or other factors influenced prawn catch, detrended indices of precipitation and prawn catch were developed. This process helped eliminate noise and other irregularities, thus enhancing the precision of predictions. For detrending, a yearly mean discharge rate in $m^{-3} s^{-1}$, mean prawn catch in tons/day, and mean proportion of prawn to fish catch was used. This was used to assess the relationship between prawn catch and discharge rates between 1988 and 1997 with a generalised linear model. Bar charts of detrended CPUE and discharge were also prepared to see when the values were above or below average.

Furthermore, a table was constructed examining the association between detrended discharge values and the detrended proportion of the prawn-to-fish catch ratio to assess if any and when changes occurred in the catch composition based on the prawn-to-fish catch ratio (Table 1).

Results

The impact of fishing effort on the prawn fishery

Prawn catches (measured in CPUE) fluctuated from the late 1980s to the closure in 2007 (Fig. 2). Prawn CPUE declined while effort increased until early 2003, when the maximum number of 26 fishing vessels was reached (Fig. 2). After that period, prawn catch dropped by 50 % from 1 320 to 661 tons in just a year (between 2003 and 2004) in spite of no drop in effort. The drop in catch prompted industrial fishers to reduce the number of fishing boats for the following three years, but CPUE continued to decline. In 2005, only 14 fishing vessels (56 % of the 25) were left operational. In 2007, the fishing companies further reduced the number of fishing vessels to 10, with no increase in CPUE. In 2007, the fisheries department officially closed the prawn fishery.

Trends of prawn catch and river discharge rate

Figure 3 illustrates the deviation from the long-term average of river discharge (m^3/sec) and CPUE (ton/day). Positive values indicate above-average conditions, while negative values indicate below-average conditions. There was a gradual rise in river discharge since 1988, which peaked in 1992. In the subsequent years, discharge rates fell below the long-term average, reaching their lowest levels in 1993 and 1994. However, from 1995 to 1996, the discharge rates increased and exceeded the long-term average. In 1997, the discharge rates fell below the long-term average again, followed by an increase in discharge rates from 1998 to 2000. Below-average discharge rates characterised the period from 2001 to 2007.

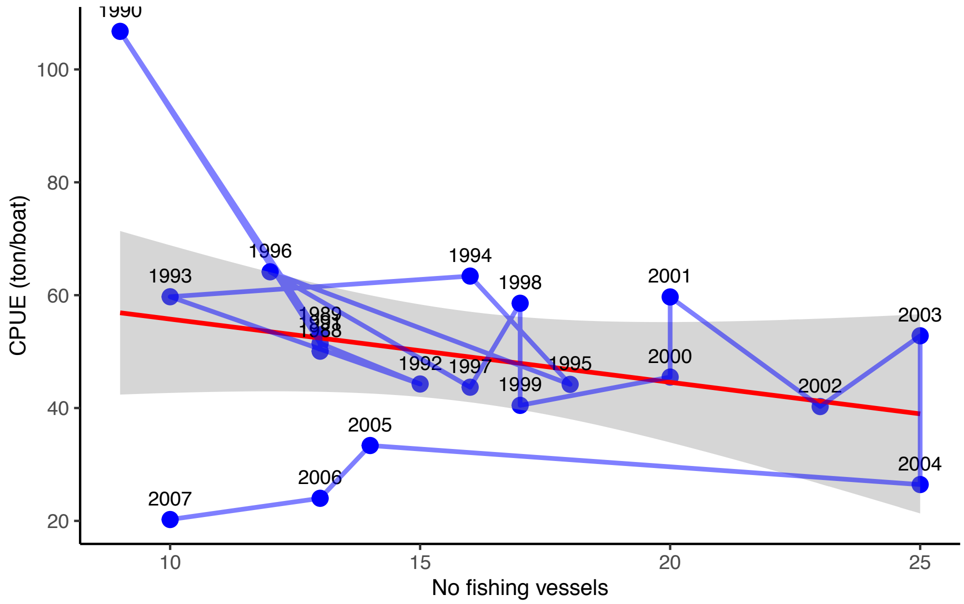

Figure 2. The relationship between CPUE; a tonnage-per-boat measure of relative prawn abundance, and the number of fishing boats from 1988 to the fishery's closure in 2007.

Except for 1989, CPUE values remained above average from 1988 to 1996, spanning almost a decade. However, in 1997, the CPUE dropped below the long-term average, and this trend persisted until the prawn fishery was officially closed in 2007. Notably, the highest CPUE value was recorded in 1990, after which there was a general decline in prawn CPUE until the fishery closure in 2007. In general, during the late 1980s to early 1990s, when the discharge rate was above average, the CPUE was also above average. Similarly, from early 2000 to 2007, when the discharge rate was below average, the CPUE was below average. However, between 1995 and 1997, discharge and CPUE were at their average levels.

Correlation between prawn catch and river discharge

Figure 4 shows a positive relationship between detrended CPUE and discharge data. This relationship implies the amount of water pouring into

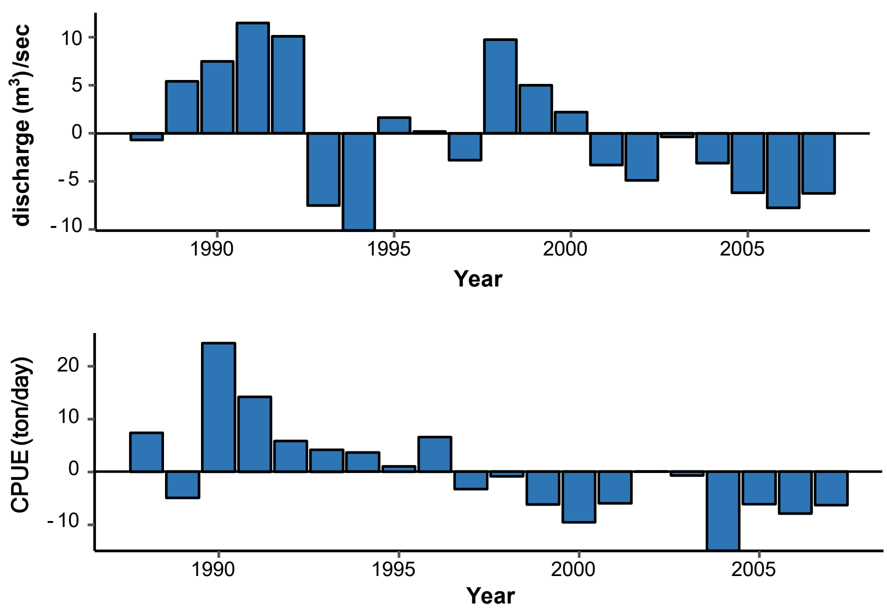

Figure 3. The trend of river discharge and prawn catch (CPUE) on the Tanzanian coast between 1988 to 2007. the CPUE and discharge rate data are detrended.

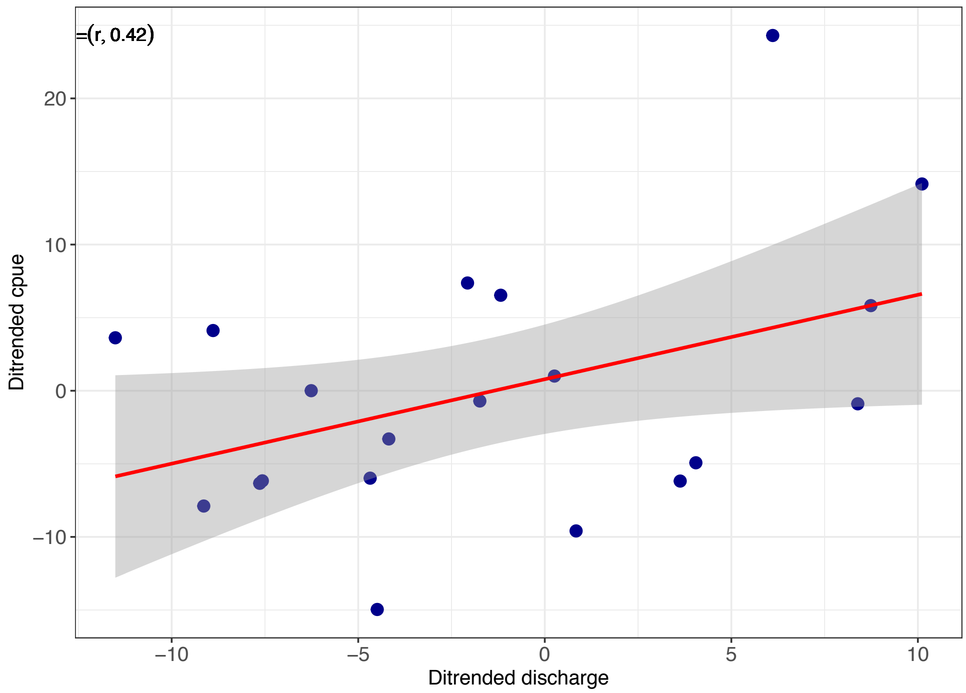

Figure 4. The relationship between prawn catch and discharge rate for two decadal periods from 1988 to 1997 on the coast of Tanzania. Data are detrended, and a generalised linear model is used for fitting while standard errors are presented in grey.

the ocean from the river or stream (discharge); if it decreases, the prawn catch per unit effort (CPUE) also declines, whereas an increase in discharge results in an increased catch.

Switch in trawl catch composition

The composition of trawl catches shifted from a prawn-dominated fishery in the 1980s to a fish-dominated one from early 2000 (see catch proportion column in Table 1). This shift was apparent nine years before the prawn fishery was closed. Based on these statistics, the change in trawl catch composition coincided with below-average river flow. This result indicates a possible link between river discharge trends and a switch in catch composition, particularly from the early 2000s. Therefore, increasing trawl vessels, particularly after the early 2000s, when changed to fish-dominated, increased bycatch levels. For instance, in the final years before the closures, the prawn composition comprised roughly 30 % of the catch, indicating that more fish were captured than prawns.

Discussion

The prawn fishery along the coast of Tanzania has been a crucial source of livelihood for coastal communities and a significant contributor to the country's economy (MLF, 2020; Silas, 2011). However, overfishing, combined with environmental factors such as decreased river flow, has led to a decline in prawn populations, ultimately resulting in the closure of the prawn fishery in 2007. This study aimed to investigate the link between extended-term trends of prawn harvest and precipitation patterns, using river discharge as a proxy for rainfall patterns. River discharge was chosen as it influences prawn populations and their well-being globally (Turschwell *et al.*, 2022). Variations in river flow, such as seasonal changes, flood events, and human-induced alterations, directly and indirectly impact prawn habitats and behaviour. During the wet season, for example, increased river flow facilitates juvenile prawn transportation into estuaries and coastal areas, promoting higher catch rates (Silas, 2011; Silas *et al.*, 2023).

Based on such considerations, the fluctuation of prawn catches for Tanzania was evaluated, and the findings suggest a positive relationship between detrended CPUE and river discharge. The presence of this relationship may suggest that a decrease in river or stream water flow (discharge) reduces the prawn abundance, resulting in low catches. Gammelsrød (1992) and Hoguane (2012) also documented comparable results of low catch at reduced discharges. The link between river flow and prawn abundance is also described for other regions. For regions where the wet and dry season persists, reduced river flow during the dry season

Table 1. Changes in trawl catch composition from prawn-dominated to fish-dominated from the prawn fishing grounds off the coast of Tanzania. Green values in the discharge column indicate above-average discharge rates, while red values indicate below-average discharge rates. In the catch proportion column, green values indicate years when the prawn catch was above-average, while red values show years when the catch was below average.

Year	Discharge	Prawn (tons)	Fish (tons)	Prawn: Fish	Detrended Discharge	Detrended catch proportion
1988	21.42	650.93	988.25	0.66	▼0.71	▼0.55
1989	27.54	688.84	978.50	0.70	▲5.41	▼0.50
1990	29.6	960.69	647.47	1.48	▲7.47	▲0.28
1991	33.6	669.02	460.77	1.45	▲11.47	▲0.25
1992	32.23	663.85	462.85	1.43	▲10.10	▲0.23
1993	14.6	597.21	398.11	1.50	▼7.53	▲0.29
1994	11.98	1014.09	575.81	1.76	▼10.15	▲0.55
1995	23.75	795.44	765.54	1.04	▲1.62	▼0.17
1996	22.31	769.65	598.72	1.29	▲0.18	▲0.08
1997	19.31	699.06	610.50	1.15	▼2.82	▼0.06
1998	31.88	995.56	537.88	1.85	▲9.75	▲0.64
1999	27.12	688.01	609.52	1.13	▲4.99	▼0.08
2000	24.33	909.72	958.13	0.95	▲2.20	▼0.26
2001	18.81	1193.69	1010.31	1.18	▼3.32	▼0.02
2002	17.23	926.08	296.35	3.12	▼4.90	▲1.92
2003	21.75	1320.06	931.16	1.42	▼0.38	▲0.21
2004	19	661.06	862.36	0.77	▼3.13	▼0.44
2005	15.92	467.04	868.97	0.54	▼6.21	▼0.67
2006	14.35	312.08	792.64	0.39	▼7.78	▼0.81
2007	15.85	202.46	642.17	0.32	▼6.28	▼0.89

concentrates prawns in specific locations, making them more susceptible to fishing pressure (Broadley *et al.*, 2020). Also, flood events are linked to disrupting prawn habitats, causing short-term declines in the catch, but in some other areas, these events enhance coastal productivity, benefiting prawn populations in the long run (Duggan *et al.*, 2019; Malauene *et al.*, 2021). Such relationships may plausibly explain a delayed recovery of prawn populations following the ban of the industrial prawn fishery in 2007 to the subsequent reopening in 2017, as prawns are highly prolific.

Similarly, the composition of trawl catches along the coast of Tanzania changed from being predominantly prawn in the early 1980s to being dominated by fish in early 2000, nine years before the prawn fishery was officially closed (Table 1). Such evidence suggests that if the catch composition switch had been observed earlier (due to the increased retention of fish bycatch as CPUE of prawns decreased), it could have alerted managers of the possible outcome of a collapse. Additionally, the data indicates that the shift in prawn composition occurred nine years following below-average river flow, which suggests a potential correlation between river discharge trends and changes in trawl catch composition. Comparable changes have been documented in other regions, where early maturing fish populations dominate as they respond easily to changes (Galván *et al.*, 2022; Levine *et al.*, 2023). For example, in the Pacific Arctic, where the water temperature is increasing and salinity is reduced due to melting ice (a phenomenon similar to increased river flow), the fish composition is reported to have changed (Levine *et al.*, 2023), a comparable effect to fish composition change in the prawn fishery of Tanzania. Though prawns are less likely to be affected negatively by increased salinity at an estuarine scale, other species may be affected. An example of such change happened in Patagonia when alien species invaded the area due to such changing conditions (Galván *et al.*, 2022).

Rapid urbanisation and large agricultural expansion characterising the coastal regions has increased water usage in most countries, including Tanzania (Lazaro *et al.*, 2019; NBS, 2018; Seeteram *et al.*, 2019). Combined with extensive land-use changes, subsequent water diversions, and the creation of dams for power projects, it will likely continue to cause river volumes to decline further. These trends are expected to further escalate the impacts on fisheries productivity, including a continued decline in some important fisheries, including prawns and other species that depend on nutrient flux from major rivers. The persistence of reduced river discharges highlights the importance of implementing an Ecosystem Approach to Fisheries (EAF) management and other conservation efforts to help mitigate and safeguard vital ecosystems that support fisheries productivity, an important component of human livelihoods (Eriksson *et al.*, 2016; Silas, 2022).

Other conservation efforts, for example, input control (limiting fishing vessels and time), persisted before the fishery was closed, and neither had a positive impact. It is now emphasised that a practical management approach should consider other factors, including the environment. For example, had the managers observed the catch composition switch and decreased discharge, they would have responded earlier. Therefore, it is suggested that to achieve the fishery's long-term sustainability, an EAF should to be implemented (FAO, 2020). To ensure a consistent and sustainable prawn supply, effective fisheries management strategies that consider the complex interactions between fishing pressure, environmental factors, and the well-being of both prawn populations and the communities that rely on them should be considered.

Though a link was found between prawn catch, trawl catch composition and river discharge, several challenges were also encountered. One of the significant challenges was the lack of consistent and reliable data on prawn catches. The available data were often reported annually and scattered across different sources, making it challenging to comprehensively analyse the monthly relationships (at a much higher resolution). Also, the ban on the prawn fishery in 2007 limited data availability during the ban period, making it difficult to establish the long-term trends of prawn catches and river discharge during the ban. Another challenge was the difficulty separating the effects of fishing pressure from those of other factors, including the environment, in this case, discharge. However, errors were minimised by detrending the data sets used.

Considering the influence of various unexplored variables in this study, including seawater temperature and salinity, on prawn abundance (Hoguane, 2012; Ndunguru *et al.*, 2022), further research is advocated to unravel the complexities of these factors. If all factors had been investigated, the way could have been paved for developing more practical and feasible management strategies for prawns. In addition, since the industrial and artisanal fishery both depend on the same stock, it would be important to understand the coupling between the two fisheries. Also, it could have helped to understand how the artisanal fishery contributed to prawn collapse or a delayed recovery, as artisanal fishers continued fishing after the ban. Understanding these interactions would have provided a more comprehensive picture of how this fishery is affected, enabling the development of an effective monitoring plan involving all relevant stakeholders. In this type of fishery, where artisanal and industrial fishers target the same stock, it is important to have an effective and sustainable management strategy that safeguards resources for the benefit of the large numbers of the population that depends on them.

Conclusion and recommendations

The results of the is study indicate a correlation between changes in prawn catch and river flow, emphasising the need for stakeholders to prioritise and address challenges affecting fish supply; for example, managing watersheds with a multisectoral approach. This may include avoiding obstructing river flow to a degree where other users are impacted. For example, when constructing dams for hydropower stations or irrigation schemes, sufficient water should be left to continue downstream to maintain critical ecosystem processes. Additionally, it is recommended that other factors (e.g., change in mangrove cover, sea water temperature) that were not explored in this study, are investigated. It is also suggested that governments and NGOs invest in alternative livelihood opportunities to reduce reliance on fisheries as the only source of income. These alternatives may include promoting ecotourism activities, developing alternative fisheries, and offering training and education programmes to support entrepreneurship and small business development, as Silas *et al.* (2020) recommended when examining why fishing communities persist in fishing when catches are declining.

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Appendix

Appendix 1. Prawn species composition in the Tanzanian marine waters.

No	Scientific name	Common name
1	*Penaeus (Fenneropenaeus) indicus*	White prawn
2	*Metapenaeus monoceros*	Speckled shrimp
3	*Panaeus semisulcatus*	Green tiger prawn
4	*Penaeus monodon*	Giant tiger prawn
5	*Penaeus (Marsupenaeus) japonicus*	Kuruma prawn
6	*Exhippolysmata ensirostris*	Hunter shrimp
7	*Macrobranchium rude*	Hairy river prawn
8	*Nematopalaemon tenuipes*	Spider prawn
9	*Metapenaeus stebbingi*	Peregrine Shrimp
10	*Penaeus (Melicertus) canalculatus*	Witch prawn
11	*Penaeus (Melicertus) latisulcatus*	Western king prawn

Source: Silas (2011) and Mwakosya *et al*. (2009)

Original Article

Mitigating proximate impacts of tropical cyclone landfalls in the Southwest Indian Ocean

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Abstract
The occurrence and impacts of tropical cyclones in the Southwest (SW) Indian Ocean were investigated over five cyclone seasons (November to April) between 2018/19 and 2022/23. Data describing cyclone characteristics, affected populations and economic losses from cyclone landfalls in Madagascar and Mozambique were extracted from the African Risk Capacity (ARC)'s Tropical Cyclone Explorer (TCE) software. Of 56 cyclones that formed in the region, 27 landfalls occurred with an average of 2.8 per season in Madagascar and 2.6 in Mozambique, mainly in January and February of each year. Most cyclone landfalls in Madagascar were categorized as moderate tropical storms (MTS, 43 %) and intense tropical cyclones (ITC, 22 %). In Mozambique, landfalls were mostly ITC (31 %) followed by MTS (23 %). Landfalls of very intense tropical cyclones (VITC) were more common in Mozambique (15 %) than Madagascar (7 %). An average of 1.8 million and 775,000 people per season were exposed to strong cyclone winds in Madagascar and Mozambique, respectively, with economic losses from cyclones per season averaging $544 million in Madagascar and $170 million in Mozambique. The African Risk Capacity (ARC), a specialized agency of the African Union, has implemented a parametric insurance solution to mitigate the proximate effects of cyclones damage on vulnerable populations. Four modules to estimate losses caused by cyclone events are described; the hazard-, vulnerability / damage-, - exposure- and insurance modules. Initial outcomes of the ARC's parametric cyclone insurance policy in Madagascar and Mozambique are discussed. Since its launch in 2020, the ARC's parametric cyclone insurance policy including its Replica partner allocated a total payout of $12.2 million to Madagascar following the landfalls of cyclones BATSIRAI in 2022 and FREDDY in 2023.

Keywords: cyclone, climate change, landfall, parametric insurance, Madagascar, Mozambique, African Risk Capacity (ARC)

Introduction
The Southwest Indian Ocean (SWIO) region is one of the most active areas in the world in terms of tropical cyclone development (Malan *et al.*, 2013). On average, 11-12 cyclones with wind speeds greater than 63 km/h and often exceeding 200 km/h occur yearly in the region (Mavume *et al.,* 2009). Several studies show that climate change is making cyclones stronger (rapid intensification, higher maximum wind speeds and more intense and very intense cyclones), wetter (strong storm surges, excessive rainfall, and risk of high coastal and inland flooding), and slower moving after making landfall on inhabited lands (Kossin *et al.*, 2020; Knutson *et al.*, 2019). In addition to huge economic losses, tropical cyclones have caused a trail of death and destruction, and physical losses across countries. Cyclone disasters significantly contribute to the high levels of poverty and food insecurity in the affected countries and exacerbate the existing conditions caused by previous disasters (World Bank, 2015;

Clayton, 2012). The strong winds, excessive rains and flooding associated with cyclones have a devastating impact on national economies and on the livelihoods of local people (Nash *et al.*, 2015; Harvey *et al.*, 2014). Moreover, they weaken people's resilience, plunge communities into indescribable poverty, and expose them to increased risks of water-related diseases such as cholera, and trauma, as recently occurred in Mozambique and Malawi during cyclone FREDDY (IOM, 2023; UNICEF, 2023).

Although most modelling studies predict a decrease in the overall frequency of tropical cyclones, several authors also predict an increase in the global average intensity of these cyclones (Knutson *et al.*, 2020). Data from international disaster databases shows that the risk of cyclones making landfall in the SWIO region over Madagascar was four times higher between 2000 and 2023 than between 1950 and 1999, and two and a half times higher for Mozambique for the same periods (EM-DAT, 2023). This implies a higher risk for Madagascar which is among the ten most exposed countries to cyclonic disasters in the world due to its geographical position in the SWIO region (Rakotoarimanana *et al.*, 2022). Despite the damage caused to Madagascar, Mozambique and many other cyclone-prone countries already struggling to recover from previous climate-induced disasters, measures taken to reduce or mitigate the effects of cyclones are still unsustainable, making local populations even more vulnerable to natural disasters. Furthermore, these countries have relatively weak disaster warning, preparedness, and adaptation strategies, and need more financial support to respond quickly and effectively to cyclone disasters. In addition, most developing countries generally lack the financial capacity to intervene quickly before, during and after disasters, often forcing them to reallocate funds from the national budgets to respond to a crisis and save vulnerable populations (Ndlovu, 2020). In most instances, humanitarian aid funds are insufficient to cover all the immediate needs of vulnerable populations (OCHA, 2012).

As an African Union Specialized Agency, the African Risk Capacity Group (ARC Agency and ARC Ltd), here referred to as ARC, was established to help African governments improve their capabilities to better plan, prepare for and respond promptly to natural disasters triggered by extreme weather events. Furthermore, through ARC Ltd, the financial affiliate of the Group, ARC offers risk pooling and transfer services. Its members are African governments comprising countries that have adopted a policy each year, as well as capital contributors such as, among others, the British Foreign, Commonwealth and Development Office (FCDO) and the German Development Cooperation (BMZ/KfW). By shifting the burden of natural disaster risks away from governments, ARC facilitates a more deliberate approach to disaster response. It disburses funds to finance pre-approved contingency plans to respond quickly to disasters. In November 2020, ARC launched its sovereign tropical cyclone parametric insurance policy for the Indian Ocean region to provide rapid financing and early response to countries affected by tropical cyclones (African Risk Capacity, 2020a). Unlike traditional insurance, which pays compensation based on the actual damage observed, parametric insurance (also known as index-based insurance) relies on the measurement of a specific index (parametric index) to establish the amount of compensation (Sengupta and Kousky, 2020). The risk transfer parameters are defined according to each country's risk profile, and the parametric insurance policy is structured accordingly. The country receives an insurance payout within a two-week period when the level of damages caused by a tropical cyclone triggers the insurance policy. The ARC cyclone parametric insurance policy is also extended to humanitarian partners under the ARC Replica programme, which allows humanitarian actors (called Replica partners) to replicate the conditions of the cyclone insurance policy of selected countries.

At the start of the season, each country participating in the cyclone risk pool pays a premium directly linked to the amount of risk it transfers to the Insurers. Several donors help countries finance premiums through a premium support facility based on agreed upon criteria. Donors often cover a bigger portion of the premium especially for new countries while encouraging a gradual increase of premium budget allocation from countries' national budget as a way of strengthening the disaster risk management and financing culture within the government system. This study aims to investigate the occurrence of cyclones in the SWIO region (Fig. 1), and their impacts on Madagascar and Mozambique. It also highlights the importance of ARC's parametric insurance policy in mitigating the risks of tropical cyclones in the Indian Ocean region.

Materials and methods

Tropical Cyclone Insurance Product

Since the fifteen tropical cyclone events that formed during the 2018-2019 cyclone season in the SWIO region, including the devastating cyclones IDAI and

KENNETH which led to the death of over a thousand people and caused extensive destruction to property, agricultural lands, and infrastructure in Mozambique (Hope, 2019), countries in the SWIO region have shown renewed interest in parametric insurances to facilitate timely response to tropical cyclone-related disasters. To respond to the needs of its member states, the ARC developed a tropical cyclone model capable of accurately estimating the risk and losses due to cyclone events, and this model underpins the insurance transaction to provide rapid financing and early response to countries affected by cyclones (African Risk Capacity, 2020b).The ARC tropical cyclone model uses cyclone track information produced by the US Joint Typhoon Warning Center (JTWC) and the Regional Specialized Meteorological Centre (RSMC)/La Reunion, based on the Automated Tropical Cyclone Forecast (ATCF) system, a global reporting system that replicates reports from WMO-mandated agencies in cyclone-affected regions. The ATCF file (resolution of 30 arcseconds ≈ 1 km x 1 km) includes near real-time data (A-deck) and archive data (B-deck) with the following characteristics for each cyclone: location of the eye (latitude and longitude), maximum wind speed (Vmax), maximum wind radius (Rmax), radius of the environment (Renv).

The tropical cyclone model, which is at the heart of the ARC parametric insurance product covers hazards related to winds and storm surges. It combines characteristics of cyclone hazards with exposure and vulnerability data to model the populations affected and the economic losses for six countries, namely, Madagascar, Mozambique, Comoros, Tanzania, Mauritius, and Seychelles. The cyclone parametric insurance product is implemented through four modules, logically sequenced to offer a reliable estimate of losses caused by cyclone events (Fig. 2):

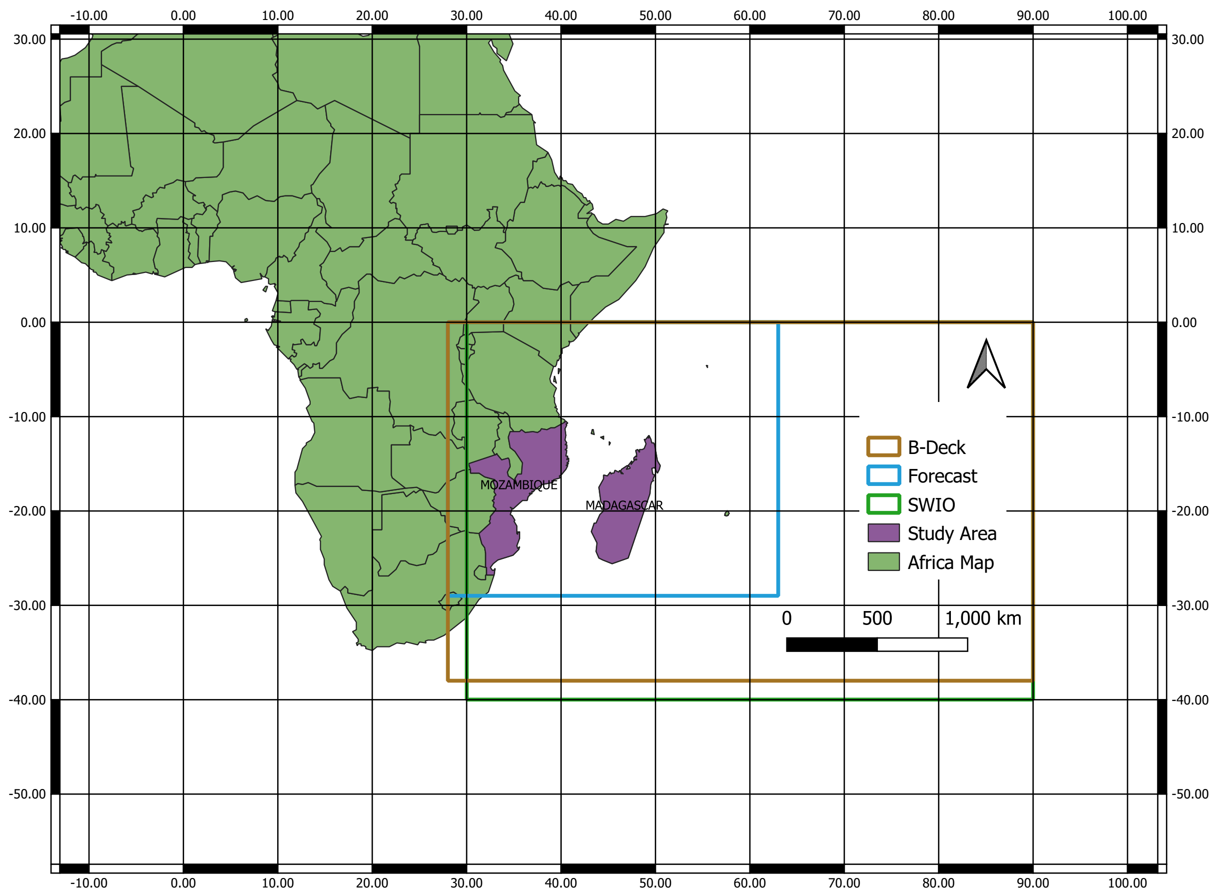

Figure 1. Study area and geographic coverage of the ARC Tropical Cyclone Explorer (TCE).

a) Hazard module:
This module uses the A-deck system files as a source of cyclone characteristics data for the modelling of cyclones wind field and storm surge height. However, to be consistent with tropical cyclone dynamics in the SWIO region, simulated events are generated using the best available historical event information for the region. Indeed, historical cyclone records since 1983

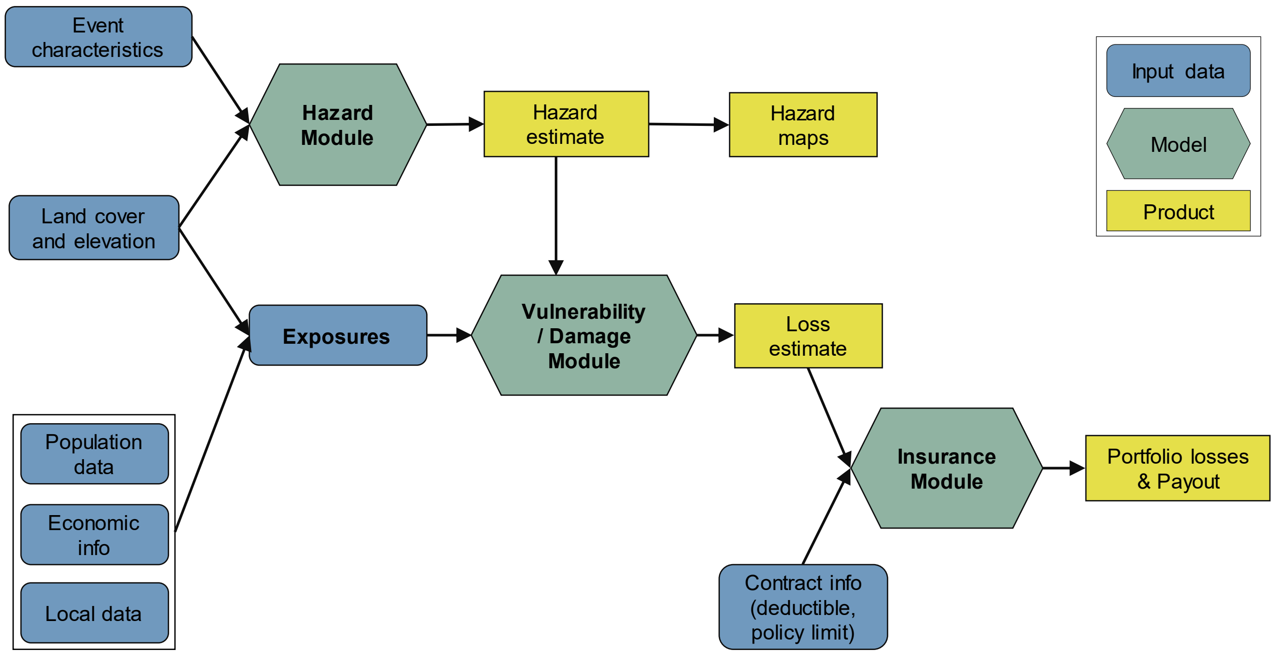

Figure 2. Generic framework of the ARC tropical cyclone insurance product.

contain only a small subset of the potential range of cyclones likely to occur. Risk modelling deploys statistical techniques to generate stochastic databases of cyclones that share the fundamental characteristics of the historical dataset but provides a solid basis for probabilistic risk assessment. Several synthetic tropical cyclone events are therefore generated for the SWIO region using the tropical cyclone tracks known as STORM (Synthetic Tropical cyclone geneRation Model) (Bloemendaal *et al*., 2020). This methodology uses a combination of all best-track data available from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp *et al*., 2010). However, as the best-track data from the JTWC are more complete than those from RSMC/La Réunion, they were used to develop stochastic tracks on 1,500-years (≈10,000 cyclones) over the period of 1983 to 2013. This stochastic catalog generated from STORM presents all the characteristics of historical data and provides a solid basis for estimating risk probabilities. For the wind field parametrisation, the ARC tropical cyclone model is based on the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) approach (Jelesnianski *et al.*, 1992) which uses the relationship developed by Quiring *et al.* (2011) and Nederhoff *et al.* (2019) to estimate the radius of maximum winds for historical storms, the radius of tropical storm force winds and the radius to environment. It includes basin specific relationships more applicable to the SWIO region, which significantly improves wind depictions for historical storms and estimation of real-time events. The hydrodynamic model used to simulate the storm surge is the three-dimensional modified Princeton Ocean Model (Blumberg, 1992), which considers wave configuration and tidal dynamics. It can carry out simulations of intrinsically satisfactory quality in post-event mode when the trajectory of the cyclone is known with the best possible estimate of the relevant characteristics associated with cyclone event. During an active cyclone event in the SWIO region, upon receipt of warnings from JTWC and RSMC, the hazard module runs a simulation of the new forecast to produce near-real time detailed, geographically distributed hazard layers of maximum winds and storm surge height induced by the tropical cyclone. Based on these hazard layers, hazard estimates are generated by applying sector-specific damage and impact models to those hazard results, and later ingested into the vulnerability/damage module.

b) Vulnerability/Damage module:

The structural vulnerability approach that relies on engineering models and information on local building characteristics to determine vulnerability curves has been considered (Pita *et al.*, 2013). This approach uses local data, including details on building composition, to model vulnerability under specific tropical cyclone conditions (Wilson *et al.*, 2022). Impact algorithms corresponding to four generic exposure classes have been developed to translate hazard estimates into economic impact estimates at exposure locations. These impact algorithms account for damage due to key event perils produced by cyclones (e.g., winds and storm surges) and accommodate the range of vulnerabilities within the composite exposure categories. The wind damage curves are derived from a third power function based on cyclone winds and the type of exposures, while the storm surge damage curves are linear, starting at 0.2 meters inundation, with maximum damage occurring with inundation of 3 meters for agricultural and low-density exposures, 6 meters for medium-density, and 10 meters for high-density exposures. The loss functions are specific to each asset class and the data for the historical database events are produced using the updated exposure data, custom damage functions for each asset class, and winds and storm surge data associated with each historical data. Loss estimation focuses exclusively on direct, physical damage to exposed assets and building contents. It is designed to estimate the replacement value of affected assets. The loss at each grid point is the sum of damage to the structure and contents, while the total loss for an administrative region is the total losses for each grid point in the region. The total loss for the country is the sum of the administrative regions. The result of calculating the modelled loss for every cyclone is an exceedance probability curve showing the value of loss which is likely to be incurred at given levels of probability.

c) Insurance module:

Using specific contract terms, this module translates exposure loss estimates into loss estimates for a portfolio of assets. Payout estimates are determined when the actual economic losses caused by a cyclone exceeds the trigger point also called the attachment point (defined by the policyholder). The maximum payout (coverage limit) is paid at the exit level (exhaustion point), which represents the value of the loss at which the full payout is due to the policyholder.

d) Exposure module:

The exposures which are inputs of the vulnerability/damage module correspond to human, structural or agricultural assets located in the risk zone; exposures to cyclones generally increase as populations continue to move and expand near coasts (UN, 2017; Crowell *et al.*, 2010). The resolution of the exposure data is consistent with the data in the stochastic database and post-event hazard footprints, and it was estimated at 30 arcseconds (≈1 km^2 grid cells) using a combination of satellite remote sensing, population estimates and GDP data. Population data is from WorldPop (www.worldpop.org), while GDP data is updated to 2017 using country-level GDP from the World Bank and CIA World Factbook databases and is used to estimate the replacement value of different asset classes (World Bank, 2023; CIA, 2023). Each 1 km^2 grid cell is classified into four classes based on MODIS land-use classification and population density: rural, mixed (rural/urban), medium-density urbanized and high-density urbanised. Each individual exposure record consists of the geographic and administrative area location, and three elements are used to estimate the loss from the hazard at that exposure location: exposure of four classes, number of units of exposure, and value per unit of exposure. In addition to the above, each administrative area is assigned weather construction variables which are applied to all exposures within that area. The construction quality variables apply as adjustments to the loss curves in loss evaluation. Construction quality is estimated based on past damaging events, or experts' judgement based on available data. This global exposure database includes an estimate of the physical assets, designed to provide reasonable estimates for losses (replacement value) from cyclone hazards.

Extraction of Cyclone Impacts Data

The tropical cyclone insurance product is integrated into the Tropical Cyclone Explorer (TCE) software, a dedicated online platform developed by ARC which allows users to visualise cyclone characteristics, calculate the affected population and economic losses caused by cyclones, and the payout amount which insured countries are entitled to receive in the event of a cyclone disaster (African Risk Capacity, 2020c). To investigate the occurrence of cyclones in the Indian Ocean region, as well as their impacts on Madagascar and Mozambique, the TCE was used to extract data on cyclone characteristics and impacts from the 2018/19 to 2022/23 seasons (a cyclone season runs from November to April in the Indian Ocean region). Indeed, when a cyclone system is active in this region, JTWC and the RSMC/La Reunion issue a warning bulletin every six hours detailing the characteristics of the cyclone. Data from these bulletins are used to forecast the track of the cyclone and this information is ingested into TCE to produce estimates of the populations affected and economic losses caused by this cyclone. TCE begins to monitor the characteristics of any cyclone when its maximum sustained wind (MSW) reaches the minimum threshold of 63 km/h based on the 10-minute average sustained winds unit at 10 meters above terrain. All named cyclones considered in this study were

Table 1. Classification of cyclones based on the maximum sustained winds (MSW)*.

Classification of cyclones	Maximum sustained winds(km/h)
Moderate Tropical Storm (MTS)	63 <= MSW <= 88
Severe Tropical Storm (STS)	89 <= MSW <= 117
Tropical Cyclone (TC)	118 <= MSW <= 165
Intense Tropical Cyclone (ITC)	166 <= MSW <= 212
Very Intense Tropical Cyclone (VITC)	> 212

*10-minute sustained wind

grouped into five categories according to the RSMC/ La Reunion's cyclone intensity scale as indicated in Table 1. Thus, in this paper, the word "cyclones" refers to all types of tropical cyclone events; and the windspeed considered for the categorisation is the maximum speed reached throughout the cyclone course. Although the TCE loss calculations are available for six countries in the SWIO region, only Madagascar and Mozambique, which experienced cyclone landfalls during these five seasons, were considered in this study.

Results and Discussion

Occurrence of tropical cyclones in the SWIO

Monitoring of tropical cyclones using TCE has shown that fifty-six cyclones of different categories have formed over the past five seasons from 2018/19 to 2022/23 in the SWIO region (Fig. 3). The most frequent cyclone categories occurring in the SWIO are Intense Tropical Cyclone (ITC) accounting for 32 % of all events, followed by Moderate Tropical Storm (MTS) (30 %), Tropical Cyclone (TC) (22 %) and Severe Tropical Storm (STS) (9 %) (Fig. 4). On the other hand, the most severe category of cyclones, namely, the Very Intense Tropical Cyclone (VITC), represents 7 %. It is worth mentioning that cyclones of moderate intensity, namely MTS, appear every season. On average, 11.2 tropical cyclones formed per season in the SWIO region. The 2018/19 was an above-average cyclone season for Mozambique, while Madagascar faced no cyclones. Indeed, the season was very active with fifteen cyclones formed, 60 % of which were ITC (Fig. 4). Three cyclones, DESMOND (MTS) in 2019, IDAI (ITC) and KENNETH (ITC) in 2019 made landfall over Mozambique. The Mozambique cyclone season was dominated by nine ITCs, including the two most devastating cyclones IDAI and KENNETH which caused significant loss of life, damage, and destruction in their paths. IDAI made landfall in the port city of Beira with winds exceeding 175 km/h on March 14, and continued inland affecting Mozambique, Zimbabwe, and Malawi. Cyclone IDAI has since been labelled the deadliest cyclone in southern Africa, and six weeks later the follow up landfall of KENNETH (195 km/h) in northern Mozambique made a record as the first time Mozambique had experienced two severe cyclones in the same season (IFRC, 2019; MISAU, 2019). Tropical cyclones IDAI and KENNETH caused significant destruction and damage in the provinces of Cabo Delgado, Sofala, Manica, Zambezia and Tete, killing at least 648 people (45 deaths from KENNETH and at least 603 deaths from IDAI), injuring nearly 1,700 people and leaving around 2.2 million people in need of urgent humanitarian assistance and protection (OCHA, 2019).

The 2019/20 season was slightly below-average in terms of cyclones (Fig. 4). Ten cyclones including four MTS (40 %) were recorded during that season. From these ten, three cyclones hit Madagascar; BELNA

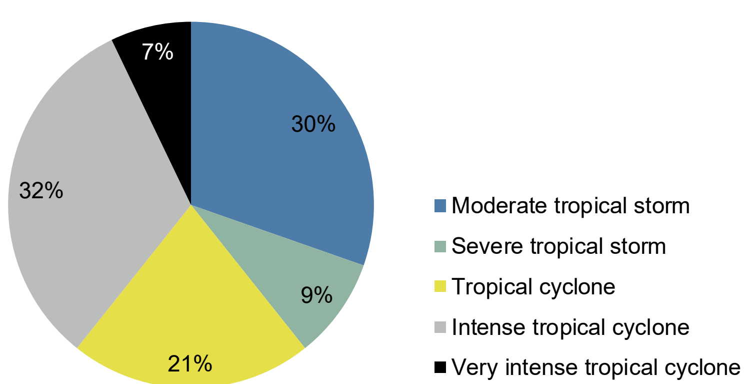

Figure 3. Proportion of cyclone occurrences (all seasons).

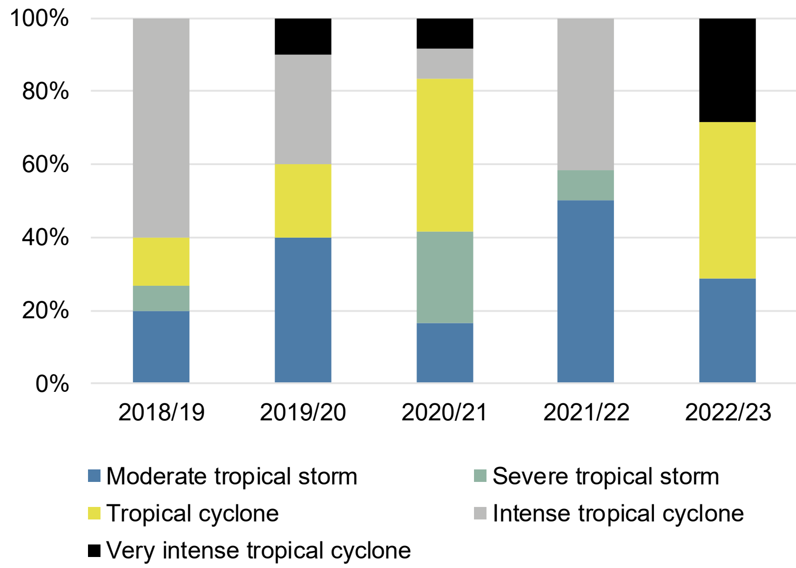

Figure 4. Category of tropical cyclones per season.

(TC) in 2019, DIANE (MTS) in 2020 and FRANCISCO (MTS) in 2020. BELNA was the season's first cyclone to hit Madagascar (Soalala, Boeny region) on December 9 at the TC stage with winds of 145 km/h. Mozambique did not experience any cyclone landfall during the 2019/20 season.

The 2020/21 season was marked by 12 cyclones, a number higher than the seasonal average. The TC category dominated the season, accounting for 42 % of all cyclones (Fig. 4). Of the 12 cyclones, three made landfall over Madagascar and Mozambique. Indeed, at the beginning of the season, both CHALANE (STS) in 2020 and ELOISE (TC) in 2021 hit Madagascar and Mozambique. ELOISE was more damaging for Mozambique which was hit on January 23 near the city of Beira with winds of 140 km/h (against 100 km/h for Madagascar). It caused widespread damage and flooding on a long swathe of coastline of Mozambique and impacted an area that was still recovering from cyclone IDAI which hit the same place in March 2019. ELOISE was followed by GUAMBE (TC) in 2021 and IMAN (MTS) in 2021 which respectively hit Mozambique and Madagascar but did not cause significant damages. Twelve named cyclones formed during the 2021/22 season, with MTS accounting for the highest occurrence (50 % of all cyclones). Among these 12 events, six made landfall over Madagascar in 2022; ANA (MTS), BATSIRAI (ITC), DUMAKO (MTS), EMNATI (ITC), GOMBE (ITC) and JASMINE (STS), and three in Mozambique ANA (MTS), GOMBE (ITC) and JASMINE (STS) during the same year. BATSIRAI was the most devastating cyclone of the 2020/21 season and the worst to hit Madagascar since ENAWO in 2017 (OCHA, 2022). It made landfall near the northern town of Mananjary (Vatovavy region) on February 5 with winds of 165 km/h and extreme gusts exceeding 230 km/h.

The 2022/23 season was a below-average cyclone season with a total of seven cyclones of which 43 % reached the stage of TC (Fig. 4). Two cyclones, CHENESO (MTS) and FREDDY (VITC) made landfall over Madagascar in 2023. From these two, FREDDY was a powerful and compact event that severely affected both Madagascar and Mozambique. After CHENESO, FREDDY was the second cyclone to hit the east coast of Madagascar on February 21 (near Mananjary) with winds of 130 km/h. It crossed Madagascar and made its first landfall on the coast of Mozambique on February 24 as a severe storm. FREDDY later re-emerged in the Mozambique Channel, and a week later made a second landfall in Mozambique near Quelimane District (Zambezia Province) on March 11 with winds of 148 km/h. FREDDY brought destructive winds and extreme rains that hit large areas in Madagascar, Mozambique, southern Malawi, northeast Zimbabwe, and southeast Zambia (OCHA, 2023). Freddy made history as the longest-lasting tropical cyclone on record.

Table 2 shows the seasonal landfalls of cyclones over Madagascar and Mozambique. With six cyclones in 2021/22, Madagascar recorded the highest number of landfalling cyclones in a single season. Madagascar and Mozambique have had at least one cyclone-free season, in 2018/19 for Madagascar and 2019/20

Table 2. Seasonal landfalls of cyclones over Madagascar and Mozambique.

Cyclone seasons	Number of occurrences	Madagascar		Mozambique	
		Number of landfalls	Ratio	Number of landfalls	Ratio
2018/19	15	0	0.0	5*	0.4
2019/20	10	3	0.2	0	0.0
2020/21	12	3	0.2	3	0.2
2021/22	12	6	0.4	3	0.2
2022/23	7	2	0.2	2*	0.2
Total	56	14	1.0	13	1.0
Average	11.2	2.8	0.2	2.6	0.2

*Take into account multiple landfalls from the same cyclone

for Mozambique. The 56 cyclones formed between 2018/19 and 2022/23 in the SWIO region caused in total 27 landfalls (48 %) in Madagascar and Mozambique. Madagascar experienced 14 landfalls (52 %), compared to 13 (48 %) for Mozambique. However, there have been three occasions when the same cyclone made multiple landfalls on the Mozambican coasts. This happened in 2018/19 with cyclones DESMOND and IDAI, and in 2022/23 with FREDDY. On average, 2.8 and 2.6 cyclones per season have made landfall in Madagascar and Mozambique respectively (Table 2). The same highest landfall ratio (0.4) recorded for Mozambique in 2018/19, and Madagascar in 2021/22 could be explained by warmer than usual sea surface temperatures produced by the propagation of ocean waves in the SWIO region (Vitart *et al.*, 2003; Mann and Emanuel, 2006; Fitchett *et al.*, 2014). As underlined by Shultz *et al.*, (2020), most storms that form over unusually warm waters tend to intensify rapidly, and many end up on inhabited lands, factors that may be linked to climate change. Figure 5 shows that most cyclones (65 %) made landfalls in Madagascar during January and February with a preponderance of cyclones in January (36 %). Rakotoarimanana *et al.* (2022) also found similar results when analysing cyclone landfalls over Madagascar from 2000 to 2022. In Mozambique, 54 % of the landfalls also occurred in January and February, with the highest number of landfalls (31 %) occurring in January. However, based on the observations from these five seasons, for Mozambique, there is as much chance of a cyclone making landfall in February as in April. For both countries, cyclone landfalls can be expected mainly in January and in February, and to a lesser extent in April for Mozambique.

Analysis of the proportion of the categories of cyclones that made landfall in Madagascar shows that they have not been regularly distributed over the past five seasons (Fig. 6a). The cyclones that most often make landfall are mainly of moderate intensity (MTS) representing 43 %, followed by intense tropical cyclones (ITC) with 22 %. Very intense tropical cyclones (VITC) seem rarer (7 %) in Madagascar. In Mozambique, the distribution of cyclones seems

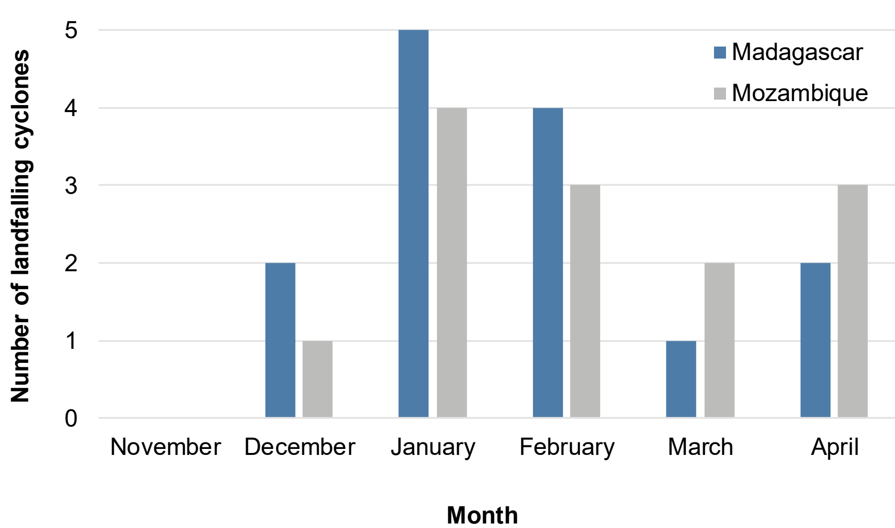

Figure 5. Monthly landfalling of tropical cyclones.

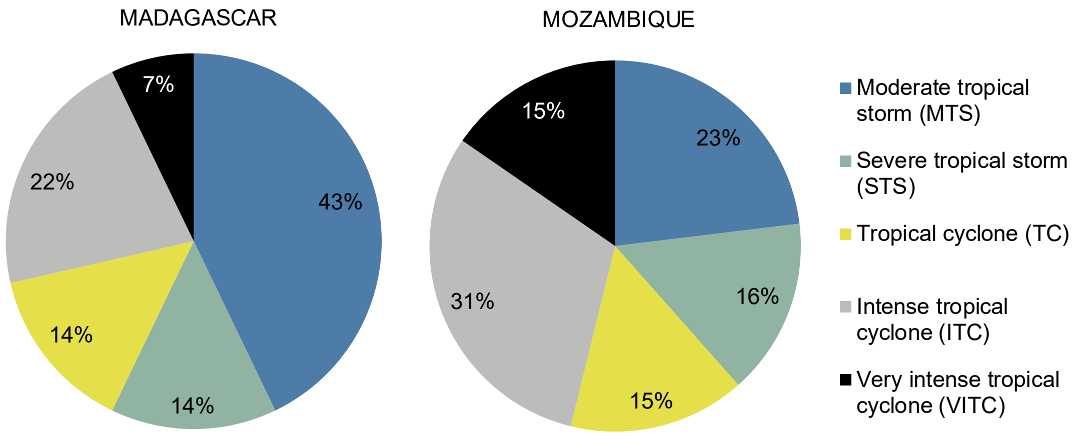

Figure 6. Proportion of the category of landfalling cyclones in Madagascar and Mozambique.

more balanced compared to Madagascar (Fig. 6b). However, unlike Madagascar, the cyclones that made landfall in Mozambique are mostly of high intensity (ITC) and represent 31 %, followed by moderate intensity cyclones (MTS), which are 23 %. On the other hand, very intense tropical cyclones (VITC) represent a more significant proportion (15 %) in Mozambique than in Madagascar. Furthermore, it is worth mentioning that in Madagascar and Mozambique, when the first cyclone that makes landfall is of high intensity, the second has been known to be of low intensity and vice versa.

Impacts of tropical cyclones as estimated by TCE

The consequences of tropical cyclones over the past five seasons have been devastating for Madagascar and Mozambique. The impacts of these cyclones on populations exposed to strong winds (≥ 118 km/h, minimum of a TC stage) and economic losses as estimated by the TCE are presented in Figures 7, 8, Table 3a and Table 3b. From 2018/19 to 2022/23, an average of 1.8 million people per season were exposed to high-intensity cyclones with winds exceeding 118 km/h in Madagascar. Although Madagascar experienced 14 landfalling cyclones, TCE estimated that in the first three seasons (2018/19, 2019/20, and 2020/21), only 32,000 people were exposed to strong winds. The number of people exposed to strong winds increased significantly with the landfall of the devastating cyclones BATSIRAI in 2021/22 and FREDDY in 2022/23, which impacted 6.8 million and 2.2 million people, respectively as

Table 3a. TCE estimated population and economic losses for Madagascar.

Cyclone seasons	Cyclone names	Populations exposed (≥ 118 km/h)	Direct economic losses (USD)	Total economic losses (USD)
2018/19	DESMOND	-	-	721,000
	IDAI	-	720,000	
	KENNETH	-	-	
2019/20	BELNA	32,261	9 million	9 million
	DIANE	0	0	
	FRANCISCO	0	0	
2020/21	CHALANE	0	5,000	270,000
	ELOISE	0	265,000	
	IMAN	0	0	
	GUAMBE	-	-	
2021/22	ANA	0	0	2,256 million
	BATSIRAI	6,868,285	2,200 million	
	DUMAKO	0	86,000	
	EMNATI	25,765	54 million	
	GOMBE	0	12,000	
	JASMINE	0	2 million	
2022/23	CHENESO	0	5 million	487 million
	FREDDY	2,202,461	482 million	

Table 3b. TCE estimated population and economic losses for Mozambique.

Cyclone seasons	Cyclone names	Populations exposed (≥ 118 km/h)	Direct economic losses (USD)	Total economic losses (USD)
2018/19	DESMOND	0	0	422 million
	IDAI	810,205	328 million	
	KENNETH	425,949	94 million	
2019/20	BELNA	-	-	-
	DIANE	-	-	
	FRANCISCO	-	-	
2020/21	CHALANE	0	1 million	227 million
	ELOISE	964,386	226 million	
	IMAN	-	-	
	GUAMBE		10,000	
2021/22	ANA	0	250,000	84 million
	BATSIRAI	-	-	
	DUMAKO	-	-	
	EMNATI	-	-	
	GOMBE	693,525	84 million	
	JASMINE	0	0	
2022/23	CHENESO	-	-	123 million
	FREDDY	980,000	123 million	

estimated by TCE. In Mozambique, the average seasonal number of people exposed to strong winds was 775,000; however, unlike Madagascar, the number of people exposed in Mozambique was almost evenly distributed over the past five seasons (Fig. 7). Mozambique has experienced five major cyclones, including IDAI and KENNETH, both of which occurred in 2018/19 and exposed 1.2 million people to winds exceeding 118 km/h. The other three devastating cyclones, ELOISE in 2020/21, GOMBE in 2021/22, and FREDDY in 2022/23, brought strong winds that severely affected 2.6 million people in Mozambique.

In addition to the populations exposed, TCE estimates direct economic losses due to cyclone winds and storm surges. Still, this does not consider indirect economic losses or losses due to flooding covered by another ARC parametric insurance product dedicated to river flooding. Tables 3a and 3b and Figure 8 clearly show that the cyclone BATSIRAI, which hit Madagascar in 2021/22, set the record as the costliest cyclone in the SWIO region over the past five seasons, with total economic losses of $2.2 billion. Indeed, TCE estimated that the Top 5 list of the costliest cyclones affecting both Madagascar and Mozambique over the

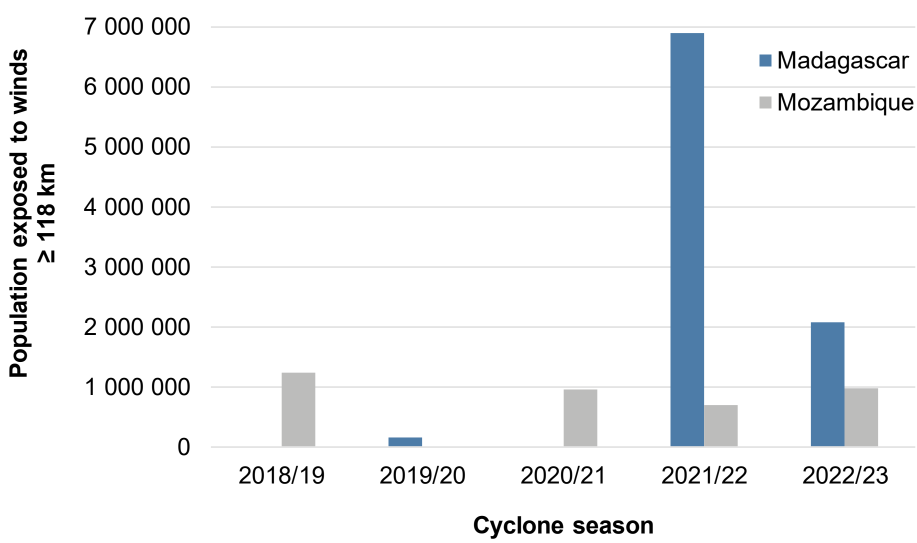

Figure 7. Population exposed to high winds (*Source: TCE*).

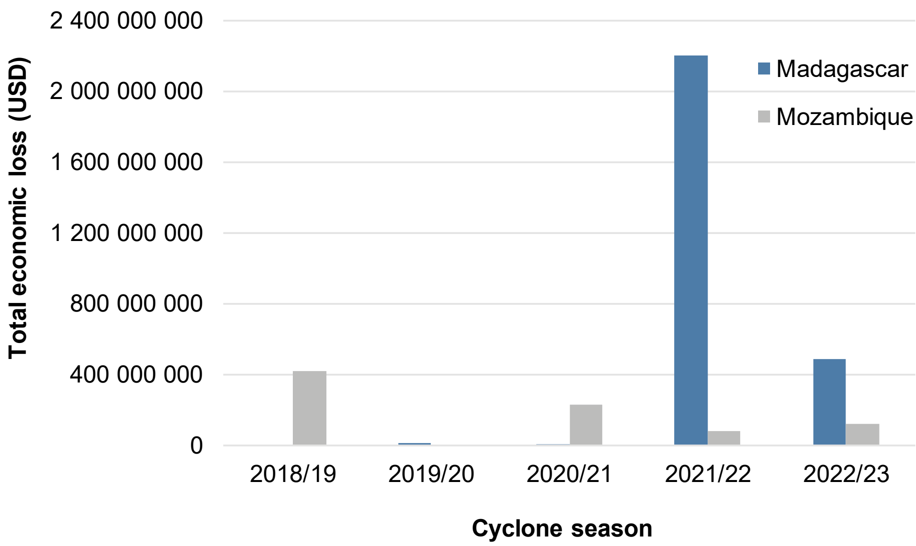

Figure 8. Total direct economic losses (*Source: TCE*).

past five seasons is dominated by BATSIRAI ($2.2 billion), followed by FREDDY ($605 million), IDAI ($329 million), ELOISE ($226 million) and KENNETH ($94 million). Furthermore, for Madagascar, the three costliest cyclones (BATSIRAI, EMNATI and FREDDY) occurred in 2022 and 2023, while for Mozambique, the three costliest cyclones (IDAI, ELOISE, and FREDDY) occurred with a two-year interval (2019, 2021 and 2023). As a result, the total direct economic losses caused by cyclones over the past five seasons is estimated at $2.72 billion for Madagascar compared to $855 million for Mozambique.

Tropical cyclone parametric insurance policy

Triggering of the cyclone policy

Under the ARC tropical cyclone insurance policy, real-time monitoring and post-event reports are issued for any cyclone affecting countries with winds exceeding 63 km/h. The TCE enabled the monitoring of the characteristics of cyclones over the past seasons. As shown in the previous section, about one-third (32 %) of cyclones forming in the SWIO region have affected mainly Madagascar and Mozambique, and the heavy rains associated with those cyclones also affected countries such as Malawi, Zimbabwe, Zambia, Mauritius, Comoros, and La Reunion. Due to its high exposure to cyclones, Madagascar was the first country to subscribe to the ARC parametric insurance policy in the 2020/21 season.

Since the launch of the ARC cyclone parametric insurance policy in 2020, Madagascar has experienced landfalls of eleven cyclones of different categories ranging from MTS to VITC.

During the occurrence of these cyclones, ARC provided countries with daily early warning information on the severity and geographic location of cyclones, areas at risk and expected impacts (number of populations at risk and economic losses) to help countries and humanitarian organisations put in place pro-active measures such as the preventive evacuation of vulnerable populations and the prepositioning of logistics necessary for emergency responses. For example, based on early warning information provided by the ARC before the landfall of the cyclone FREDDY in February 2023, the government of Madagascar evacuated 7,000 people in the coastal region who were in the path of the cyclone, while school and public transportation were suspended (African Risk Capacity, 2023). Three business days after the end of a cyclone event, ARC sent the policyholder a post-event loss report showing the total economic losses due to the cyclone and the amount of the payout the insured country was entitled to under the insurance policy. The policy is triggered when the total economic losses exceed the attachment point (or trigger point) pre-defined in the policyholder's contract.

Of the 11 cyclones that have made landfall in Madagascar since 2020, only two of high intensity, namely BATSIRAI and FREDDY, triggered the ARC cyclone parametric insurance policy. Indeed, BATSIRAI a devastating cyclone that hit Madagascar in February 2022, near the northern town of Mananjary (Vatovavy region) triggered the insurance policy for the first time. The economic losses associated which BATSIRAI were estimated at $2.2 billion by TCE. These losses are direct losses solely due to wind and storm

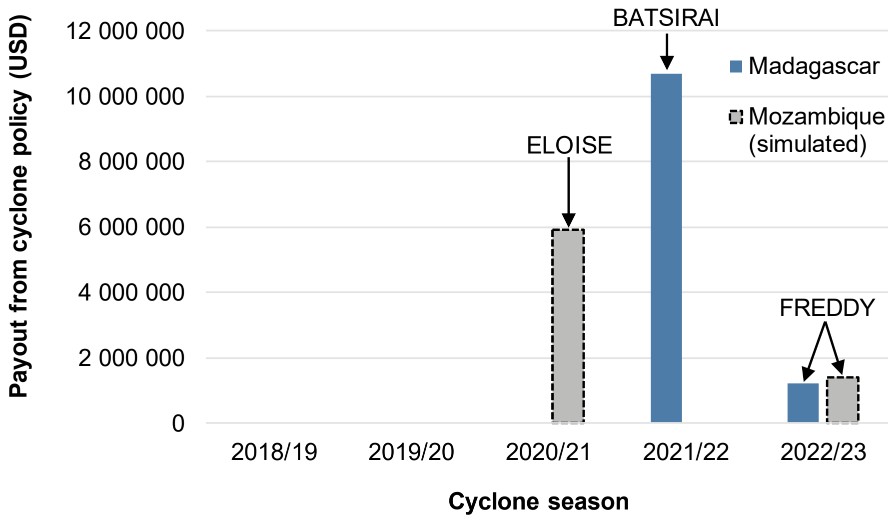

Figure 9. Payouts from ARC's cyclone parametric insurance coverage (*Source: TCE*).

surge hazards, and do not consider damages due to flooding, nor indirect economic costs (Table 3a). The calculation of the payout as per the ARC parametric insurance policy showed that these economic losses had exceeded the attachment point of $155 million pre-defined in Madagascar's cyclone policy. As a result, a payout of $10.7 million was paid by ARC to the Government of Madagascar under the 2021/22 parametric insurance policy against the risks of tropical cyclones (Fig. 9). In February 2023, FREDDY, a powerful and long-lasting cyclone, made landfall in Madagascar, near Mananjary, an area already affected by BATSIRAI in 2022. FREDDY has caused economic losses estimated at $482 million (Table 3a), thus exceeding the attachment point of $165 million indicated in Madagascar's cyclone policy. Therefore, in the aftermath of FREDDY, the government of Madagascar received a $1.2 million payout from ARC (Fig. 9). In both cases of cyclones BATSIRAI and FREDDY, the transfer of the payouts to the Government of Madagascar was processed within two weeks after the publication of the post-event loss report. These payouts enabled the government of Madagascar to quickly implement response activities to protect the vulnerable populations and save lives.

Response activities implemented to mitigate cyclone risks

Under the tropical cyclone insurance policy, ARC works in tandem with countries to develop contingency plans where a list of intervention activities is agreed upon beforehand, which may include the provision of health and nutrition support, food assistance to the affected populations, educational materials, reconstruction of schools, etc. These pre-approved plans ensure there is a strategy for a rapid use of the insurance payout (if any) for response activities, in the event the country is hit by a cyclone. For example, following the landfall of BATSIRAI, the government of Madagascar has managed to intervene for immediate assistance and early recovery in the eastern regions of Vatovavy, Fitovinany, and Atsimo Atsinanana by assisting over 85,000 beneficiaries. The main intervention activities consisted of food assistance to 26,500 households, nutritional and health support for children and pregnant/ breastfeeding women for about 6,500 households, reconstruction of 850 traditional huts and provision of household kits, supplying construction materials to health and education centres for 315 classrooms, etc. (African Risk Capacity, 2022). With the payout received following FREDDY's landfall in Madagascar, interventions were conducted in the six most affected towns, namely, Benenitra, Morombe, Sakaraha, Morondava, Manja, and Mahabo (African Risk Capacity, 2023). The intervention activities included food distribution to 13,300 households, seeds, and fertilizers to 6,000 households and cash transfer to 4,300 households. The Replica cyclone policy for Madagascar, backed by ARC's cyclone parametric insurance, also triggered a payout of $301,000 due to damages caused by the cyclone FREDDY. Therefore, the World Food Programme (WFP), the Replica partner for Madagascar, provided food assistance in the form of food distribution to over 33,000 beneficiaries at high risk of acute food insecurity, mainly in the district of Mananjary in the Vatovavy region (African Risk Capacity, 2023). Through WFP, beneficiaries received more than two months of assistance to meet their immediate needs.

Since its launch in 2020, the ARC's cyclone parametric insurance policy and its Replica partner have allocated a total payout of $12.2 million to the government of Madagascar to provide a rapid and effective response following the landfalls of cyclones BATSIRAI and FREDDY, thereby protecting its vulnerable population and saving countless lives and livelihoods. This participation of Madagascar in the ARC parametric insurance policy and the Replica programme complemented the government efforts towards reducing the impacts of cyclone disasters on their most vulnerable populations. This is very important because, the faster the response, the more lives and livelihoods are protected after a natural disaster such as a cyclone.

As seen above in Table 2, over the past five seasons, Mozambique has experienced thirteen landfalls of cyclones that have caused devastating damage. These cyclones have caused an average economic loss of $170 million per season as estimated by TCE. Table 4 indicates the TCE simulated payouts that Mozambique would have benefitted if the country had subscribed to the ARC's cyclone parametric insurance policy. The results of the simulations showed that the economic losses caused by cyclones during the 2020/21 and 2022/23 seasons, would have exceeded the attachment point. As a result, a total amount of $7.3 million would have been paid to the government of Mozambique for damages caused by the cyclones ELOISE in 2021 and FREDDY in 2023 (Table 4). These funds would have enabled the government of Mozambique to quickly assist the affected population by evacuating populations at risk, provision of health and nutritional supplies, food distribution, school materials, or reconstruction of schools and health centers.

Conclusions

Although the analysis of five cyclone seasons and a total of 27 cyclones that made landfall may not allow for statistically significant comparisons, it provides valuable information on the frequency, intensity and impacts of cyclones in the SWIO region, particularly in Madagascar and Mozambique, as well as highlights the relevance of the payouts generated by the ARC parametric insurance policy. This study showed that the ARC's parametric insurance policy and its cyclone monitoring engine, the TCE, successfully captured the occurrence and impacts of tropical cyclones in the SWIO region, especially in Madagascar and Mozambique.

As shown for Madagascar, the innovative parametric insurance solution offers by ARC works well as demonstrated by the two successive payouts that the country received following the landfalls of BATSIRAI and FREDDY which enabled the government's timely response to protect its vulnerable populations. The ARC's cyclone parametric insurance policy is an integral part of countries' disaster risk management and climate resilience strategies. Not only does it helps reduce the financial burden on countries, but it also gives incentives to take prevention and preparedness measures. This is especially critical given how the landfall of tropical cyclones has endangered the lives and livelihoods of millions of people in Madagascar and Mozambique. As post-cyclone recovery efforts are limited by financial constraints due to the significant investments required to assist vulnerable populations, ARC will continue to work with all cyclone-prone countries in the SWIO region to encourage them to join the cyclone risk pool. Their participation in the cyclone insurance policy will help build their climate resilience, strengthen their disaster response and recovery capacities, and reduce their vulnerability to climate threats. Comoros has followed Madagascar's example by subscribing to the ARC's cyclone parametric insurance policy. Discussions are underway with other countries in the SWIO region for their future participation in the coming cyclone risk pool. Modelling studies have suggested that there will be a global increase in cyclone intensity in the 21st century (Bengtsson, 2007; Knutson *et al.*, 2010). Given this vulnerability of populations in southern African regions, the need for parametric insurance coverage

Table 4. Payouts simulated by TCE for Mozambique.

Cyclone seasons	Cyclones names	Direct economic losses (USD)	Simulated insurance payouts (USD)*
2020/21	ELOISE	326 million	5.9 million
2021/22	GOMBE	84 million	0 million
2022/23	FREDDY	123 million	1.4 million

*Risk Transfer Parameters: Exhaustion point = $502 million, Attachment point = $91 million, Coverage limit = $18 million, Ceding percentage = 4.38% and Premium = $1.7 million must be a high priority for all cyclone-prone countries. It is indeed an effective way to provide faster and more flexible funds to victims of cyclones that would otherwise be difficult to ensure. Furthermore, since tropical cyclones are typically accompanied by heavy rains that cause widespread flooding and considerable damage, ARC is considering upgrading its parametric insurance product to account for the effect of excessive precipitation associated with cyclones.

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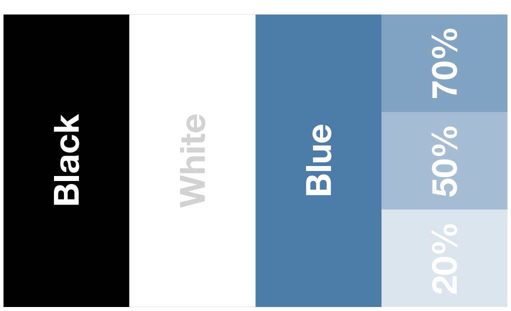

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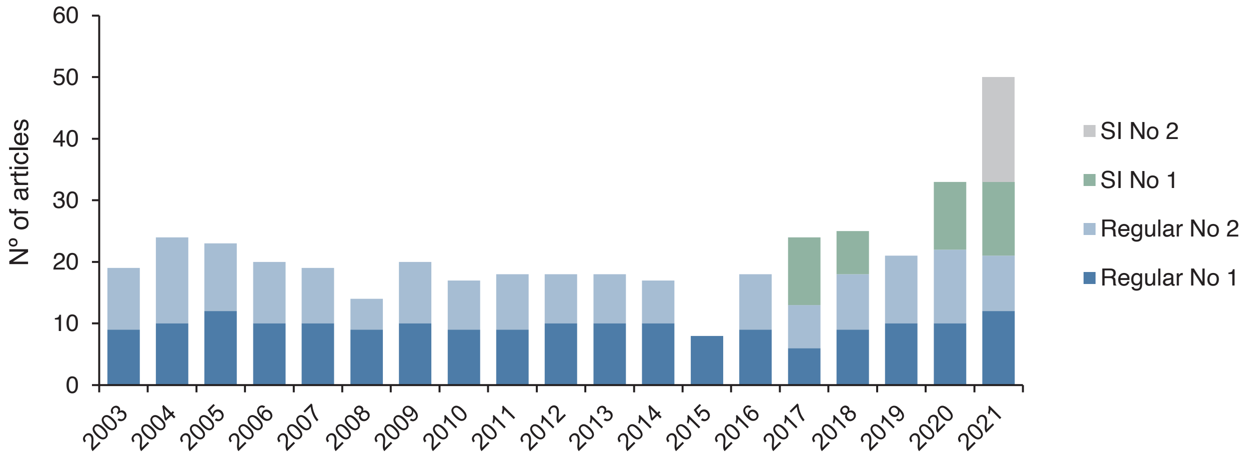

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