Remote sensing-based assessment of mangrove forest changes and related regulatory frameworks for the sustainability and conservation of coastal ecosystems in Zanzibar Island, Tanzania-East Africa

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Abstract

Mangroves are vital components of the world's coastal ecosystems, yet they face significant threats from storm surges, tidal waves, commercial aquaculture, and expanding human settlements. These challenges have heightened the need for accurate mangrove maps to gauge ecosystem degradation. However, mapping mangroves at species and community levels is challenging due to the inaccessibility of these environments. Remote sensing offers an efficient alternative to conventional field-based methods by enabling data collection in these challenging ecosystems. This study aimed to apply remote sensing techniques to map mangrove forest changes and species in two protected bays in Zanzibar, Tanzania.

The thesis focuses on four key areas. First, it examines the history of mangrove management in Zanzibar, from colonial times (1890) to the present, highlighting policies, laws, and community involvement in conservation. The colonial authority implemented several land administration laws and regulations to protect mangrove forests. However, mangrove forests suffered significant degradation from 1930 to the end of World War II. The post-independence policy framework established the legal foundation for the introduction of community involvement in mangrove conservation. The legal foundation for introducing community participation in mangrove protection was established by post-independence policy structures such as the National Forest Conservation and Management Act of 1996. Nevertheless, sustainable mangrove use remains inadequate. Second, the study compared community perceptions of mangrove ecosystem services using chi-squared tests and one-way ANOVA. Household surveys showed that provisioning services (PS) were the most identified (84%). Supporting (SS), regulating (RS), and cultural services (CS) were rated by 46.2%, 45.4%, and 21.0%, respectively. Statistical analyses indicated significant differences in the awareness of RS ($\chi2 = 6.061$, $p = 0.014$) and SS ($\chi2 = 6.006$, $p = 0.014$) between Chwaka, Charawe, Ukongoroni, Unguja Ukuu, and Uzi wards. There were no significant differences in the identification of PS ($\chi2 = 1.510$, $p = 0.919$) and CS ($\chi2 = 1.601$, $p = 0.901$). The study found that residents' occupations did not determine their reliance on mangrove ecosystem services ($\chi 2 = 8.015$; $p = 0.1554$). Third, changes in mangrove cover in Menai Bay and Chwaka Bay between 1973 and 2020 were analyzed using Landsat data. TerrSet geospatial software was used to classify land cover. The SEGMENTATION module grouped pixels based on spectral similarity, and the images segments were transformed into training sites and signature classes using the SEGTRAIN module. Finally, the segments were classified with the SEGCLASS module into a pixel-based land cover map. Separation of land cover classes was determined using the Jeffries–Matusita (J-M) distance and the transformed divergence (TD) index. For Chwaka Bay, overall classification accuracy ranged from 82.5% to 92.7%, while for Menai Bay, it ranged between 85.5% and 94.5%. Producer and user accuracies ranged from 72% to 100%, with kappa coefficients (κ) between 0.72 and 0.90. Menai Bay experienced a 6.8 ha yearly decline in mangrove cover between 1973 and 2020, while Chwaka Bay saw a 48.5 ha annual decrease. Fourth, the study aimed to map mangrove species in Menai Bay using metrics extracted from the Landsat 9 OLI-2 dataset, i.e., vegetation indices (VIs) and gray-level co-occurrence matrices (GLCMs). A critical step in this study was identifying the contribution of vegetation indices and texture features to classifying mangroves. Training data from very high-resolution (VHR) unmanned aerial vehicle (UAV) data covering parts of the study area helped identify five major mangrove species, i.e., *Rhizophora mucronata, Ceriops tagal, Sonneratia alba, Avicennia marina, and Bruguira gymnorrhiza*. Results showed that textural features attained overall classification accuracy of 68.29% (kappa = 0.62) and 67.07% (kappa = 0.60) for random forest (RF) and support vector machine (SVM), respectively. Vegetation indices (VIs) recorded overall accuracy of 72.64% (kappa = 0.67) and 67.78% (kappa = 0.61) for RF and SVM.

Overall, this study demonstrates the potential of remote sensing technologies for mapping mangrove forest changes and species in challenging environments like Zanzibar’s protected bays. By integrating historical policy analysis with modern geospatial techniques, the research highlights the significant role of both legal frameworks and community involvement in mangrove conservation. The community surveys underscore the varying perceptions of mangrove ecosystem services across different wards, with provisioning services being the most recognized. These findings underscore the importance of advancing remote sensing applications and refining conservation strategies to ensure the sustainability of mangrove ecosystems. Additionally, the analysis of long-term changes in mangrove cover from 1973 to 2020 reveals a concerning decline, particularly in Chwaka Bay. Lastly, the study’s classification of mangrove species using Landsat 9 OLI-2 data, vegetation indices, and texture metrics achieved notable accuracy, emphasizing the value of remote sensing in distinguishing species-level characteristics.

Preface

This doctoral thesis details research conducted at the School of Geography, Archaeology, and Environmental Studies, University of the Witwatersrand, Johannesburg from October 2018 to February 2024, under the supervision of Professor Elhadi Mohammed I. Adam (School of Geography, Archaeology, and Environmental Studies, University of the Witwatersrand, Johannesburg).

I have taken reasonable precautions to ensure that the work in this document is original, as it is the outcome of my investigations. Unless otherwise indicated, a list of all the literature references utilized is provided at the conclusion of each chapter. This PhD thesis is not being presented in conjunction with a candidature for any degree, nor has it ever been submitted or accepted in whole for any degree previously.

Mohamed Khalfan Mohamed  Date: 15.10.2024___________________

I, the candidate's supervisor, attest to the aforementioned assertion and have given the go-ahead for the submission of this thesis**.**

Prof. Elhadi Mohammed I. Adam  Date: _____17.10.2024___

Declaration 1-Plagiarism

I, Mohamed Khalfan Mohamed, declare that:

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Signed __ 

Declaration 2-Publication and manuscripts

1. **Mohamed**, M.K., Adam, E., and Jackson, C.M. (2023). Policy review and regulatory challenges and strategies for the sustainable mangrove management in Zanzibar. *Sustainability*, 15*,* 1557. https://doi.org/10.3390/su15021557

2. **Mohamed**, M.K., Adam, E., and Jackson, C.M. (2024). Assessing the perception and contribution of mangrove ecosystem services to the well-being of coastal communities of Chwaka and Menai Bays, Zanzibar. *Resources*, *13*, 7. https://doi.org/10.3390/resources13010007

3. **Mohamed**, M.K., Adam, E., and Jackson, C.M. (2023). The spatial and temporal distribution of mangrove forest cover from 1973 to 2020 in Chwaka Bay and Menai Bay, Zanzibar. *Applied Science*, 13*,* 7962. https://doi.org/10.3390/app13137962

4. **Mohamed**, M.K., Adam, E., and Jackson, C.M. (under review, *Estuarine, Coastal and Shelf Science*). Mangrove species mapping in Menai Bay, Zanzibar, using Landsat 9 OLI-2 and machine learning algorithms.

Dedication

To my beloved children, Khalfan, Hisham, Rushd, Nashmia, Rinad, Zeana, Zahid, and Zaim, for their unwavering love and well wishes for my achievements, and to my beloved father, Khalfan, my beloved mother, Zeyana, my beloved wife, Fatma, my brothers and sisters.

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First and foremost, I express my gratitude to Allah "**The Most Glorified, The Highest**" for the blessings of life, health, and intelligence, which have allowed me to pursue my studies uninterrupted.

I am deeply grateful to the many organizations and individuals who made this thesis possible. My profound appreciation goes to those listed below for their vital assistance with this project. The study was carried out at the University of the Witwatersrand's School of Geography, Archaeology, and Environmental Studies, Faculty of Science, in Johannesburg, South Africa.

I extend my heartfelt thanks to Professor Elhadi Mohammed I. Adam, my supervisor, for accepting me as a PhD candidate and for his unwavering supporting throughout my journey. His guidance and expertise have been instrumental in my progress. I am especially grateful for his encouragement, motivation, and spiritual support during my studies.

I am also indebted to my closest friend, Dr. Colbert M. Jackson, for his leadership, patience, and wisdom throughout my doctoral journey. His encouragement and insightful feedback were invaluable in helping me complete this thesis.

I truly appreciate my family's constant support throughout my academic career. Thank you for your love, compassion, and kindness—you have always been there for me. I am especially grateful to my dear wife, Fatma, for her unwavering moral support. Your kindness and friendship have been a pillar of strength during our challenges, and I could not have completed my doctorate without you.

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Finally, I appreciate the support I received from everyone at Abdulrahman Al-Sumait University. I will always remember the partial publication coverage I received for my two published articles during my difficult financial circumstances.

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Abbreviations and acronyms

ACCNNR	The African Convention on the Conservation of Nature and Natural Resources
AGB:	Above-Ground Biomass
AIGF:	Area-Integrated Gap Fraction
ALS:	Airborne Laser Scanning
ARI:	Anthocyanin Reflectance Index
ASM:	Angular Second Moment
AutoMCU:	Automated Monte Carlo Unmixing
CARI:	Chlorophyll Absorption Ratio Index
CCA:	Contextual Classification Algorithm
CFA:	Community Forest Association
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CLAS:	Carnegie Landsat Analysis System
CON:	Contrast
COR:	Correlation
CRI-1:	Carotenoid Reflectance Index 1
CRI-2:	Carotenoid Reflectance Index 2
CV:	Cross-Validation
DAP:	Digital Aerial Photograph
ENT:	Entropy
EO:	Earth Observation
ETM+:	Enhanced Thematic Mapper Plus
GLCM:	Grey Level Co-occurrence Matrix
GPS:	Global Positioning System
GSFD:	Gap Size-Frequency Distribution
HOM:	Homogeneity
HR:	High Resolution
HRW	Human Right Watch
HYDICE:	Hyperspectral Digital Collection Experiment
ITC:	Individual Tree Crown
J-M:	Jeffries-Matusita
κ:	Kappa
LAI:	Leaf Area Index
LBP:	Local Binary Pattern
LDA:	Linear Discriminant Analysis
LiDAR:	Light Detection and Ranging
MCARI:	Modified Chlorophyll Absorption Ratio Index
MDA:	Mean Decrease in Accuracy
MDG:	Mean Decrease in Gini
MDS:	Multi-Dimensional Scaling
MENR:	Ministry of Environment and Natural Resources

ML:	Machine Learning
MLBP:	Multivariate Local Binary Pattern
MLC	Maximum likelihood classification
MSAVI:	Modified Soil-Adjusted Vegetation Index
MSAVIaf:	Modified Soil Adjusted Vegetation Index aerosol free
NDVI:	Normalized Difference Vegetation Index
NIR:	Near Infra-Red
NNC	Neural Network Classification
OA:	Overall Accuracy
OBIA:	Object-Based Image Analysis
OLI:	Operational Land Imager
OOB:	Out-Of-Bag
PA:	Producer's Accuracy
PFM:	Participatory Forest Management
RADAR:	Radio Detection and Ranging
RENDVI:	Red Edge Normalized Difference Vegetation Index
RF:	Random Forest
RGB:	Red, Green, Blue
RMSE:	Root Mean Square Error
RS:	Remote Sensing
SAM:	Spectral Angle Mapper
SAR:	Synthetic Aperture Radar
SDI:	Shadow Detection Index
SEM	Southeast monsoon (SEM
SFM:	Sustainable Forest Management
SLR	Sea level rise
SMA:	Spectral Mixture Analysis
SME	Society for Mangrove Ecosystems
SVM:	Support Vector Machine
TD:	Transformed Divergence
TM:	Thematic Mapper
TS:	Tree Species
UA:	User's Accuracy
UN	United Nations
UNESCO:	United Nations Educational, Scientific and Cultural Organization.
UNFCCC	United Nations Framework Convention on Climate Change
URT	United Republic of Tanzania
VHR:	Very High Resolution
VI:	Vegetation Index
VNIR:	Visible and Near Infra-Red
WV-2:	WorldView-3
WV-3:	WorldView-2
ZNA	Zanzibar National Archives

CHAPTER ONE

General Introduction

1.1 Status of global mangroves

According to Lee and Yeh (2009) and Alsaaideh *et al*. (2013), mangrove forests are tidal wetlands that have a varied mix of trees and shrubs, located in tropical and subtropical regions between approximately 30^0N and 30^0S latitude. Mangroves, which span 147,359 km^2 across 118 countries, are vital ecosystems (Bunting *et al*., 2022). Mangroves support a variety of ecosystem services, such as supporting biological diversity, stabilizing coastlines, water purification, and serving as nursery habitats for numerous marine fisheries (Bunting *et al*., 2022). Additionally, mangroves play a significant role in the recreation and tourism sectors (Rahman *et al*., 2013; Chen *et al*., 2017). Because mangrove forests are tropical forests with the highest carbon content, they have attracted interest from researchers due to their current decline in cover caused by degradation. The mangrove forest ecology is among the most delicate on Earth yet it has been severely affected by human activity and climate change, which has led to rising sea levels (Cherrington *et al*., 2020). Rising sea levels impact mangroves by causing: (i) saltwater intrusion, which increases salinity in freshwater systems and can stress or kill sensitive species; (ii) coastal erosion, which reduces the area available for mangrove growth and destabilizes their root systems; (iii) prolonged flooding, which can drown trees and hinder their development; (iv) altered sediment dynamics that disrupt essential processes for mangrove regeneration; and (v) habitat loss due to submersion, limiting their ability to migrate landward (Li *et al*., 2022). Deforestation is said to have caused the loss of 20–35% of the world's mangrove forest areas since the 1980s (Lovelock *et al*., 2022). According to Zeng *et al*. (2023), mangrove forests are potential candidates for conservation under initiatives like Reduce Emission from Deforestation and Degradation (REDD+). The rapid disappearance of mangroves has driven extensive monitoring efforts at local and global scales (Sannigrahi *et al*., 2019).

According to Bunting et al. (2022), mangrove species exhibit similar morphological, biological, and reproductive features despite their taxonomic unrelatedness. A small number of species have developed specific adaptations to thrive in saline, intertidal environments. Major ocean currents and the 20^0C ocean water isotherm in winter are key factors explaining the global distribution of mangroves. Himes-Cornell *et al*. (2018) classify mangroves found between latitudes 30^0N and 30^0S as tropical, accounting for around 98.6% of the world's total coverage, while those at higher latitudes are classified as temperate, making up approximately 1.4% (Bunting *et al*., 2022). As latitude increases, mangrove species diversity and richness decrease. The current global distribution of mangroves is a result of historical geological phenomena (Liu et *al*., 2021). Geological history suggests that mangroves may have evolved separately from their terrestrial predecessors (Cao *et al*., 2018). In ancient times, sea level rise (SLR) submerged ancient mangroves, forcing them to adapt to intertidal conditions (Yang *et al.,* 2019). Relative SLR and shifting climatic conditions affected the spread of mangroves during the Holocene, from approximately 11,700 years ago to the present (Li *et al*., 2022).

1.2 Significance of mangroves

Despite comprising only 3–5% of the world's total forest area, mangroves are disproportionately important for biodiversity and ecosystem services (Bunting et al., 2022). The significance of mangroves as habitats for both marine and terrestrial animals has been extensively reviewed (Himes-Cornell *et al*. 2018; Cherrington *et al*., 2020; Bunting *et al*., 2022; Zhao *et al*., 2023). According to Barbier (2016), the mangrove ecosystem services provided by mangroves have a combined economic worth of US$ 1940 per km^2 annually, totaling to US$ 2.7 trillion globally. Local populations in Africa depend on mangrove wood for various uses, e.g., fish smoking, fuelwood, charcoal, fish traps, lumber, and medicinal purposes, making mangroves highly valuable economically.

The African mangrove ecoregion is remarkably prolific, serving as nutrient traps for watersheds and offers refuge for the young of numerous important fish, shrimp, crab, and mollusk species (Mangora, 2011). Important foraging locations for migratory birds are also provided by the shallow intertidal wetlands frequently connected to the mangroves along coastines (Ghorbanian *et al*., 2021). Notably, mangrove forests and related wetland habitats are internationally significant for migratory species such as the curlew sandpiper, little stint, roseate tern, and Caspian tern (Jia *et al*., 2021). Upstream mangroves in more intact mangrove areas are habitants for blue monkeys, spot-necked otter, hippopotamus, and Nile crocodiles (Ghorbanian *et al*., 2021). Olive ridley, hawksbill, and green turtle populations rely on the Tana River Delta and the Rufiji Delta for mating and foraging (Jia *et al*., 2021).

Seagrass beds, tidal marshes, and mangrove forests are examples of blue carbon (BC) ecosystems that sequester and retain organic carbon (Li *et al*., 2022). Blue carbon (BC) ecosystems are essential for mitigating the effects of climate change and provide additional benefits, such as serving as carbon sinks, improving water quality, preventing flooding and extreme weather events, providing refuge for fish and other organisms, and reducing coastal erosion (Alongi, 2014). Although they comprise a very small portion of the world's total forest area, mangrove ecosystems are among the best on Earth for carbon sequestration. Compared to other tropical forests, mangroves trap roughly three to four times as much carbon (Powers *et al*., 2023) and store over 21 gigatons of carbon globally (Chamberlain *et al*., 2021).

The African Carbon Markets Initiative (ACMI) was presented at The Conference of the Parties (COP 27) in 2022, with the goal of significantly extending voluntary carbon markets throughout Africa (Bhargava et al., 2022). African Carbon Markets Initiative (ACMI) aims to encourage carbon credit generation across the continent. A carbon credit is a document that certifies the removal of one tonne of carbon dioxide (approximately 1000 kg) from the atmosphere through various methods, such as planting new trees. By restoring and conserving degraded mangroves, countries can produce carbon credits (Halder *et al*., 2021).

1.3 Status of mangrove in Zanzibar

Zanzibar has ten different types of mangroves species. On Unguja and the Pemba Islands, eight common species include *Xylocarpus granatum, Heritiera littoralis, Lumnitzea racemosa, Soneratia Alba, Ceriops tagal, Rhizophora mucronata, Bruguiera gymnorrhiza*, and *Avicennia marina* (Leskinen *et al*., 1997). These species belong to six families: Meliaceae, Combretaceae, Rhizophoraceae, Lythraceae, Avicenniaceae, and Lauraceae. The mangroves of Zanzibar encompass all species present in the Western Indian Ocean, forming an intricate network with coral reefs, sea grass beds, algae, and sandy beaches (Leskinen *et al*., 1997). On Unguja Island, mangroves are only found in protected bays like Makoba, Chwaka, and Menai (RGoZ, 2013), while Pemba Island has mangroves along its entire shore, making them more abundant than on Unguja Island (Mohammed, 2002).

The coral rag forest is Zanzibar's largest forest, followed by the mangrove forests, although details regarding mangrove coverage are scanty (RGoZ, 2013). Previous surveys showed that mangrove forests were only listed in a few of the creeks on the islands of Unguja and Pemba (Nahonyo, 2005). Early studies used a planimeter to estimate the areas covered by mangrove cover and visually assessed the percentage distribution of different species (Leskinen *et al*., 1997). Using aerial photos from 1989, researchers later estimated the volume and spatial distribution of mangroves, finding a total of 205,000 m^3 of mangroves in Unguja and 436,100 m^3 in Pemba (Mchega *et al*., 2010). Subsequent research identified approximately 20,000 ha of mangrove forest along Zanzibar's coastline, representing 8.6% of the country's total land area of 232,800 ha, with 6,000 ha are in Unguja and 14,000 ha are in Pemba (Mchega *et al*., 2010).

In 1997, the first thorough inventory of wood biomass was conducted, revealing that about 1,000 ha of natural forests, including mangroves, are lost each year (RGoZ, 2013). This is demonstrated by a notable reduction of 19,748 ha in Zanzibar's mangrove forest, with 5,829 ha are in Unguja, and 13,919 ha are in Pemba (Mchega *et al.,* 2010). According to the 2012 comprehensive mangrove biomass inventory, updated using RapidEye images, Zanzibar's mangrove coverage was estimated at 16,488 ha, including 5,274 ha for Unguja Island and 11,214 ha for Pemba Island (Mchega *et al*., 2010). Different surveys employ different methodologies for assessing mangrove coverage, making it difficult to compare results and establish the accuracy of mangrove cover assessments in Zanzibar. According to Leskinen *et al.* (1997), SONARECOD (2008), and RGoZ (2013), Unguja Island's mangrove growing stock has experienced a significant decline of 18.9 ha, more than twice the 41.0 ha decline noted in the last inventory from 1992–1993 (Mchega *et al*., 2010). On the contrary, the reduction in mangrove growing stock per hectare in Pemba Island was insignificant, decreasing from 39.8 ha to 38.3 ha (Mchega *et al*., 2010; Saleh, 2012). Various factors, including changes in sea level, human activities, and geomorphological processes, have contributed to changes in the mangrove ecosystem (RGoZ, 2013).

Over the past few decades, Zanzibar's mangroves have faced significant challenges and pressures. In the eighteenth century, the Sultan of Zanzibar collected mangrove wood for building and exported it to the Middle East, Europe, and America, marking the beginning of mangrove exploitation (Griffith, 1950). This exploitation, particularly on Unguja Island, led to severe destruction of mangrove forests due to a lack of management plans (Griffith, 1950). Many parts of Zanzibar Island have reported degradation of mangrove forests due to a variety of factors, including salt production, collection of fuel wood, construction, and urban expansion (Paramita *et al.,* 2013; Saleh, 2012). The species most commonly exploited are found on the upper and middle shore, specifically *C. tagal, R. mucronata*, and *B. gymnorrhiza*. Some studies have reported that many of Zanzibar's creeks have less diverse faunal communities as a result of the degradation of mangroves (Saleh, 2012). Despite increasing management efforts in certain areas, the losses in mangrove biodiversity persist, since these efforts have not been sufficient (Paramita *et al*., 2013).

Both governmental and non-governmental organizations are working hard to prevent further destruction of mangrove forests (RGoZ, 2013). Community awareness of the restoration of mangroves has noticeably increased in Kisakasaka, Pete, Muungoni, and Muwanda in Unguja, and in Gawani, Mkoani, Kisiwa Panzaa, Makoongwe, and Micheweni in Pemba (RGoZ, 2013).

Studies on mangrove forests in Zanzibar highlight their critical ecological, socio-economic, and cultural significance, while also identifying areas that require further research. Previous studies have emphasized the role of mangroves in providing key ecosystem services such as coastal protection, carbon sequestration, biodiversity conservation, and support for fisheries (Kukkonen *et al*., 2014; Nagelkerken *et al*., 2015). However, there are still gaps in understanding the full extent of mangrove degradation due to both natural factors like sea-level rise and anthropogenic pressures, including unsustainable harvesting, urbanization, and aquaculture development (Wang *et al*., 2021; Ellison *et al*., 2020).

Detailed investigations into the socio-economic drivers of mangrove exploitation are necessary, particularly in relation to population growth, economic development, and land-use changes, which often exacerbate deforestation and habitat fragmentation (Jia *et al*., 2021). Moreover, while remote sensing technologies have been widely used to map and monitor changes in mangrove coverage, there is a need for higher-resolution imagery and advanced classification techniques to better capture small-scale alterations in mangrove structure and health (Maung *et al*., 2024). These improvements could enhance the accuracy of conservation strategies and inform policymakers on the most vulnerable areas requiring intervention.

The influence of climate change on mangrove resilience and regeneration remains under-researched, particularly in terms of how changing environmental conditions may affect species composition, productivity, and ecosystem services over time. Another area requiring further attention is the integration of local ecological knowledge and participatory governance models into mangrove conservation policies. While some efforts have been made to involve local communities in management practices, more research is needed to understand how traditional knowledge and community-based conservation initiatives can be better aligned with national and international regulatory frameworks to ensure sustainable use and long-term preservation of Zanzibar's mangrove ecosystems (Stringer *et al*., 2006; Scholte *et al*., 2015).

The potential for Payment for Ecosystem Services (PES) schemes to incentivize mangrove protection has been discussed in the literature, however, empirical studies are necessary to evaluate their feasibility and effectiveness in the Zanzibari context, particularly regarding their impact on poverty alleviation and ecosystem restoration (Pagiola *et al*., 2007). Addressing these research gaps will be crucial for developing more comprehensive and adaptive management strategies that safeguard Zanzibar's mangroves against future environmental and human-induced threats.

The policy and regulatory landscape governing mangrove management in Zanzibar faces numerous challenges that hinder the effective conservation and sustainable use of these critical ecosystems. Despite significant legislative efforts, including the introduction of the Forest Resources Management and Conservation Act of 1996 and subsequent reforms aimed at protecting mangroves, gaps in policy implementation and enforcement persist (Slobodian *et al*., 2019). A key challenge lies in the overlapping jurisdiction between different government agencies and the lack of coordination among stakeholders, which often leads to fragmented and inefficient management practices (Mohamed *et al*., 2023). Moreover, while policies exist to regulate activities like mangrove harvesting and land use in coastal areas, weak enforcement mechanisms and limited resources for monitoring contribute to continued degradation from illegal logging, urban expansion, and unsustainable aquaculture practices (Kukkonen *et al*., 2014).

Local communities, who are heavily dependent on mangrove ecosystems for livelihoods, often have limited involvement in decision-making processes, leading to policies that fail to align with the realities on the ground (Mohamed *et al*., 2023). The integration of local ecological knowledge and traditional resource management practices into formal governance structures remains underdeveloped, further complicating efforts to achieve sustainable management (Scholte *et al*., 2015). To address these challenges, there is a need for comprehensive strategies that emphasize community engagement, capacity building, and the development of adaptive management frameworks that respond to both ecological and socio-economic dynamics (Mohamed *et al*., 2023).

Strengthening the institutional capacity of local government bodies, enhancing cross-sectoral collaboration, and ensuring that national policies align with international environmental agreements, such as the Ramsar Convention and the UNFCCC, are critical for advancing mangrove conservation. Furthermore, the promotion of Payment for Ecosystem Services (PES) schemes and eco-tourism initiatives could provide financial incentives for local communities to engage in mangrove restoration and conservation efforts. These strategies, combined with increased investment in monitoring technologies such as remote sensing, could enhance the resilience of Zanzibar's mangrove ecosystems and support their sustainable management in the face of growing environmental and anthropogenic pressures (Pagiola *et al*., 2007).

1.4 Role of remote sensing in monitoring mangroves

According to Ou *et al*. (2023), fieldwork observation and survey techniques have historically been employed to monitor mangrove ecosystems. However, the dense understory and intertidal zones of mangroves make in situ monitoring and measuring challenging (Kumar *et al*., 2020). These survey methods are often expensive, time-consuming, and have limited scope. Many surveys are qualitative in nature, making them challenging to repeat or analyze over time, with many being qualitative in nature, which complicates repeatability and long-term analysis. Remote sensing has emerged as a sustainable method for studying mangroves, addressing the challenges posed by these ecosystems (Yang *et al*., 2018; Kumar *et al*., 2020). Over the past 40 years, RS has significantly improved in terms of spatial resolution, revisit time, and cost, thereby overcoming the shortcomings of conventional field surveys (Congalton *et al*., 2019). Identifying mangrove species is crucial for effective management because understanding each ecosystem's unique features provides essential insights into geomorphic and environmental variables and changes (Wan *et al*., 2020). However, mangrove mapping is still difficult because individual trees may be too small to be accurately identified in imagery, and different mangrove species are found in diverse ecosystems with closely associated species that have similar spectral reflectance (Huang *et al*., 2022).

Due to spectral and spatial limitations, traditional image classification methods have not been able to distinguish between mangrove variables. Nevertheless, relatively high spatial resolution data and innovative techniques have successfully mapped mangroves accurately (Kumar *et al*., 2020). Space-borne systems, such as GeoEye, IKONOS, WorldView, and QuickBird, can produce high-resolution images with spatial resolutions of less than 5 m. The panchromatic data from GeoEye, WorldView, IKONOS, and QuickBird have spatial resolutions of 0.50 m, 0.61 m, 0.83 m, and 2 m, respectively. Aerial photos and high-resolution satellite images, such as WorldView-2, can be interpreted visually. Nonetheless, the overall accuracy of these methods has historically been relatively poor, ranging from 42% to 68% (Wei *et al*., (2021). The distribution of mangrove species is often determined using pixel-based image classification techniques, particularly for data from high spatial resolution sensors like QuickBird and IKONOS.

On these data, pixel-based maximum likelihood classification (MLC) can yield results with an accuracy of 63% to 82% (Fu *et al*., 2022). When using pan-sharpened QuickBird data, pixel-based fuzzy classification techniques can distinguish between many mangrove species with an overall accuracy of 72%. However, when utilizing hyperspectral CASI-2 data, the accuracy drops to less than 60% (Wang *et al*., 2023).

Mangrove species mapping has recently used object-based image classification techniques utilizing image segmentation, such as object-based image analysis (OBIA) (Mao *et al.,* 2020). Several studies indicate that OBIA methods can identify mangrove species populations with greater overall accuracy than pixel-based methods (Jiang *et al*., 2021). Hyperspectral datasets like the EO-1 Hyperion and the CASI-2 further aid in mangrove species classification (Wang *et al*., 2023). Object-based image analysis (OBIA) algorithms generally outperformed traditional pixel-based techniques when mapping mangrove species using hyperspectral data with fine spatial resolution (see Jiang et al., 2021). For medium spatial resolution imagery, such as Landsat, and for higher resolution Pléiades-1 imagery, machine learning algorithms can increase the accuracy of mangrove species classification (Jiang *et al*., 2021). Additionally, feature extraction from very high spatial resolution imagery helps in distinguishing between mangrove species and communities (Fu *et al*., 2023). The grey-level co-occurrence matrix (GLCM), increasingly used for mangrove species classification, has demonstrated promising accuracy of ~89% for WorldView-2 and >81% for IKONOS imagery (Yi *et al*., 2022).

A recent study by Magalhães *et al*. (2022) demonstrated that an object-based logistic model tree (LMT) method can be used to map mangroves in Vietnam with an accuracy of >80%, utilizing data from the Advanced Land Observing synthetic aperture radar (SAR) (Wang *et al*., 2023). More recently, Chen *et al.* (2023) demonstrated the potential use of a pixel-based classifier based on the normalized difference vegetation index (NDVI) for mapping mangrove species in Fujian Zhangjiangkou National Mangrove Nature Reserve using GF-2, GF-3, and UAV-LiDAR. They concluded that higher spatial resolutions result in higher accuracy.

1.5 Mangrove species mapping using machine learning classifiers

New machine learning techniques have been developed due to recent advancements in artificial intelligence (AI), pattern recognition, and computer vision technologies (Holloway *et al*., 2018). These techniques enable more accurate mapping of mangroves compared to traditional classification methods. Machine learning algorithms can be employed to map mangroves and discriminate between species using synthetic aperture radar (SAR) data (Behera *et al*., 2021), optical data (Mandianpari *et al*., 2017; Aja *et al*., 2022; Shen *et al*., 2023), and hyperspectral imaging (George-Chacon *et al*., 2019; Yang *et al*., 2022; Tian *et al*., 2023). Traditional machine learning methods, such as decision trees (DT), also known as CART (classification and regression trees), and C4.5 algorithms, are rarely used for classifying mangrove species (Mondal *et al*., 2019). Instead, researchers typically use support vector machines (SVM), random forests (RF), and artificial neural networks (ANN) to classify mangrove communities, as these methods can create non-parametric classification models (Chicco *et al*., 2020; Liu *et al*., 2021; Chan-Bagot *et al*., 2024). For example, Chan-Bagot *et al*. (2024) used Pléiades-1 data to examine how well a few machine learning methods performed while mapping artificial mangrove species (Wessel *et al*., 2018). Some studies have found that RF yielded the best results for object-based image classification, while SVM produced superior overall accuracy for pixel-based image analysis (Behera *et al*., 2021). Using pan-sharpened WorldView-2, algorithms like SVM can accurately classify mangrove species with over 87% accuracy (Yang *et al*., 2022). Additionally, using time-series data from Gaofen-1 (GF-1) and Satellite Pour l'Observation de la Terre (SPOT), these algorithms produced overall accuracy ranging from 67% to 92% (George-Chacon *et al*., 2019).

When machine learning algorithms combine textural and differential spectral information, they show great promise in identifying mangrove species (Ghorbanian *et al*., 2021). For instance, clustering-based neural networks can use high-resolution multispectral imagery and textural data from the panchromatic band to distinguish between certain mangrove species with an overall accuracy of >90%. Zhao *et al*. (2023) compared a few machine-learning techniques for categorizing mangrove species and proposed that the classification accuracy might be increased by combining radar and optical methods. Fu *et al*. (2023) found that employing rotation forest (RoF) to discriminate between mangrove species can increase the Kappa coefficient and overall accuracy when optical and SAR data are combined. In addition, Wei *et al*. (2023) tested a number of machine learning algorithms for the classification of mangrove species and found that RoF performed better than SVM and RF algorithms, achieving a performance of 85.23%.

1.6 Remote sensing of mangrove: constraints and uncertainties

Remote sensing data has varying spatial, radiometric, temporal, and spectral resolutions that limit the ability to classify tree species and estimate Above Ground Biomass (AGB) (Pastor-Guzman *et al*., 2018). Landsat 8 (Operational Land Imager - OLI), Landsat 7 (Enhanced Thematic Mapper - ETM+), and Landsat 5 (Thematic Mapper ™) with a spatial resolution of 30 m, are examples of medium to low spatial resolution data that contain many mixed pixels, each with information on different tree species. Due to the complexity of mangrove communities, it may be challenging to classify mangrove species using medium spatial resolution data. Moreover, spectral resolution must be considered while selecting a satellite sensor. Sentinel-2 offers superior spatial and spectral resolutions, making it a valuable tool for classifying tree species and retrieving AGB data (Manna and Raychaudhuri, 2020). On the other hand, Landsat sensors comprise one thermal band and six multispectral bands, ranging from visible to near-infrared and shortwave infrared, which may make it more difficult to identify some mangrove species. Maung *et al*. (2024) stated that the most crucial feature for mangrove classification is the red-edge band obtained from Sentinel-2 imagery. Rahmandhana *et al*. (2022) found that the red-edge band obtained from the WorldView-2 exhibits more sensitivity to mangrove AGB than vegetation indices and other multispectral bands. Apart from radiometric and spectral resolution (e.g., the eight-bit Landsat 5 TM and the 12-bit Landsat 8 OLI data), it is important to consider that similarities between biomass and digital number (DN) values can saturate AGB estimation. Due to its greater number of bands with small wavelengths, hyperspectral images may help overcome these limitations (Bonilla-Roman *et al*., 2024).

In order to decrease atmospheric conditions such as water vapor concentration and aerosols, and to mitigate the effects of topography, especially in forested areas, optical imaging often requires atmospheric and radiometric correction (Shen *et al*., 2023). Air and radiometric corrections may impact on the precision remote sensing of mangrove species and AGB (Pons *et al*., 2014). Consequently, atmospheric and radiometric correction methods have been developed (Shen *et al*., 2023). For example, Li *et al*. (2022) employed principal component analysis (PCA)-based correction and multivariate alteration detection (MAD) transformation-based normalization to extract forest features.

A more sophisticated and automatic radiometric adjustment of Landsat imagery was created by Pons *et al*. (2014) using surface reflectance reference values from MODIS. Speckling is a prevalent issue with SAR data that affects the accuracy of above ground biomass (AGB) retrieval and SAR image classification. Applying a filter to despeck SAR data can help eliminate noise while preserving image features. However, this can also lead to filtered or blurry images, which may impact the accuracy of AGB retrieval and image classification. To address the speckle limitation in future research, applying nonlocal filters to reduce noise in SAR images is essential (Shen *et al*., 2023).

Since optical and SAR sensors differ in how they reflect forest structures and land surfaces, it is recommended to combine complimentary satellite remotely sensed datasets to improve information about mangrove species, structure, and AGB. Merging data from multiple sensors can significantly improve mangrove species mapping. Numerous studies have explored data fusion based on the integration of various optical sensors, such as SPOT multispectral and panchromatic bands (Rahmandhana *et al*. 2022), or SPOT High Resolution Visible (HRV) and Landsat Thematic Mapper (TM) (Chahbi *et al*., 2018). Furthermore, improved accuracy in quantifying biophysical factors, including Leaf area index (LAI), leaf pigments, and canopy height, as well as assessing tropical forest biomass, can be obtained through the combination of SAR and optical data, such as ALOS-2 PALSAL-2 and Sentinel-2A (Shao *et al*., 2024), or Landsat TM and ALOS PALSAR. Despite the benefits of data fusion, image processing has time and labor constraints that should be considered, particularly when processing vast areas (Chan-Bagot *et al.,* 2024).

1.7 The use of Landsat data for mangrove studies

This study used Landsat images to map mangrove species and their changes. Landsat plays an essential role, providing high-quality, free images since 1972. Because of Landsat's long history of availability and consistency, it has become a vital tool for scientists, planners, and decision-makers worldwide (Wang *et al*., 2020). The vast data archive of Landsat data provides an unmatched perspective of Earth's evolution over time, greatly advancing scientific understanding and management of natural resources. With its long-standing commitment to free data and strong spectral and geographic resolution, Landsat is an indispensable instrument for various Earth observation applications (Chan-Bagot *et al*., 2024). According to Pandya *et al*. (2024), Landsat imagery is one of the most valuable instruments for mapping mangrove ecosystems, as it allows for the classification of land use features in a region of interest. Landsat's easy accessibility and excellent spatiotemporal resolution provide a wide range of options for conducting mangrove studies (Purwanto *et al*., 2023).

Various techniques for identifying or extracting mangrove forests from Landsat images include spectral indices, object-based methods, neural network classification, and supervised and unsupervised classification (Beckschäfer, 2017). Ulqodry *et al*. (2021) attest to the applicability of satellite imagery and vegetation indices in mapping mangroves, yielding satisfactory results. Nevertheless, there are relatively few studies that specifically assess mangrove cover using Landsat satellite images (Vu *et al.,* 2022).

Remote sensing yields more precise and efficient results for tracking and mapping mangrove ecosystems (Shen *et al*., 2023; Shao *et al*., 2024). Nonetheless, a primary constraint of such studies is the lack of satellite images with uniform tide levels. Varying tide levels may considerably distort the detection of mangroves. Landsat sensors help address this issue with their time-series images (Vu *et al*., 2022). Thus, Landsat's temporal resolution enables choosing images during seasons with similar tide levels (Ulqodry *et al*., 2021).

1.8 Research aims and objectives

The main goal of this study was to understand the dynamics of mangroves and their ecosystem services in Menai Bay and Chwaka Bay over the past forty years using remote sensing (RS) technology and community-based methods.

The specific objectives of this study were:

1. To review policy and regulatory challenges, and strategies for sustainable mangrove management in Zanzibar.
2. To assess the perception and contribution of mangrove ecosystem services to the well-being of coastal communities in Chwaka and Menai Bays, Zanzibar.
3. To map the spatial and temporal distribution of mangrove forest cover from 1973 to 2020 in Chwaka Bay and Menai Bay, Zanzibar.
4. To map the mangrove species in Menai Bay, Zanzibar, using Landsat 9 OLI-2 and machine learning algorithms.

1.9 Scope of the study

In this study, remote sensing techniques were primarily used to map and monitor mangrove species and dynamics, while field-based methodologies were employed to assess mangrove ecosystem services in Menai and Chwaka Bays. Mangroves are a key source of ecosystem services and support a wide variety of wildlife in both bays. Subsequently, the effectiveness of policies, regulations, institutional arrangements, and laws in conserving and managing mangrove forests was evaluated.

1.10 The study area

This study focused on two protected areas—Chwaka Bay and Menai Bay located on Unguja Island in Zanzibar, Tanzania (Figure 1.1). Zanzibar accounts for 18,000 ha of Tanzania's 125,000 ha of mangroves. The two study sites cover roughly 4400 ha (Klein *et al*., 2008). One of the two major islands in Tanzania's semi-autonomous Zanzibar archipelago is Unguja, which has a surface area of roughly 1660 km^2 (Lugomela, 2012). The island is located between 5°70′ and 6°50′ S and 39°18′ and 60′ E, south of the equator. The northeast and southeast monsoon winds have an impact on the climate (Shunula, 2001).

Zanzibar experiences two primary rainy seasons, influenced by the movement of the Intertropical Convergence Zone (ITCZ): the long rains (Masika) from March to May and the short rains (Vuli) from October to December (Lugomela, 2012). The Masika season is marked by heavy, sustained rainfall, with April being the wettest month, while the Vuli season brings lighter, more sporadic showers (Shunula, 2001). Annual rainfall averages around 1,500 mm, though it varies between the coastal regions and the interior (Lugomela, 2012). This rainfall plays a crucial role in supporting Zanzibar's largely agricultural economy, particularly the cultivation of essential crops such as cloves, coconuts, and bananas (Kukkonen *et al*., 2014). Zanzibar's tropical climate provides warm and consistent temperatures year-round, with some seasonal fluctuations (Kukkonen *et al*., 2014). Average temperatures typically range from 24°C to 32°C, with the hottest period occurring between January and March when daytime highs often surpass 30°C (86°F) (Lugomela, 2012). The cooler months, from June to August, see temperatures dip slightly to between 25°C and 28°C (77°F to 82°F) (Shunula, 2001). This cooler period aligns with the southeast monsoon season, which brings pleasant winds that help ease the heat (Kukkonen *et al*., 2014). Zanzibar experiences high humidity year-round, ranging from 70% to 90%, largely due to its tropical climate and proximity to the ocean (Lugomela, 2012). Humidity is at its peak during the rainy seasons, especially during Masika, when the air is filled with moisture, leading to muggy conditions (Shunula, 2001). Even in the dry season, humidity seldom drops below 70%, keeping the atmosphere consistently humid (Aziz *et al*., 2015). Zanzibar benefits from plentiful solar radiation throughout the year, especially during the dry season from June to October when there is little cloud cover (Shunula, 2001; Abdul Aziz *et al*., 2015). During this time, the islands receive an average of 8 to 9 hours of sunshine daily. Solar energy is becoming an increasingly important renewable energy source in Zanzibar, particularly in rural areas with limited access to the electrical grid. The strong solar radiation also leads to high evaporation rates, which can worsen water shortages during dry periods. Zanzibar's wind patterns are largely influenced by two monsoon systems: the northeast monsoon (Kaskazi) from November to March and the southeast monsoon (Kusi) from June to September (Machiwa *et al*., 1995). The Kaskazi brings warm, dry winds with moderate speeds of 10-20 km/h, whereas the Kusi brings cooler, stronger winds, with speeds ranging from 20-30 km/h (Machiwa *et al*., 1995; Kukkonen *et al*., 2014). Chwaka Bay, located 34 kilometers east of Zanzibar Town on the east coast of Unguja, has the largest mangrove coverage in Zanzibar, spanning over 2294 ha (Shunula, 2001).

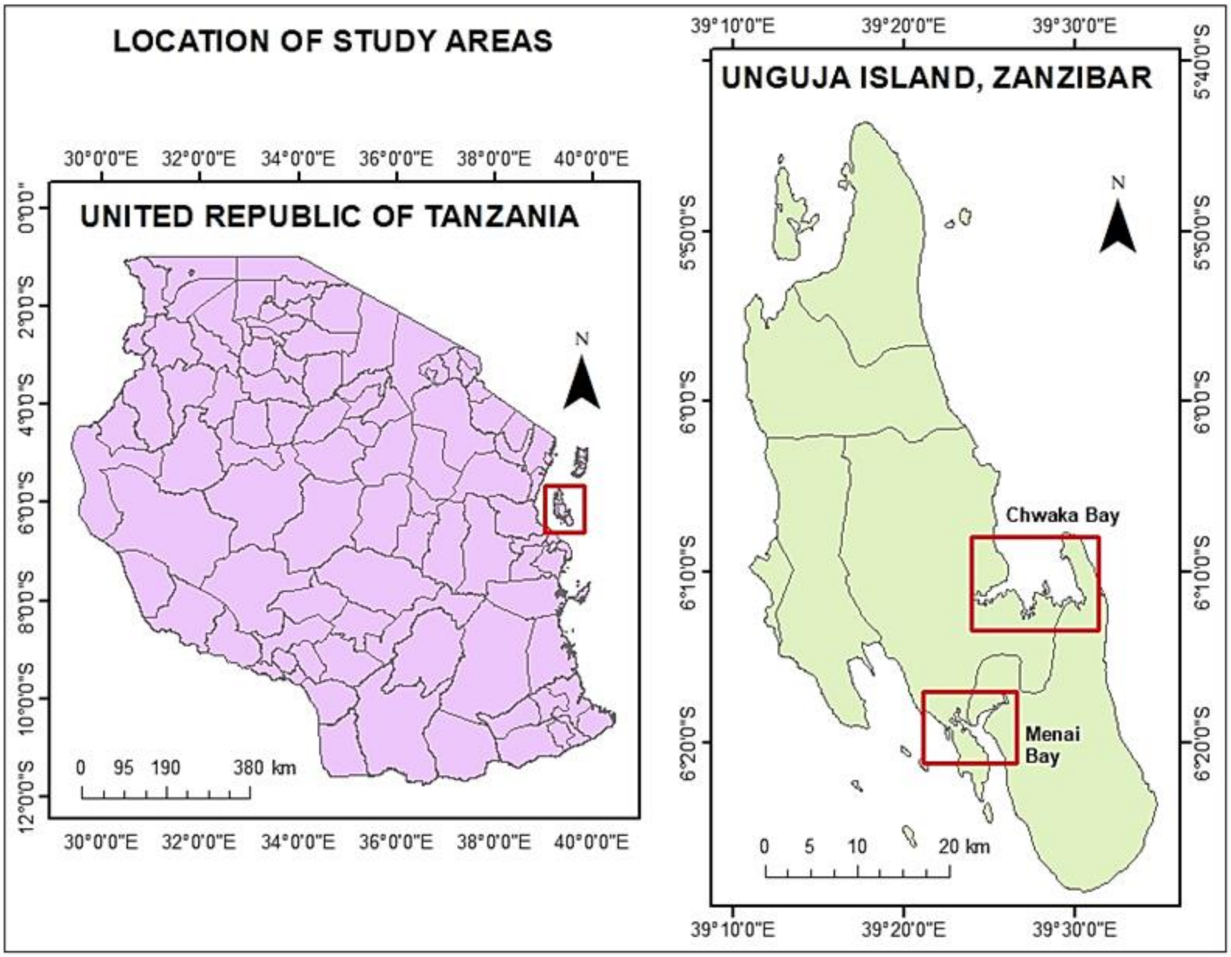


Figure 1.1. *Map of Tanzania on the left and of Semi-autonomous Island of Unguja, Zanzibar showing the location of the Chwaka and Menai Bays.*

According to Aziz *et al*. (2015), Chwaka Bay is home to ten different species of mangroves: *Bruguiera gymnorrhiza, Rhizophora racemose, Ceriops tagal, Pemphis acidula, Sonneratia alba, Xylocarpus moluccensis, Avicennia marina, Xylocarpus granatum, Lumnitzera racemose* and *Heritiera littoralis*. The Menai Bay Conservation Area (MBCA), located southwest of Unguja, contains six islets (Aziz *et al*., 2015). Both bays have numerous mangrove stumps but lack fully developed trees (Shunula, 2001; Aziz *et al*., 2015). A few immature *Ceriops tagal* and *Bruguiera gymnorrhiza* trees are found along the forest's edge. Other mangrove species include *Rhizophora mucronata*, *Avicennia marina, Sonneratia alba*, *Lumnitzera racemosa, Heritiera littoralis* and *Xylocarpus granatum*. Menai Bay comprises about 988 acres of mangroves; however, due to deforestation, its ecological composition differs from that of the neighboring Jozani mangrove forest. Chwaka and Menai Bays are surrounded by five major wards—Charawe, Chwaka, Ukongoroni, Unguja Ukuu, and Uzi—whose populations, according to the 2022 census report, are 954, 3,196, 896, 1,563, and 1,801, respectively. The mangroves in the two bays occupy specific ecological niches; this zonation pattern, combined with the unique spectral and textural characteristics of each species, enabled effective mapping using remote sensing imagery. The mangrove ecosystems in the two bays are essential for the survival of these communities. Zanzibar boasts of amazing beaches, coral reefs, and rich culture. In 2000, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) declared Zanzibar a World Heritage Site (Kukkonen *et al*., 2014).

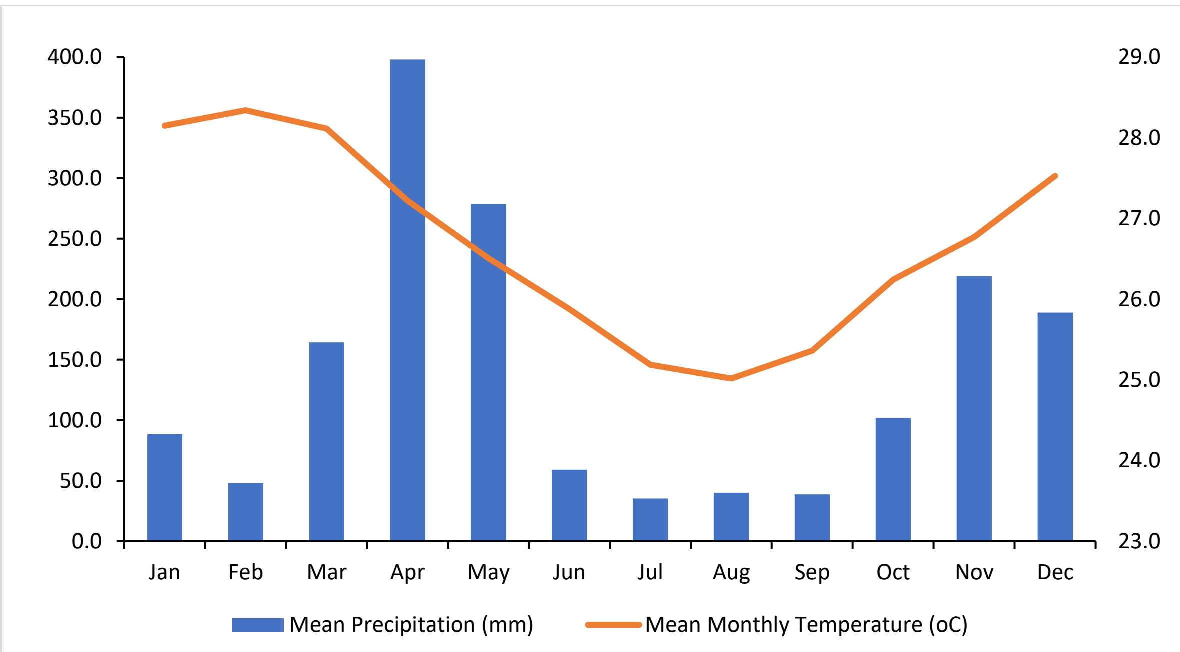


Figure 1.2. *Mean precipitation (in millimetres) and mean monthly temperature (in degrees Celsius) in Zanzibar.*

1.11 Thesis overview

The thesis aims to achieve the main objectives of the study through four research papers submitted to international peer-reviewed journals. Three of which have already been published, while the fourth is under review. Each paper is written as a stand-alone article that can be read independently of the other parts of the thesis, though each draws conclusions linked to the overall research objectives and questions. As a result, there are overlaps and replications in the 'Introduction" and

"Method" sections in the various chapters. However, considering the rigorous peer-review process and the fact that the various chapters are papers that can be read independently without losing the overall context, this problem is of relatively minor importance. The thesis is divided into seven chapters.

Chapter 2 primarily examines issues related to Zanzibar's sustainable mangrove management from 1890 to the present, focusing on the regulatory framework and related initiatives. Both secondary and primary data were gathered for the study. Secondary data were obtained through a review of past regulations, contracts, bylaws, reports from government ministries and departments, studies, newspaper articles, and research reports. Semi-structured interviews and focus group discussions (FGDs) were the key methods used to gather primary data.

The primary goal of Chapter 3 was to assess how mangrove ecosystem services are perceived and how they contribute to the well-being of the coastal populations in Chwaka and Menai Bays, Zanzibar. Data were gathered through focus group discussions (FGDs), key informant interviews (KIIs), and household surveys. The awareness and perception of the services provided by the mangrove ecosystem were compared using chi-squared tests and one-way ANOVA. Snowball sampling was employed to recruit participants for the FGDs, targeting local residents of Menai Bay and/or those knowledgeable of the services provided by mangrove ecosystems. Five focus group meetings were held, with nine to eleven participants per group. Statistical analyses were conducted using IBM SPSS software, version 23 (Armonk, NY, USA).

Chapter 4 mapped the spatial and temporal distribution of mangrove forest cover in Zanzibar's Chwaka and Menai Bays between 1973 and 2020. Mangrove forest changes over this period were computed using the CROSSTAB module of the TerrSet Geospatial Monitoring and Modeling Systems. The CROSSTAB module produced cross-classification images and tabular matrices created from cross-tabulation, showing the number of pixels corresponding to each combination of classes in two classified maps. Additionally, the CROSSTAB module computed tabular matrices of the percentage of total pixels along with summary data.

The main objective of Chapter 5 was to map mangrove species in Menai Bay using metrics extracted from the Landsat 9 OLI-2 dataset, i.e., vegetation indices (VIs) and gray-level co-occurrence matrices (GLCMs). A critical step was identifying the contribution of VIs and texture features to the classification of mangrove species. Before using the random forest (RF) model, the number of decision trees (*ntree*) in the ensemble and the number of predictor variables (*mtry*) randomly selected at each node were defined. A 10-fold grid search strategy was applied to find the best-performing parameters to train the classifier. Random forest (RF) improves prediction accuracy by turning a large number of weak learners, or decision trees, into a stronger predictor by aggregating their predictions. The final class for unknown values was determined by the majority "vote" of all the trees. The study utilized the mean decrease in accuracy (MDA) as a statistic to evaluate the explanatory power of input variables. When a variable is eliminated from the model, the MDA shows how much accuracy is lost. The MDA indicates how much accuracy is lost when a variable is removed from the model, with higher MDA values signifying greater importance. In addition to texture features and VIs, the classification models also evaluated the spectral bands of Landsat 9 for mangrove species classification.

Chapter 6 synthesizes the key findings from the previous chapters, offering an overarching analysis of the mangrove ecosystems in Zanzibar, specifically in Chwaka and Menai Bays. It highlights the historical and current state of mangrove management, the application of remote sensing techniques for mapping and species classification, and the socio-economic importance of mangrove ecosystem services to coastal communities. The chapter provides actionable recommendations for improving mangrove conservation efforts, addressing both policy and practical measures. Additionally, it outlines potential avenues for future research, such as refining remote sensing techniques for species-specific monitoring, integrating community-based approaches in ecosystem management, and developing methods to better quantify and map the ecological services provided by mangroves. By combining technological advances and local knowledge, the chapter advocates for a holistic approach to sustainable mangrove management in Zanzibar.

At the end of the thesis, a reference list is provided.

CHAPTER TWO

Policy review and regulatory challenges and strategies for the sustainable mangrove management in Zanzibar

This chapter is based on:

Mohamed, M.K., Adam, E., and Jackson, C.M. (2023). Policy Review and Regulatory Challenges and Strategies for the Sustainable Mangrove Management in Zanzibar. *Sustainability*, 15, 1557. https://doi.org/10.3390/su15021557.

Abstract

The aim of this study was to examine the challenges of the policies and regulatory framework and strategies for the sustainable mangrove management in Zanzibar, from 1890 to present. The study collected both primary and secondary data. The secondary data were collected through a review of previous policies, legal documents, by laws, ministry/department reports, research reports, newspapers and articles. The primary data were mainly collected through focus group discussions (FGDs) and semi-structured interviews. The study found that, before Zanzibar became a British protectorate in 1890, the forests were communally managed with the guidance of forest guardians, chiefs and elders. The colonial government enacted a number of land administration laws, policies, and arrangements aimed at conserving the natural resources, including the mangrove forests. From 1930 to the end of the Second World War (WWII), mangrove forests were severely degraded because the colonial government paid little attention to their conservation and management. The policy arrangements put in place after independence, such as the National Forest Conservation and Management Act of 1996, laid the legal groundwork for the introduction of the participation of the local communities in the conservation of mangroves. However, they were not sufficient enough to promote the sustainable use of mangrove forests. This study proposes that there is a need for more inclusive and diverse regulations. Furthermore, for the effective conservation and management of mangroves, conflicting laws and responsibilities between government departments should be harmonized.

***Keywords*:** **M**angrove management. Conservation policies. Regulatory framework. Mangrove governance. Community-based management. Coastal communities. Population growth.

2.1 Introduction

Mangrove forests, considered one of the world's most crucial ecosystems, were originally estimated to cover about 18.1 million hectares (Spalding, 2002). However, later studies reduced this estimate to 13.8 million hectares (Giri *et al*., 2010) and eventually to 8.3 million hectares (Hamilton *et al*., 2016). These coastal forests are essential to local economies, supporting tourism, fishing, and agriculture, especially in Zanzibar (Kukkonen *et al*., 2014; Mkumbukwa, 2014; Nagelkerken *et al*., 2015). Mangroves also serve as natural storm barriers, aid in climate regulation, and provide nurseries for endangered marine species (Nagelkerken *et al*., 2015). In addition to their ecological benefits, mangroves are highly effective carbon sinks, storing 3 to 5 times more organic carbon than tropical upland forests due to their capacity to trap sediments and accumulate biomass (Donato *et al*., 2011; Alongi, 2012). They also function as nutrient sinks and water purifiers, further highlighting their significance (Ewel *et al*., 1998; Pelegrí *et al*., 1998). Their crucial role in coastal protection and climate regulation has increased the urgency for mangrove conservation, especially as climate change accelerates (Kukkonen *et al*., 2014). Several international initiatives have been established to encourage sustainable mangrove management, such as the Convention on Biological Diversity (CBD), the Ramsar Convention, and the UN Framework Convention on Climate Change (UNFCCC), all of which highlight the importance of mangroves in climate change mitigation and biodiversity conservation (InforMEA, 2022). At the regional level, efforts like the Nairobi Convention for the Protection of the Marine and Coastal Environment of the Eastern African Region aim to protect these critical ecosystems (InforMEA, 2022).

Mangrove conservation and utilization policies to international frameworks reveal both synergies and gaps in local implementation. Mangrove ecosystems are vital globally, recognized for their role in biodiversity, carbon sequestration, and coastal protection, which has led to their inclusion in several key international environmental agreements. Zanzibar's mangrove management policies are rooted in national legislation but must align with international commitments to ensure sustainable outcomes. The Ramsar Convention on Wetlands is a cornerstone in international mangrove conservation, recognizing wetlands, including mangroves, as ecosystems of international importance. Countries party to the convention, including Tanzania, commit to the sustainable use of wetlands through the designation of Ramsar sites and the implementation of national wetland management strategies that align with the convention's principles (Ramsar Convention, 1971). The Convention on Biological Diversity (CBD) emphasizes the conservation of mangrove ecosystems as part of global biodiversity targets. Specifically, the CBD's Aichi Biodiversity Target 11 calls for the protection of 17% of terrestrial and inland water areas, including coastal and marine ecosystems like mangroves, through well-connected systems of protected areas by 2020 (CBD, 2010).

Zanzibar's national policies for mangrove conservation and utilization are embedded within broader frameworks such as the Zanzibar Environmental Policy and the Zanzibar Forest Resources Management and Conservation Act. These policies aim to safeguard mangrove ecosystems by promoting sustainable use, restoring degraded areas, and preventing illegal exploitation. The government has also developed mangrove management plans, focusing on integrating community-based management approaches, reflecting global principles of participatory conservation (RGoZ, 2014).

Proper governance of mangroves necessitates coordinated policies across various sectors, supported by institutional and legal frameworks. In Zanzibar, the forestry sector has experienced substantial reforms to improve mangrove conservation and management. However, effective implementation of these policies relies on incorporating local communities into conservation initiatives, alongside national action plans that are aligned with sustainable development goals. This study seeks to evaluate the development of policy and regulatory frameworks governing mangrove conservation in Zanzibar from the 1890s to the present, identifying challenges and suggesting strategies for sustainable management. Effective governance, supported by an appropriate legal and institutional framework, is crucial for the preservation of mangroves. This requires coordinated policies across various sectors that directly address the management and conservation of these ecosystems. Governance encompasses the interactions between institutions, processes, and cultural norms that shape how authority is exercised, decisions are made, and how the public and other stakeholders can express their views (Graham *et al*., 2003; Slobodian *et al.,* 2019). In response to the loss of mangroves, Zanzibar has implemented several laws aimed at their conservation and management. The forestry sector in Zanzibar has undergone significant legislative and policy reforms, altering the laws, regulations, and institutions involved. However, effective policy implementation must be supported by action plans or strategies developed in line with strategic issues related to sustainable development, to effectively manage mangrove ecosystems and improve the welfare of coastal communities. The involvement of local communities is essential for successful mangrove conservation.

The objectives of the policy review and regulatory challenges for sustainable mangrove management in Zanzibar from the 1890s to the present, focus on ensuring the long-term preservation and responsible use of mangrove ecosystems, which are vital for both environmental and socio-economic well-being. Key objectives include evaluating existing policies and regulatory frameworks to identify gaps, inconsistencies, or weaknesses that hinder effective mangrove conservation and sustainable use. This review aims to harmonize the legal and institutional mechanisms, emphasizing mangrove biodiversity conservation. Additionally, it seeks to address regulatory challenges such as inadequate enforcement, lack of public awareness, and conflicting land-use practices, which often lead to deforestation and degradation of mangrove forests. Furthermore, the policy review aims to strengthen institutional capacities and foster collaboration between government agencies, local communities, and international partners. By doing so, Zanzibar can ensure that its mangrove ecosystems are managed in a way that supports livelihoods, safeguards biodiversity, and contributes to climate resilience.

2.2 Materials and methods

2.2.1 Data collection methods

A focal group discussion (FGD) was used to collect the primary data in the study. The focus groups were suitable for obtaining multiple perspectives from the stakeholders—this method was meant to solicit the attitudes and perceptions, knowledge and experiences, and practices of the participants, concerning the conservation of mangroves in Zanzibar. The focus groups are quick and comparatively easy to set up—they can also provide more information, compared to individual data collection (Nyumba *et al.,* 2018). As well, FGDs are advantageous in gaining the understanding of topics that are difficult, when using other methods of data collection (Nyumba *et al.,* 2018). A FGD was conducted in each of the following wards—Charawe, Chwaka, Ukongoroni, Unguja Ukuu, and Uzi. The participants were thought to possess in-depth knowledge of the policy and regulatory framework used in the conservation and management of Zanzibar's mangroves. The targeted individuals were *shehas* (local administrative leaders), villagers who have vast experience in mangrove conservation and rehabilitation, and boat builders, retired and active fishermen, previous and present mangrove cutters and dealers, traditional healers, as well as fish vendors, and non-governmental organization (NGO) and ward-level forest officers. The questions in Appendix A were used to guide the interviews for government officials and FGDs.

The purposive sampling was also used to attract key government officials. A semi-structured interview was used to interview 24 government officials. The participants included were directors in the Ministry of Agriculture and Natural Resources, the deputy general secretary of the ministry, four members of the House of Representatives (Zanzibar Parliament), the regional commissioner and district officer for the South Region. The topics selected for the semi-structured interviews were:

- The importance of mangroves;
- Factors that led to the degradation of mangroves in Zanzibar;
- History of the conservation of mangroves in Zanzibar;
- Policies for the protection of mangroves in Zanzibar;
- Factors in the successful mangrove restoration;
- Community-based mangrove conservation;
- How Zanzibar is doing in the conservation of mangrove forests, compared to other countries;
- The future of mangroves in Zanzibar;
- The role of technology in the conservation, protection, and awareness of mangroves.

Appendix 1 shows an interview schedule for government officials and the FGD guide.

A review of the literature on the mangroves of Zanzibar was also conducted, including the management plans and research reports. Relevant peer-reviewed articles were searched in the web-based databases. A review of previous and present memorandums of understandings (MoUs), policies, laws, agreements, and legislation regarding mangrove forests and the related natural resources, was also conducted. Information on the status of mangrove forests, use patterns, and past and present management regimes were analyzed. Most of this data were taken from documents accessed from the Zanzibar National Archives (ZNA) and from libraries at the Department of Forest, the University of Dar es Salaam Marine Institute—Zanzibar, the State University of Zanzibar (SUZA), the Western Indian Ocean Marine Science Association (WIOMSA) in Zanzibar, as well as the Zanzibar Indian Ocean Research Institute (ZIORI). The information acquired from the different sources, using the different methods was compared to check for the missing links and to clarify indistinct issues.

2.2.2 Sample size and sampling design

The study's primary focus was the heterogeneity of the participants, which was important, in order to obtain a wide range of perspectives from the FGD members. The selection of the key informants, was based on age (≥40 years), the desire to share information about mangrove forests, an understanding of the history of the mangrove management in the ward, whether one was born and stayed in the ward, and the influence they had in mangrove decision making. Twenty-four government officials were interviewed.

2.2.3 Data evaluation and analysis

Two techniques for qualitative data analysis were used to examine and process the information acquired for this study—constant comparison and discourse analyses. In the initial stage of the constant comparison analysis, the data were grouped into small units, and then codes were attached to each of the units. Secondly, the codes were grouped into categories. Finally, themes that expressed the content of each of the groups were developed (Strauss *et al.,* 1998; Nyumba *et al.,* 2018). The discourse analysis involved the assessment of language use by members of the FGDs—to understand them in detail (Phillips *et al.,* 2002; Nyumba *et al.,* 2018). The qualitative data analysis assisted in examining the points of departure related to policy and regulatory practices in the management and conservation of Zanzibar's mangroves by various actors over time. Therefore, the policy analysis associated with the relevant aspects and other related policies, was carried out as one of the enabling factors in putting the study's recommendations into practice. The outcomes of the policy review identified policies and related stakeholders, as well as their roles and obligations.

2.3 Results

2.3.1 Characteristics of the respondents

This study included government officials who have served in the department for no less than 15 years (19 males and 5 females), villagers, heads of wards (Shehas), representative from the

Department of Forestry, fisherman, people who collect medicine and poles from the mangrove, a forest officer at the ward level, a member from the local NGOs. Gender balance was considered in selecting those who participated in the FGDs. The age of respondents varied from 40 years to 84 years, and their educational level varied from an informal education to tertiary education. The monthly earnings of those who participated in the FGDs ranged between USD 121 to USD 148. Their main source of cooking energy was firewood. About 44% of the participants' houses were connected with tap water and 54% of their houses were supplied with electricity.

2.3.2 Stakeholders' analysis

Both the 1992 National Environmental Policy and the 1992 Forestry Policy used an integrated strategy for the resource management (RGoZ., 2009; Mkumbukwa, 2014). The Department of Environment is taking a coordinating role in implementing the integrated coastal management (ICAM) approach (Mkumbukwa, 2014). The regional and district levels have the roles of managing the natural resources—the staff are well-trained and well-equipped to manage the coastal area sustainably and to balance between the environmental, social, and development needs (RGoZ., 2009; Mkumbukwa, 2014). The natural resource management sectors, such as fisheries, forestry, and agriculture have district officers who oversee the conservation and use of natural resources—including mangrove forests (RGoZ., 2009; Mkumbukwa, 2014). Higher education institutions are crucial for studying and consulting on issues relating to forests—yet they receive little financial assistance from the government. Government-managed councils at the local level are in charge of creating and carrying out their local development plans. Additionally, some NGOs are focused on the conservation of coastal resources—examples are the Zanzibar Association for Cleaning Environment and Development of Youth (ZACCEDY), the Zanzibar Climate Change Alliance, the Zanzibar Volunteers for Environmental Conservation (ZAVECO), and the Jozani Environmental Conservation Association (JECA). Faith-based organizations have not involved themselves in matters of environmental conservation.

2.3.3 Underlying drivers of the mangrove loss in Zanzibar

As in many other parts of the world, the loss of mangroves in Zanzibar can be largely attributed to the development and population growth along the coast (Kukkonen *et al.,* 2014; Ngoile *et al*., 2021). The specific reasons include urbanization, aquaculture, agricultural conversion, and timber overexploitation (Kukkonen *et al.,* 2014; Ngoile *et al*., 2021). The losses are significant because mangroves offer both nature and people a wide range of services and benefits. Mangroves have been a significant source of building materials and firewood for Zanzibar's coastal communities since the pre-colonial era (Machiwa *et al*., 1995). From the mid-nineteenth century, there has been increased pressure on the exploitation of mangroves and other aquatic resources (Hamad *et al*., 2019). In the 1840s, the Omani-Arabs Sultanate established its headquarters in Zanzibar, and developed cloves and coconut plantations—large tracts of land and forests were turned into agricultural land (Mkumbukwa, 2014). Near the coast of Malindi, a new capital, known as Stone Town, was established (Sheriff, 1991) The marine environment and resources, including mangroves, were not exempted from the adverse effects of such developments (Ngoile *et al*., 2021). The deforestation and degradation of mangrove forests, which took place before the First World War (WWI), continued even after the Second World War (WWII) (Ngoile *et al*., 2021). Currently, the rapid population increase and rising poverty levels have contributed to the further destruction of the mangrove ecosystems (Ngoile *et al*., 2021).

Information on the area coverage of Zanzibar's mangroves remains scanty (Mchenga *et al*., 1995). Ngoile *et al*. (2021) used a planimeter to perform a visual estimation of the abundance of mangrove species in some creeks in Unguja and Pemba Islands. Leskinen *et al*. (1993) used 1989 aerial photographs to calculate the volume and distribution of mangroves in Zanzibar—Unguja and Pemba Islands had a volume of 205,000 m^3 and 436,100 m^3, respectively. The mangrove area coverage for Unguja was 5003 ha and 10,943 for Pemba. Shunula (1996) reported on a mangrove forest of *c*. 14,000 ha in Pemba Island and 6000 ha in Unguja Island. Leskinen *et al*. (1997) reported on a mangrove forest cover area of 5829 ha in Unguja and 13,919 ha in Pemba. According to RGoZ (2013), an inventory completed using RapiEye satellite images showed that the mangrove forests in Zanzibar covered 5274 ha in Unguja Island and 11,214 ha in Pemba Island.

2.3.4 Mangrove Governance and Policy in Zanzibar

2.3.4.1. Mangrove utilization and conservation policy interventions from 1890 to 1933

Initially, the forests were managed communally, according to laws established by forest guardians, elders, and their chiefs (Sheriff, 1991). In 1890, the British colonial administration made significant administrative and economic changes, many of which had an impact on how Zanzibar's mangrove forests and other marine resources were used and preserved. The colonial authority aimed to secure markets for manufactured goods from Europe, while minimizing and funding the operational expenditures (Griffith, 1950). In the 1930s, urbanisation and the rising population accelerated the use of mangroves, affecting their conservation. The colonial authority of Zanzibar regulated the coconut and clove farming for export, since the island lacked mineral resources (Mlahagwa, 1991). Other items traded during this period included mangrove poles and bark (Gilbert, 2004). The government placed mangroves under the Department of Agriculture—two units, namely Agriculture and Forestry, made up the Department and each was governed by an agriculture officer and a forestry officer, respectively (Zanzibar Protectorate, 1950). The Department of Agriculture was in charge of guaranteeing the preservation and sustainable usage of mangrove forests, as well as ensuring that mangroves retained their economic potential (Zanzibar Protectorate, 1950). The Pemba and Unguja forestry officers were tasked with surveying and evaluating the state of the mangrove forest before recommending, to the Director of Agriculture, the issuance of permits for mangrove concessions and harvesting (Griffith, 1950). The British resident in Zanzibar was authorized, under the constitution, to give contractors or merchants concessions on mangrove products (Mkumbukwa, 2014).

Prior to the colonial era, Zanzibar's agricultural economy was based on slave labour, until the abolition of slavery, in 1897 (Depelchin, 1991). Agricultural productivity was severely affected, as well as the economy, as a whole. As a result, there was a significant decrease in mangrove use because the number of wealthy traders and farmers decreased, resulting in the lower demand for houses (Depelchin, 1991). Furthermore, in the early years of British colonialism, a decline in the export of mangrove poles was recorded (Gilbert, 2004). Around the same time, the British forbade the construction of mud houses in Zanzibar Town that used mangrove poles and coconut palm thatch for roofing, and this led to more mangrove poles for construction (Depelchin, 1991). Zanzibar's population was growing rapidly, so did the demand for mangrove poles, therefore, the British colonial government made attempts to intervene and control the invasion of mangrove forests—this severely affected Zanzibar's economy (Mlahagwa, 1991).

In order to increase the sustainable land production and manage resource usage in Zanzibar, the colonial authority developed a number of land administration laws, regulations, and arrangements. While some of them indirectly impacted mangroves, others were specifically added to control how mangrove forests were used. In 1909, the government passed the "Land Acquisition

Decree" with a view to acquiring land for public use (Abdulla, 2021). The colonial authority created the "Land Survey Decree" in 1912 to supervise and regulate all survey activities in Zanzibar (Abdulla, 2021). The British stepped up their attempts to produce cloves in 1915 (Ferguson, 1991). By the 1930s, the colonial government diversified into the exportation of mangrove bark (Gilbert, 2004). During the British colonial era, such decrees laid the path for highly detailed regulations and policies that governed the management of mangroves in Zanzibar.

2.3.4.2. Mangrove utilization and conservation policy interventions from 1933 to 1950

The colonial authority gave little attention to the oversight and management of marine resources during the Second World War (WWII) (Gilbert, 2004). The establishment of clove plantations, and later a British colonial government campaign to increase the food production, led to an increase in the clearing of forests (Seithy, 2000). Additionally, because mangroves were a part of the culture and a source of income for the communities engaged in the mangrove business, it was exceedingly challenging to maintain control over them (Mkumbukwa, 2014). The number of forest guards was insufficient; therefore, the mangrove bark business was in disarray (Department of Agriculture, 1952). Thus, mangroves were overexploited—they never recovered to their original status. In fact, the requirement for bark stripping on *Rhizhophora* and *Bruguiera* mangrove species, a minimum diameter of 8 inches, was no longer in place after WWII (Mkumbukwa, 2014). However, in addition to trying to preserve and safeguard the seized mangrove bark markets, the colonial authority also needed money to fund its operations (Abdulla, 2021). As a result, it was necessary to reduce the minimum diameter requirement for bark stripping, which was set at 6 inches (Mkumbukwa, 2014).

Once the slave trade was outlawed, the agricultural production declined to the point where debt arrears caused clove producers to lose their farms (Gilbert, 2004; Mkumbukwa, 2014; Abdulla, 2021). In addition, cloves from Zanzibar were facing stiff competition from Madagascar and other African countries (Gilbert, 2004; Mkumbukwa, 2014). The 1935 Land Alienation Decree was put in place to regulate and restrict the transfer of land ownership (Mkumbukwa, 2014). Later on, the Department of Surveying and Registration was established in 1936. In addition to all of the efforts made by the British government, cash crop famers returned to the mangrove business during the 1940s (Gilbert, 2004; Mkumbukwa, 2014). In 1945, the "Wood Cutting Decree" was introduced by the colonial government for the purpose of protecting all types of forests, mangroves included (Mkumbukwa, 2014). In 1949, the colonial government established the "Land Acquisition Decree", in order to make sure that the land tenure system was clear and the government land was protected (Mkumbukwa, 2014). From 1940, the colonial government introduced several tree plantations to meet the high demand of forest products (Nahonyo, 2002; Mkumbukwa, 2014; Abdulla, 2021). This was followed by the introduction of the "Forest Reserve Decree" in the 1950 to encourage village dwellers in planting trees in their farms (Mkumbukwa, 2014).

2.3.4.3. Mangrove utilization and conservation policy interventions from 1950 to 1963

Following the introduction of the "Forest Reserve Decree", three forest reserves were gazette within the next 15 years (Ferguson, 1991). In the 1950s, any portion of public land could be designated as a forest reserve by the British residents in Zanzibar (Nahonyo, 2002). The decree prohibited any socio-economic activities in the protected forests. According to the decree, new buildings were not permitted in the forest reserves. No one was permitted to take any forest products out of the forest reserves without authorization—neither cut, damage forest produce, cultivate, construct roads, construct cattle enclosures or graze cattle, be in possession of an implement meant for cutting, or removing forest produce, unless it was proved that the implement was not for the purpose of contravening any provision of the decree (Zanzibar Protectorate, 1950; Nahonyo, 2002). According to a government official, the government developed a number of community-based ownership programs, as part of the implementation of the forest reserve order to involve locals in the management and conservation of the forests. By 1955, the colonial government had put in place several rules and regulations—the Forest reserves rules—to strengthen the management and conservation of Zanzibar's planned forest reserves (Mkumbukwa, 2014). The Town and Country Planning Decree (1956) developed the process and guidelines to be used when submitting proposals for planning schemes in both urban and rural areas (Törhönen, 1998; Abdulla, 2021). Table 2.1 shows the policies that were applied to conserve and manage mangroves in Zanzibar under the colonial rule.

Table 2.1. Policy and regulatory frameworks that led to the conservation of mangroves in Zanzibar during the colonial era.

Year	Policy	Aim
1890s	The town began to grow rapidly	To accelerated the demand for mangroves
1890	Zanzibar was officially declared a British Protectorate	To set up a colonial economy
1900	Establishment of the Land Survey Section	To control land management
1909	Land Acquisition Decree	The purpose of securing space for public services
1912	Land Survey Decree	To regulate all survey activities in the protectorate
1930	Expansion of foreign markets for mangrove bark	To finance the colonial government
1935	Land Alienation Decree	To control the over use of land
1935	Land Survey Section	To control and limit the transfer of land ownership
1936	Department of Surveying and Registration	To guide land management
1945	Wood Cutting Decree	To control the cutting of mangroves
1949s	Comprehensive mangrove study by Dr. A. L. Griffith	Identifying mangrove species, threats and coverage
1949	Land Acquisition (Assessment for Compensation) Decree	To control land management
1950	Forests Reserves Decree	To place mangroves under government control
1955	Forest reserves rules	To concretized the management of the forest reserves

2.3.4.4. Mangrove utilization and conservation policy interventions after independence

Due to the importance of mangroves for both the local communities and the nation as a whole, the historical mangrove use in Zanzibar has led to degradation in many areas, highlighting the need for management measures (Masoud, 2004; Mkumbukwa, 2014). Bark stripping for mangroves was outlawed after independence (Masoud, 2004). All mangrove forests in Unguja and Pemba Islands were declared forest reserves by the Zanzibar government in 1965, under the Forest Reserve Order. In accordance with this directive, the forests were closed and made harvestable every ten years. In light of this, the preservation of mangrove forests in Zanzibar was ideally aimed at controlling the resources from further degradation (Levine, 2004). The Forest Reserve Order also placed restrictions on other uses, such as lime burning, charcoal production, pole gathering, and bark collection. In the 1990s, the Zanzibar Integrated Land and Environmental Management project (ZILEM) was established (Ali *et al*., 2002). Zanzibar's NLUP (National Land Use Plan), which established a physical planning framework with a perspective goal by the year 2015, incorporated the Tourism Zoning Plan (TZP) and Coastal Zone Management Plan (CZMP) (Ali *et al*., 2002). The TZP identified tourism development zones and proposed strategies for implementing them, while the CZMP provided for the most sustainable long-term use of the nation's terrestrial and marine resources (Ali *et al*., 2002). A number of marine protected areas (MPAs) were created by the Revolutionary Government of Zanzibar (RGZ) in Unguja and Pemba, including Chwaka Bay, Misali, Mnemba and Chumbe Islands, and Menai Bay (Levine, 2004). These strategies were not sufficient, since mangroves experienced overexploitation—reported by a forest officer. It was clear from the FGDs that, the failure to control the mangrove forest degradation might have been caused by a lack of community involvement in decision-making and a sense of loss of community ownership of the mangrove resources. The National Forest Conservation and Management Act of 1996 laid the legal groundwork for the introduction of the participation of the local communities in the conservation of mangroves (Mkumbukwa, 2014; Abdulla, 2021). Furthermore, the FDGs reported that a lack of awareness among local communities, on the fragility of mangrove forests, the politics of Zanzibar, and the lack of livelihood options, accelerated the failure of the act to work accordingly.

The Zanzibar National Forest Resources Management Plan 2008–2020 was intended to protect, conserve, and develop forest resources for the social, economic, and environmental gain of the present and future generations of Zanzibar (RGoZ, 2008). In order to achieve this objective, the plan was developed to have collaborations between sectors, such as fisheries, tourism, land, water, and local administrations. Table 2.2 shows the policies that were applied in the conservation of mangroves in Zanzibar, after independence.

Table 2.2. *Policy and regulatory frameworks that led to the conservation of mangroves after independence in 1963.*

Year	Policy	Aim
1964	Decree for the nationalisation of land and other properties	To control resources and means of production
1965	Government gazetted all mangroves under the Forest Reserves	To conserve and manage mangrove forests
1965	Establishment of cooperative societies	To reduce mangrove degradation
1965	Prohibition of trade in mangrove bark	To enhance mangrove conservation
1970	Cooperative societies were more political than economic	To control mangrove degradation
1980	Government policies began to be participatory	To involve local communities to conserve mangroves
1980	New liberalisation policies, e.g., marine protected areas	To strengthen the conservation of mangrove forests
1982	Establishment of land policy	To protect land resources
1985	Establishment of the Zanzibar Tourist Corporation (ZTC)	To reduce the over-dependance on natural resources
1986	Private Investment Act	To spearhead privatisation and to promote tourism
1989	The Commission for Lands and Environment	To reconcile between the changing land organizational systems
1989	Land Adjudication Act	To control land, land ownership, control boundaries of government land and reserve zones, as well as environmental activities
1989	The Registered Land Act	
1992	The Land Tenure Act	
1993	The Land Transfer Act	
1994	Land Tribunal Act	
1995	Introduction of the multiparty system	To enforce more restrictions against the foreign trade of mangrove products

2.4 Discussion

2.4.1 Mangrove utilization and the conservation policy interventions in Zanzibar

This study attempted to comprehend the institutional and legal frameworks that have governed mangroves in Zanzibar from 1890. In Zanzibar, the management of mangrove can go back in history to the colonial era—in 1890 (Depelchin, 1991; Mkumbukwa, 2014). The effective governance is essential for the conservation of mangroves, but it is challenging, given the number of agencies and parties—the tourist and aquaculture sectors, global carbon sequestration interests, and regional subsistence users (Friess *et al.,* 2016). Mangroves are also both terrestrial and marine, in nature, therefore the boundaries of their range are sometimes ill-defined, as a result of shifting intertidal zone boundaries (FAO, 2005; Mkumbukwa, 2014). Mangrove conservation measures range from conventional methods, such as designating areas as protected from clearing, and enacting legislation that limits or forbids clearing, to conservation, education, and restoration initiatives on a local, national, regional, or global level (Mkumbukwa, 2014). A number of colonial laws that addressed the land management concerns in Zanzibar, only had a small, indirect impact on the utilization and preservation of mangrove resources. The "Wood Cutting Decree" for mangrove forests, in 1945, guided the recovery of the severely damaged mangroves (Department of Agriculture, 1952). Although finding a balance between the use of forests and other natural resources and their conservation has been a significant challenge. In some places, the mangrove degradation covered extensive areas, such that they were declared closed for mangrove cutting Department of Agriculture. The 1950 "Forest Service Decree" ensured that mangroves and forest resources, in general, were not degraded. The decree also guided the restoration of trees in degraded areas, and the sustainable exploitation of forest resources. Unfortunately, the decree disregarded local traditional and customary demands concerning mangrove forests and associated resources—this sparked conflict between the colonial government officials and the local communities (Mohammed, 2004; Mkumbukwa, 2014). The colonial government imposed a 10-year harvest rotation in the corresponding mangrove reserves, to impose sustainable use and the conservation of mangroves (Mohammed, 2004).

By 1958, the increasing urbanization accelerated the need for the construction of homes, many of which required the use of mangrove wood and coral stones—these degraded mangroves in many areas (Mlahagwa, 1991; Mohammed, 2004). Between 1964 and 1990, the Zanzibar government attempted to manage marine resources—including mangroves—by enforcing strict laws that forbad any trade, especially outside the country. However, the illegal extraction of mangrove products continued. The Zanzibar government began to change its policies in the 1980s to reflect the rapidly changing global environment. Local communities and international development partners—the Finish International Development Agency (FINIDA), Women in

Development (WID), and the World-Wide Fund for Nature (WWF) worked together to manage and conserve the mangrove forests (Benjaminsen, 2019). With the creation of marine protected areas (MPAs), the new forest conservation measures began.

The Zanzibari social, political, and economic systems were affected by the Zanzibar Revolution of 1964 (Hunter, 2010). In 1965, the government issued a decree for the nationalization of all property, particularly land, and confiscated and reallocated private properties, such as houses, schools, shops, farms, and enterprises (Hopkins, 1971; Hunter, 2010). This had an impact on the use of forest resources, including mangrove forests. It resulted in an influx of emigrants, particularly from Tanganyika, by putting additional strain on the natural resources, such as mangroves. Both urban and rural areas saw an increase in the demand for charcoal and firewood—this might have encouraged the increased illegal mangrove harvesting (Mkumbukwa, 2014).

According to the 2012 Population and Housing Census, the population of the Mjini Magharibi (Urban West) was approximately 593,678, accounting for 46.0% of Zanzibar's population (URT, 2012). Therefore, despite the government's effort to restrict the use of mangroves, there was a lot of strain on mangroves and other natural resources (Seithy, 2000). During the same time, some measures were put in place to control the invasion of mangrove forests. The government placed an embargo on harvesting forest products—to the contrary, the Forest Department had the obligation of generating revenue for the state by charging license and harvesting fees for forest products—the government needed more money to run its operations (Curtin, 1981).

The Zanzibar Revolution led to a number of significant reforms, including in 1965—all mangrove forests were designated as forest reserves, and a ban was imposed on mangrove bark, and mangroves, as a source of firewood (Masoud, 2004). Nonetheless, despite the Government's increased protective measures, pressure on the demand for mangrove resources increased. The conservation of mangrove forests and other marine resources, after independence, was interpreted in such a way that there was too much control from the government—the locals felt deprived of the natural resources that surrounded them (Masoud, 2004). Generally, the greater the number of users, the greater the prevalence of the unlawful cutting of mangroves—this might have affected mangrove conservation activities. A major concern is that when illegally extracting mangrove products, one is not bound to follow conservation regulations. This has an adverse effect on the conservation and management of mangroves. The FGDs reported that, even after the ban, mangrove forests were invaded, especially by people who lived next to the forests. Evidence suggested that there were some instances where mangroves were overharvested, exceeding the number of trees that were legally permitted (Bagile *et al.,* 2000). The Chwaka FGD concurred that because the government was not offering a dependable alternative source of energy to the rural and urban populations, the locals continued to engage in other prohibited activities in the mangrove forests, such as illegally collecting firewood and extracting bark on a small scale for use. Furthermore, mangrove bark was harvested illegally by fishermen to protect the cotton fishing nets from insects. The discovery of the synthetic tannic materials helped to prevent the further degradation of the mangroves by reducing the exploitation and use of the mangrove bark (Griffith, 1950).

New land and environmental rules and regulations in Zanzibar were made possible by the establishment of the Commission for Lands and Environment, in 1989 (Omar, 2020). Additional statutes and rules include the Land Adjudication Act (1989), the Registered Land Act (1989), the Land Surveying Act (1989), the Land Tenure Act (1992), the Land Transfer Act (1993), and the Land Tribunal Act (1994), as well as the Forest Resources Management and Conservation Act (1996), the Environmental Management for Sustainable Development Act of 1996, the Plant Protection Act (1997), the Land Transfer Act (2007), and the Land Commission Act No. 6 of 2015. These acts have been amended several times to address issues that have arisen over time—they were crafted solely for the purpose of managing land resources—including mangroves—in a sustainable manner. The Zanzibar National Forest Resources Management Plan (2008–2020) was aimed to meet the demand of the country's forest policy frameworks, contribute to the attainment of the Vision 2020, the Zanzibar Strategy for Growth and Reduction of Poverty (ZSGRP), the millennium development goals (MDGs), and the ongoing policy reform affecting the forestry development in Zanzibar (RGoZ, 2008).

2.4.2 Community-based management of mangrove forests as a new approach

Once the local communities felt they were denied access to the maritime resources, the government of Zanzibar developed more participatory methods of policy and decision-making as a way to involve them in what was known as community-based conservation. In particular, the National Forest Conservation and Management Act of 1996 established the legal foundation for the formation of community forest management committees, and granted them user rights to community forests. Community forest management was first tested by the Zanzibar government in the 1980s (RGoZ, 1996; Mohammed, 2004) The local community's participation in the protected area management gave them the chance to manage marine resources, including mangrove forests. Community-based forest management agreements were developed and signed between the community conservation committees and the Director of the Department of Forestry. According to the act, a community forest management area must be managed, in accordance with the terms of a community forest management agreement drafted, in accordance with the act (RGoZ, 2008). The community management group states the types of activities it proposes to undertake in the proposed area. Except as otherwise provided in the management agreement, the community management group's obligations and rights, under the agreement, include the right to harvest and sell forest products and to utilize other benefits of the area, in accordance with the management agreement.

According to the Forest Resources Management and Conservation Act No. 10 of 1996, the goal of a community forest management area is to give local communities a way to acquire the secure rights to plan, manage, and benefit from their local forest resources. This was to be achieved in a sustainable manner, in order to meet their needs, promote economic growth and income generation, and improve the environmental stability (RGoZ, 2008). The growing community participation in the forest management, in the 1990s, drew international donors, primarily through non-governmental organizations (NGOs), to fund community-based conservation programs (Levine, 2004). Examples include the Jozani Environmental Conservation Association (JECA), a local village-based NGO, which was established by the Cooperative for Assistance and Relief Everywhere (CARE) in 1995, to involve local residents in natural resources management activities and in sharing revenues from the reserve (Bagile *et al*., 2000). The 1996 launch of the Integrated Coastal Zone Management (ICZM) plan in the Chwaka Bay area was another significant undertaking [65]. The ICZM was supported technically by the University of Rhode Island's coastal resource center and funded by USAID. Later, the international donor community changed its funding priorities and stopped giving the state direct aid (Levine, 2004). In response to corruption and human rights violations related to Zanzibar's elections in 1995 and 2000, a number of international donors withdrew their support (HRW, 2002)

2.4.3 Stumbling blocks in the forest governance of mangroves in Zanzibar

Policymakers acknowledged that the population growth and poverty were major factors impeding the government's efforts to achieve the sustainable management of Zanzibar's mangrove forests. The scarcity of resources makes the population turn to the protected areas in search of livelihood. *"The local communities consider themselves to be entitled to the ownership of and access to the benefits provided by mangrove forests."* – Government Official #6. Almost in all five FGDs, the participants were indifferent when asked if they are aware of their rights under the law and regulations governing forest management. *"There are still villagers who believe that there is unequal access to forest resources, therefore, they do not see the need to participate in mangrove conservation activities."* – Government Official #11. The problems connected to the conservation and management of mangrove forests may not be addressed by flawed forest policy and legal frameworks for the forest law enforcement and governance. Conflicting policies, due to overregulation, have further exacerbated the problem—overregulation is considered one of the main drivers of environmental degradation (FAO/ITTO, 2005). Additionally, a forest policy may place little emphasis on giving forestry programs the financial and technical resources they need. *"In Zanzibar, the community-level management systems are very new, and the personnel lacks the knowledge and expertise needed to effectively manage the mangrove resources."* – Government Official #5. There are not enough well-designed organizations and procedures in Zanzibar to guarantee that management regimes can incorporate civic traditions. *"In some cases, the operational regulations may be unclear and open to arbitrary interpretation by those in charge. The laws that are perceived as being unfair, such as those that ignore or even punish local customs and norms, can be socially unacceptable."* – Government Official #2. Thus, poor or absent public participation in their design and decision-making processes, may have long-term, irreversible effects on the social, economic, and environmental conditions (FAO/ITTO, 2005; Contreras-Hermosilla, 2011). The forest-adjacent communities will not comply with forestry laws if they believe they will jeopardize their livelihood (FAO/ITTO, 2005; Contreras-Hermosilla, 2011). The responses from the FGDs reported that, small producers and disadvantaged rural communities may disregard forestry-related laws and regulations because they perceive them to be prohibitively expensive and burdened with complex legal requirements. Furthermore, logging bans enacted to combat illegal logging in mangrove forests have had little effect (Masoud, 2004). *"Forest land* *tenure is also unclear and/or discriminatory, posing significant barriers to the effective mangrove forest governance in Zanzibar."* – Government Official #16. Despite the fact that the communities near the forests may have been the original owners, traditional rights may not be recognized by the law (Slobodian, 2019). Therefore, a lack of secure and legal forest land tenure may lead to a never-ending conflict between communities and the government (Contreras-Hermosilla, 2011). Due to a lack of political will, institutional failure, discrimination to some ethnic background, corruption, or outright criminal mentality, forestry laws may be underutilized or not used at all (FAO/ITTO, 2005; Contreras-Hermosilla, 2011). *"As a result, forestry laws and regulations are selectively applied and enforced, creating opportunities for neglect and abuse, resulting in poor forest governance. The villagers and the decision-makers concurred that corruption makes it difficult to manage the mangrove forests sustainably."* – Government Official #4. Leakage in law enforcement and low penalties for offenders make many people perceive the law as unfair (Contreras-Hermosilla, 2011). The poor enforcement and governance of forestry laws are caused by a lack of sufficient human and financial resources (FAO/ITTO, 2005). This makes the monitoring of mangroves nearly impossible. Weak government institutions have encouraged illegal activities in mangrove forests, because the likelihood of punishment is low (FAO/ITTO, 2005). In most cases, forests are subject to more intense and detailed regulation than other land uses, but over-regulation is frequently associated with increased corruption (FAO/ITTO, 2005).

The FDGs concluded that, community-based mangrove forest management could result in significant advantages—however, there were worries that the strategy was not as pro-poor as it appeared because co-management procedures and institutional arrangements were easily manipulated by the more powerful members of society, casting doubt on the strategy's longer-term viability. However, the most powerful people in society understand how to navigate the complex web of forestry laws and regulations, in order to obtain permission to harvest forest resources (Myers, 1999). *"Undoubtedly, others in society, who are less affluent, will come up with their own schemes for breaking into forests to steal the forest resources. The issue is made worse by the lack of regular training for community members, on their roles, rights, and obligations in forest conservation and the need to conserve them for the greater benefit."* – Government Official #16. Programs and policies for institutional and policy reform are delicate and may take years, as they do in Zanzibar. As a result, it may not be evident which reforms to governance and law enforcement will or will not be successful. The commitment and political will of the government are critical. A forest officer reported that, a weak judicial system remains another challenge toward the mangrove conservation in Zanzibar. According to a senior forest officer from the Department of Forestry, the courts are mostly understaffed and underfinanced, corrupted, politically affiliated, and overburdened with caseloads. Therefore, for the effective application of forestry laws, a reasonably functioning judiciary is necessary. Furthermore, the training of judges who deal with typical forest-related issues may be inadequate and may not include any training in forestry laws.

However, despite efforts to align with international objectives, challenges remain. Weak enforcement, inadequate funding, and conflicting land-use pressures, such as tourism development and agriculture, hinder effective mangrove management. While the international community stresses the urgency of mangrove restoration, Zanzibar’s implementation mechanisms often lag. For instance, while the CBD promotes ecosystem-based conservation and the Paris Agreement highlights the role of mangroves in climate resilience, local policies sometimes fail to comprehensively integrate climate change adaptation into their conservation strategies.

2.4.4 Recommendations for an improved mangrove forest governance in Zanzibar

Several gaps in policy implementation exist between Zanzibar’s national strategies and international commitments. For example, although Zanzibar has ratified the Ramsar Convention, there is limited designation of Ramsar sites specifically protecting mangrove ecosystems, indicating a need for greater prioritization of these habitats within international frameworks. Moreover, data collection and monitoring systems essential for meeting CBD and SDG targets are often lacking, which impedes effective conservation planning and reporting on progress toward international biodiversity targets. To strengthen the alignment with international policies, Zanzibar needs to enhance its focus on the ecosystem-based adaptation approaches emphasized by the Paris Agreement and incorporate them into national development and conservation plans. Additionally, improving stakeholder engagement and promoting the sustainable livelihoods of local communities that depend on mangrove ecosystems will align with the CBD's Aichi Biodiversity Targets and the broader SDGs. Enhanced institutional capacity, better funding mechanisms, and international partnerships can further bridge the gap between national policies and global conservation efforts.

Through improved governance frameworks, Zanzibar can claim better management of the mangrove forest resources. Major institutional, legal, and policy changes have been made to achieve this. Recommendations are presented here on areas that require special attention, to achieve sustainable forest resource management. Concerning the conflicting regulations resulting from various forestry laws, this study proposes that such laws must be harmonized, for them to be consistent with one another, and be able to specify who is responsible for what (FAO/ITTO, 2005). Moreover, the mangrove ecosystem management is challenging because these ecosystems are both terrestrial and marine, and are valued differently by stakeholders. Stakeholders may be different government departments, learning institutions such as universities, forest research institutes, independent researchers, or even faith-based institutions, financial institutions, such as banks, loan boards, and development partners, such as the European Union, Africa Development Bank, World Bank, etc. The tenets of legitimacy, justice, and integration play a significant role in determining whether mangrove conservation projects succeed or fail. This underlines the significance of the stakeholder involvement at all phases of the mangrove management. Natural resources are typically managed and owned at several levels, from private to public ownership—therefore, all governance actors should have roles that are clearly defined, that stakeholders are informed in a transparent manner about the policy development, that both the process and the results be fair, and that sustainable access to conservation resources be carefully taken into account [6,67,68]. Assuring transparency, preventing corruption, fostering a greater equity, minimizing the unwarranted influence of the "powerful" in society, and advancing the rule of law, are all benefits of a participatory approach to forestry law-making. This will allow stakeholders to air their grievances and protect their rights from absolute unilateral decisions made by governments. A forest policy that is widely accepted demonstrates a sense of shared ownership—the involvement of stakeholders from all sectors legitimizes the policy in society. Furthermore, a coordinating unit involving all stakeholders in charge of developing the mangrove conservation and management plans should be instituted to ensure the proper implementation of the same. Accurate and recent data should be used to support the measures included in the plans—the collection and dissemination of accurate data enables science-based decision-making. The mangrove conservation implementation plans should be funded from, for example, the Zanzibar Forest Service and the Zanzibar Forest Fund, to avoid a dependency on donors.

The capacity for law enforcement is low—due to a lack of sufficient human and financial resources. Therefore, more funds are required to achieve effective policing. Although another issue with law enforcement is the contradictory and/or impossibility of complying with regulations governing the forest sector. In cases where regulations reduce profitability, preventing realistic compliance, the government may provide assistance, such as financial incentives and/or compensation, to encourage forest actors to willingly follow the law (FAO/ITTO, 2005). However, incentives for the mangrove conservation must be aligned with the sustainable exploitation of mangrove forests (FAO/ITTO, 2005; Contreras-Hermosilla, 2011). It is obvious that the Department of Forestry does not receive sufficient funding from the state—it should strive to secure a budgetary increment from the government, as well as engaging development partners for the funding of mangrove conservation activities (although the over-dependence on donor funding has its shortcomings—reparation and subsequent implementation of the National Land Use Plan depended entirely on the financial assistance from FINNIDA, and when it pulled out in June 1996, many of the planned activities could not be implemented. Other innovative ways of raising revenue ought to be sought. For example, several popular destinations around the globe have introduced a tourism tax as they reevaluate, following the COVID-19 pandemic. With the return to normalcy, the use of these fees has shifted towards the conservation of natural tourist attractions and surrounding amenities. Zanzibar can implement such initiatives to boost the conservation of its mangroves and the raise economic status of its people. More funds will also help to acquire more personnel and working facilities. The Arab countries, such as Oman, are key development partners for Zanzibar and regularly fund conservation projects in the country.

Finding practical alternatives for local residents' livelihoods is a foreseeable way to curbing the invasion of mangrove forests in Zanzibar—but it is a challenge for both the government and the communities (Mohammed, 2004). Because the land surrounding the bays is primarily coralline soil and typically unsuited for agriculture, farming is not a potential alternative livelihood for the locals who completely depend on fishing and mangrove goods. As a result, additional research is needed to find communities alternative means of support. One possibility is to integrate the local communities in tourism—even non-marine related activities should be sought (Slobodian *et al.*, 2019).

Statutory systems do not take into account the customary mangrove tenure rights or mangrove usage and management practices. According to research, tenure agreements that grant complete ownership or longer-term rights seem to be more beneficial for the mangrove protection than the opposite. Therefore, various community management approaches should be used in an effort to increase the tenure rights and advantages. Gender equity is a crucial component that

Zanzibar's management and protection of mangroves lacks. Local customs significantly restrict women's participation in the mangrove maintenance and rehabilitation—they are forced into low-skilled work and excluded from local resource group leadership. The management and conservation of Zanzibar's mangroves should give women more opportunities. It is necessary to create laws and regulations that are tailored to the unique management requirements of mangroves, since mangroves are governed by legal frameworks meant for forests, the environment, water, land, or marine fisheries. There is no single legal instrument that can address all of the threats to mangrove conservation, therefore, a variety of legal tools can be applied to address the threats to the mangrove forests (Mchenga *et al*., 2015; Slobodian *et al*., 2019). Institutions with an expertise in forestry research, both local and international, should cooperate and adequately address the key problems impeding the implementation of a sustainable mangrove forest management. The forestry governance institutions, along with other stakeholders, should advocate for broad judicial reforms. The judiciary's often inadequate knowledge and appreciation of forestry law issues should be addressed through professional training programs in forestry and related natural resource laws (FAO/ITTO, 2005). Finally, the following should also be implemented (Slobodian *et al*., 2019):

- Frequent national mangrove inventories;
- Strengthen the institutional capacity at all levels;
- Mangrove conservation and sustainable use should be grounded in constitutional norms and international obligations; and
- Adoption of a dedicated nation-level policy/plan.

Examples of mangrove success stories that Zanzibar needs to emulate are:

1. Gazi Bay in the Kenyan coast—it is the world's first conservation project to connect the mangrove forests to the global carbon market (UNEP, 2017). The project sells carbon credits to people and organizations willing to lower their carbon footprint—this supports the planting and conservation of mangrove trees (UNEP, 2017). The payments for "mangrove carbon" are also used in the provision of fresh water to the community, to buy textbooks for local schools, and to improve the infrastructure in the neighbouring schools (UNEP, 2017). About 4000 mangrove seedlings are planted annually, resulting in carbon savings to generate direct income for the local community (UNEP, 2017);
2. The state of Maharashtra in India—as part of the intensifying conservation in the urban region, constant patrolling was entrusted to armed personnel. For the mangroves owned

privately, the government constituted a committee to deal with all mangrove-related cases (CIFOR, 2021). Overall, the following measures had been put in place CIFOR, 2021):

- A ban on the cutting of mangroves;
- Immediately stopped all construction within 50 m of all sides of mangroves;
- Banned the development permits in respect to any areas under mangroves;
- All mangroves on government land were declared as Protected Forests; and
- Cleaning solid waste from mangrove areas.

A substantial increase in the mangrove cover, from 186 km^2 in 2013 to 304 km^2 in 2017, was recorded in Maharashtra CIFOR, 2021). A different approach was adopted in rural areas—mangrove co-management communities, which were formed in coastal panchayats, were allowed to practice community-led village ecotourism and employ the livelihood activity that best suited their needs CIFOR, 2021).

3. Guyana—a national-scale mangrove planting program showed that, in some cases, restored mangrove forests thrived more than forests that were intact over the last decade (CI, 2021). According to Ram et al. (Ram, 2021), "Aboveground biomass in restored sites (103 $Mg\,ha^{-1}$) was 13 and 99% greater than intact (89.4 $Mg\,ha^{-1}$) and degraded (0.12 $Mg\,ha^{-1}$) sites, respectively." Therefore, planting new mangrove seedlings can very well restore degraded mangrove forests (CI, 2021). Therefore, planting new seedlings has proved to be a way of regaining some of the ecological benefits of mangrove forests (CI, 2021);
4. Madagascar—since 2015, men, women, and children from the village of Manombo in the Melaky region on Madagascar's west coast, have become key players in the mangrove conservation and restoration (Ram, 2021). This was after the local populations were sensitized on the importance of mangroves and how to maintain a healthy environment—people were willing to voluntarily avail any information on land-use changes, such as illegal activities in logging or agriculture (WWF, 2016). Mangrove restoration benefits the local communities by improving access to fish and crab stock, which provide a regular income, and builds resilience against climate change (WWF, 2016);
5. Vietnam—due to the fact that forest management in Ca Mau has become more decentralized on paper, the following measures were proposed to be applied at the local level by public servants and officials (Ha *et al.,* 2014):

- Distribution of mangroves and forestland to households for long-term use;
- Management rights between contractors and sub-contractors;
- Equity in benefit sharing;
- Allocating forests to different organizations; and
- Improved monitoring and control mechanisms against corruption.

The remote sensing and GIS techniques were also used to detect mangrove spatial/temporal changes, in response to either natural or anthropogenic forces, or both—in order to facilitate the appropriate planning, management, and regulation of coastal wetland (Ha *et al.,* 2014).

2.5 Conclusions

Marine resources, particularly mangrove forests, have contributed significantly to the socioeconomic success of the Zanzibar population since pre-colonial times. The mangrove management in Zanzibar has faced numerous challenges, as a result of overexploitation for commercial and subsistence purposes. Both the colonial government and the Revolution Government of Zanzibar (RGoZ) tried other forest conservation and management approaches, but the community-based forest conservation approach by the RGoZ has proven to be effective. Communities that are close to mangrove forests are involved in managing the forests in a way that improves the communities' quality of life and conservation awareness. Because of this strategy, people have felt a sense of ownership and are now actively involved in forest conservation efforts. Despite the efforts to raise awareness of the threats they face, promote alternative livelihoods, and improve forest management, mangrove forests continue to face a myriad of threats. There are specific underlying issues in the current policy and legal frameworks that have been identified because they deter the adequate conservation and management of mangrove forests. Recommendations have been made that will help streamline and strengthen Zanzibar's Forest policies and laws. Still there is a need to have appropriate policy interventions that specifically address the conservation and management of mangrove forests in Zanzibar. Another challenge remaining is in coordinating and involving the relevant stakeholders, including those who will be impacted by the mangrove use and conservation policies. Therefore, national policies should incorporate future mangrove needs and trends, to develop a broader vision for Zanzibar's forestry sector. In reviewing Zanzibar's mangrove conservation and utilization policies to international frameworks, it is evident that while significant efforts are being made to align with global commitments, challenges in enforcement, funding, and integration of climate adaptation strategies persist. Addressing these gaps and strengthening policy frameworks through a more cohesive, international approach will be key to ensuring the long-term sustainability of Zanzibar’s mangrove ecosystems (Mohamed *et al.,* 2023).

CHAPTER THREE

Assessing the Perception and Contribution of Mangrove Ecosystem Services to the Well-Being of Coastal Communities of Chwaka and Menai Bays, Zanzibar

This chapter is based on:

Mohamed, M.K., Adam, E., and Jackson, C.M. (2024). Assessing the Perception and Contribution of Mangrove Ecosystem Services to the Well-Being of Coastal Communities of Chwaka and Menai Bays, Zanzibar. *Resources*, 13, 7. https://doi.org/10.3390/resources13010007.

Abstract

The mangroves in Zanzibar are crucial to the survival of the local population, as they provide essential ecosystem goods and services. However, the actual value of mangrove products is not easily recognized. As a result, it is chiefly concluded that mangrove forests should be converted to uses that generate directly marketable products. This research sought to assess the perception and value of mangrove ecosystem services to the local communities around the Chwaka and Menai Bays. Key informant interviews, focus group discussions, and household surveys were used to collect data. The chi-squared test and one-way ANOVA were used to compare the awareness and perception of mangrove ecosystem services, respectively. The results show that provisioning services were the mangrove ecosystem services most identified by the household surveys, i.e., c. 84%. Supporting, regulating, and cultural services were rated in that order by 46.2%, 45.4%, and 21.0% of the respondents, respectively. This study found that there were statistically significant differences between Chwaka, Charawe, Ukongoroni, Unguja Ukuu, and Uzi wards in terms of households' awareness of regulating services ($\chi^2 = 6.061$, $p = 0.014$) and supporting services ($\chi^2 = 6.006$, $p = 0.014$). There were no significant differences in the identification of provisioning ($\chi^2 = 1.510$, $p = 0.919$) and cultural ($\chi^2 = 1.601$, $p = 0.901$) services. Occupations did not determine the reliance on mangrove ecosystem services ($\chi^2 = 8.015$; $p = 0.1554$). The approach used in this study can provide policymakers and land planners with a framework for the sustainable management of the ecosystem services provided by mangroves.

Keywords: mangrove ecosystem services. Focus group discussions. Key informant interviews. Household survey. Chi-squared test. Tukey's test. Zanzibar.

3.1 Introduction

The concept of ecosystem services was first coined by King (1966) and Helliwell (1969), referring to how nature helps to support human societies. Afterward, Pearce (1993), Pearce and Moran (1994), Daily (1997), Costanza and Folke (1997), De Groot et al. (2002), MEA (2005), and Afonso et al. (2022) were also interested in the concept of ecosystem services. The commonly recognized definition of ecosystem services states that they are the benefits that ecosystems provide to humans, which contribute to making human life both possible and worth living (Layke *et al*., 2012; Johnston and Caretti, 2017; MEA, 2022) Ecosystem services are not a luxury but a crucial necessity for the well-being of humanity (MEA, 2005). Ecosystem benefits are vital to our survival, providing us with the clean air, fresh water, fertile soil, and biodiversity that we depend on for food, raw materials for medicine, buildings, and industry (Layke *et al*., 2012; Johnston and Caretti, 2017; MEA, 2022). Ecosystem services can be divided into four classes, i.e., provisioning, regulating, supporting, and cultural services (MEA., 2005; Chowdhury *et al*., 2017; Nyangoko *et al*., 2021). Cultural services relate to the non-material world; they consist of activities like relaxation, art, thought, and religion that are difficult to measure in monetary terms (MEA, 2005). Regulating services include those relating to the capacity of natural and semi-natural ecosystems to control essential ecological processes and life support systems through biogeochemical cycles and other biosphere processes (MEA, 2005). Provisioning services include ecosystem products and services provided for human consumption, such as food, raw materials, and energy (MEA, 2005). Supporting services refer to natural processes such as cleaning the air and water, climate regulation and carbon sequestration, and the cycling of nutrients between organisms and the soil (MEA, 2005). Supporting ecosystem services are essential for the production of all other ecosystem services.

Human perception of ecosystem services varies across communities, depending on their socio-economic, cultural, and environmental contexts. Ecosystem services (ES) are often classified into provisioning, regulating, supporting, and cultural services, which different groups value based on their direct interaction with the environment. For instance, rural and indigenous communities typically place higher importance on provisioning services, such as food, freshwater, and raw materials, as these directly contribute to their livelihoods (de Groot *et al*., 2010). In contrast, urban populations often appreciate regulating and cultural services, such as air quality improvement, recreation, and aesthetic landscapes, given their indirect relationship with natural resources (Martín-López *et al*., 2012). Studies suggest that people's awareness and understanding of ecosystem services are significantly shaped by their daily experiences with these services and their level of environmental education (Fagerholm *et al*., 2016).

Regulatory policies play a pivotal role in influencing public perception of ecosystem services by formalizing their recognition and promoting conservation efforts. Governments and international bodies often implement policies that emphasize the economic, social, and ecological benefits of ecosystem services to foster public support. For example, Payment for Ecosystem Services (PES) programs, where landowners or communities are financially compensated for maintaining services like water purification or carbon sequestration, have been instrumental in raising awareness of the economic value of ecosystem functions (Pagiola *et al*., 2007). However, policies that prioritize economic growth, such as subsidies for agricultural expansion or industrial development, can lead to the undervaluation of crucial services like biodiversity conservation or climate regulation (Rodríguez *et al*., 2006). These policy frameworks often shape how the public perceives the trade-offs between development and environmental conservation, which can either promote or hinder the sustainability of ecosystems.

The integration of participatory approaches in regulatory policy design can enhance public perception and support for ecosystem services. Literature indicates that when local communities are involved in the decision-making process regarding environmental policies, there is greater recognition of the long-term benefits of ecosystem services, such as disaster risk reduction, carbon storage, and habitat preservation (Reed, 2008). Participatory governance, particularly in regions where communities rely heavily on natural resources, fosters a sense of ownership and responsibility toward ecosystem management, leading to more effective conservation outcomes (Scholte *et al*., 2015). Conversely, top-down policies that fail to account for local ecological knowledge and cultural values may result in weak public engagement and poor conservation results (Stringer *et al*., 2006). Thus, regulatory frameworks that incorporate local stakeholders' perceptions and ecological knowledge are more likely to result in sustainable ecosystem service management.

The intensification of human activities has led to various environmental problems, putting more pressure on ecosystem services (Bechtel and Churchman, 2003). The degradation of ecosystem functions is an undeniable global challenge; it has attracted the attention of international sustainable development research (Leh *et al*., 2013). The management of ecosystem services is a persistent challenge that demands effective solutions across diverse levels of decision-making. Without their proper management, humans risk losing the vital services provided by ecosystems (Schleyer *et al*., 2005). Therefore, the adequate management of ecosystems is critical to their continued existence and sustainability (Schleyer *et al*., 2005). A deep understanding of each ecosystem's unique characteristics and the stakeholders' diverse interests is crucial (Schleyer *et al*., 2005). Thus, evaluating ecosystem services helps decision-making by highlighting the environmental functions gained and lost through exploitation and development (Węsławski *et al*., 2009).

Mangroves are distinctive halophytic plants that grow at the intersection of terrestrial, estuarine, and marine systems in subtropical and tropical coastal regions of about one hundred and twenty-three countries (Omar and Misman, 2018; Stiepani *et al*., 2021; Ruslan *et al*., 2022). Mangroves provide various ecosystem services (Giri *et al*., 2011; Gupta *et al*., 2018), e.g., wood, water, fuel wood, charcoal, paper, medicines, honey, and fodder (MEA, 2005; Afonso *et al.,* 2022). Mangroves also provide recreational, educational, and research opportunities worth at least USD 1.6 billion annually (Pearce, 1993). Examples of mangrove-regulating services include mitigating the effects of climate change, such as protecting the coast from storms, floods, and erosion, and promoting biodiversity growth (MEA, 2005; Afonso *et al*., 2022). Mangrove forests contribute significant regulatory services, costing roughly 36,100 USD/ha (Tanner *et al*., 2019). Mangroves play a substantial role in regulating the climate by trapping carbon in soil and forest biomass. Mangroves provide around USD 6.7 billion in benefits, most of which come from carbon sequestration (Thorhaug *et al*., 2018). Also, mangroves exchange carbon dioxide with and emit methane into the atmosphere. Other regulating services include maintaining water quality in coastal areas by preventing saltwater intrusion. Examples of supporting services include habitats for breeding and spawning and commercial shrimp and fish farming (MEA, 2005; Afonso et al., 2022).

Mangroves are in a grave decline despite international legislation protecting them due to rapid population growth and urbanization (Getzner and Islam, 2020; Lee *et al*., 2014). Over the past few decades, excessive exploitation of mangroves has severely diminished and fragmented mangrove ecosystems (Giri *et al*., 2011), eventually leading to a significant loss in terms of biodiversity (Li *et al*., 2019). The need for food, safe water, wood, fiber, and firewood, which has been rapidly rising, is primarily to blame; this has proven to be problematic for communities whose livelihoods largely depend on mangrove ecosystems (MEA, 2005). Mangrove forests are currently disappearing at rates that are faster than those of tropical rainforests (Ruslan *et al*., 2022). According to Hamilton and Casey (2016) and Alam *et al*. (2022), the growth of shrimp farms is responsible for up to 38% of global mangrove deforestation. Ecologists are concerned about the destruction and disappearance of mangroves due to the expansion of agriculture due to rapid population growth in coastal areas (Kusumawardani, 2019). In addition, due to accelerated coastal development during the past 20 years, an annual decrease of between 0.16 and 0.39% of mangroves has been reported worldwide (Marlianingrum *et al*., 2021). Severe damage to and fragmentation of mangroves impairs their ability to provide ecosystem services in the future (Lee *et al*., 2014; Quoc *et al*., 2012).

Zanzibar's population of 1.1 million is marine-environment-reliant; the marine environment generates about 30% of Zanzibar's gross domestic product (URT, 2022). The gross domestic product per person in Zanzibar increased marginally to USD 1208 in 2022 from the previous year's 1099; approximately 50.3% of the population lives in poverty (WB, 2022). Zanzibar's mangroves are severely deteriorating due to unchecked tourism growth and related infrastructural development (Purida and Patria, 2020). Other factors include the rapid increase in population, poor fishing methods, excessive harvesting of mangrove products, disposal of untreated sewage from urban areas, and periodic coral bleaching (URT, 2022). Therefore, the unrestrained exploitation of mangroves has damaged the ecosystem and altered the significance of the ecosystem services that mangroves provide to the local communities, leading to increased poverty in Zanzibar. Because promoting human well-being, sustainability, and distributive justice is a significant requirement regarding harnessing mangrove ecosystem services, understanding the value of mangrove ecosystem services is essential (RGoZ, 1997).

Several studies, e.g., Nicholson (2009), Lugomela (2012), Hamad et al. (2014), Kukkonen and Käyhkö (2014), Othman (2014), Quinn *et al*. (2017), Käyhkö *et al*. (2022), Mohamed *et al*. (2023a), and Mohamed *et al.* (2023b), have been conducted in Zanzibar to study mangrove ecosystems. However, these studies have documented very limited or no information regarding analyzing the contribution of mangrove ecosystem services in Zanzibar. In this regard, the present study aimed to assess the perception and value of mangrove ecosystem services to those living in the Chwaka and Menai Bay areas. This study specifically responded to the following queries: (1)

Which mangrove ecosystem services exist in the Chwaka and Menai Bays? (2) What is the significance of the mangrove ecosystem services to the well-being of the Chwaka and Menai Bay communities? (3) Does the extraction of mangrove ecosystem services contribute to the destruction of mangrove forests? And (4) what are the factors affecting the supply of mangrove ecosystem services and how have they affected the livelihoods of the bay-adjacent communities?

3.2 Methodology and study locations

3.2.1 Data collection, sample size and sampling design

This study employed a mixed-methods approach that integrated both qualitative and quantitative research components. The fieldwork was carried out between February and May 2022, utilizing household surveys, focus group discussions, and key informant interviews to gather data. Participants were briefed on the objectives of the study and provided informed consent before participating. The focus group discussions aimed to capture the participants' beliefs, perceptions, attitudes, and experiences regarding their interactions with the ecosystem services provided by mangroves (Bechtel and Churchma, 2003). These discussions involved a deliberately selected group of individuals rather than a statistically representative sample from a wider population (Nyumba et al., 2018). The discussions took place in the wards of Chwaka, Uzi Ukongoroni, Unguja Ukuu, and Charawe, and included local administrators (Shehas), villagers, herbalists, both active and retired fishermen, current and former mangrove harvesters, and fish product vendors. Additionally, members of the Jozani-Chwaka Bay Community Organization and ward-level forest officers participated.

Moreover, key informant interviews were conducted with government officials from the Ministry of Agriculture and Natural Resources, representatives from Zanzibar’s House of Representatives, the regional commissioner’s office, the district office, and academic experts from various universities in Zanzibar specializing in mangrove ecosystems. Interviewees also included government representatives. The semi-structured interview topics encompassed the following: the concept of ecosystem services, specific ecosystem services of mangroves, the categorization of these services, perceptions regarding mangrove services, the functioning of mangrove ecosystems, threats—both anthropogenic and natural—to mangroves, and issues related to mangrove socio-ecology and management. Additionally, a household survey was carried out using a structured questionnaire (Appendix 2), which is generally recognized as suitable for large respondent populations and for gathering detailed information. These questionnaires were administered to heads and/or adult members of households and were revised based on insights obtained from focus group discussions and key informant interviews.

For the focus group discussions, a snowball sampling technique was implemented to identify participants who were knowledgeable about mangrove ecosystem services and/or resided in the Chwaka and Menai Bay areas. A total of five focus group discussions were conducted, each consisting of 9 to 11 members. The criteria for selecting key informants included age (generally 40 years and older), expertise in mangrove ecosystems, willingness to participate, familiarity with local mangrove services, and having been born and raised in the respective wards. Additional considerations included the participants' influence on sustainable mangrove management decisions and their status as beneficiaries (directly or indirectly) of mangrove ecosystem services. A total of 31 key informants were interviewed using purposeful sampling. According to the 2022 Population and Housing Census, the households in Chwaka, Ukongorono, Charawe, Unguja Ukuu, and Uzi numbered 317, 179, 181, 160, and 174, respectively. Consequently, 10% of these households, amounting to 102 households, were selected to participate in the household survey. A multistage sampling technique was employed to choose respondents, involving initial selection of villages within the wards, followed by random selection of homesteads and, finally, households. To ensure the research instruments' effectiveness, a pilot study was conducted with 10% of the sample (Cooper and Schindle, 2006).

The analysis of group dynamics during focus group discussions (FGDs) revealed that the diverse backgrounds of participants significantly influenced the insights generated. Participants, including local administrators, fishermen, herbalists, and community organization members, contributed varying experiences, knowledge, and perspectives that enriched the discussions. However, challenges emerged, such as power imbalances and differing communication styles, where certain individuals dominated conversations, potentially sidelining quieter voices. Additionally, pre-existing interpersonal relationships either facilitated a collaborative atmosphere or created tensions that impeded open dialogue. The role of the facilitator proved crucial in managing these dynamics; effective facilitation promoted inclusivity, encouraged equitable participation, and addressed conflicts, thereby fostering a respectful environment that valued all viewpoints. This strategic management enabled a deeper exploration of shared beliefs and attitudes among participants, ultimately enhancing the richness of the data collected during the FGDs.

During focus group discussions (FGDs) and key informant interviews, data organization involved several key steps to ensure effective analysis. Initially, structured guides were prepared to outline key topics and questions, maintaining focus during discussions. In some cases, data were recorded using audio devices with participant consent, complemented by detailed field notes to capture non-verbal cues and spontaneous insights. Following the discussions, audio recordings were transcribed verbatim, allowing for a comprehensive text document. The transcriptions underwent thematic coding, where key themes and patterns were identified, often using NVivo (qualitative data analysis software) to facilitate organization and retrieval. Codes were grouped into broader themes to synthesize findings, and comparisons were made between insights from FGDs and key informant interviews to identify consistencies and discrepancies. Finally, the organized data were documented and summarized in reports, often enhanced with visual representations, and validated through member checking with participants to ensure an accurate reflection of their perspectives.

3.2.2 Data analysis

This study used the SPSS statistical software version 23 (IBM Corp., Armonk, NY, USA) to conduct the statistical analysis. For comparison purposes, three groups were created by merging some of the initial five wards. Chwaka ward formed the first group because it had a substantially higher number of participants than the other four wards, i.e., 32. Ukongorono and Charawe wards have similar social and physical characteristics and are close to each other; therefore, they were merged to form a second group, i.e., 18 + 18 = 36. Unguja Ukuu and Uzi wards were combined to create a third group since they also share the same physical and social characteristics, i.e., 16 + 18 = 34. Awareness of mangrove ecosystem services was compared using a chi-squared test. In contrast, one-way ANOVA was used to compare the perception of the respondents on the relative importance of mangrove ecosystem services between the wards. The relationship between the significance of the perceived mangrove ecosystem services and the occupation of the participants was determined using a posteriori multiple comparison test (Tukey's test).

The communities in the study area depend on mangrove ecosystems for their livelihoods (Bechtel and Churchma, 2003); therefore, their socio-economic status and government forestry policy determine how they perceive mangrove ecosystem services. To determine how the variables affected the awareness of ecosystem services of the community, the respondents were classified based on (i) age, (ii) gender, (iii) marital status, (iv) level of education, (vii) household income, (vi) household size, (vi) occupation, (vii) accessibility to mangrove forest, (viii) how long the household has been in the area, and (ix) government forestry policy (Table 3.1). The Likert scale was used to rate responses (Ranganathan *et al.,* 2017).

Table 3.1: *Variables used in the logistic regression analysis.*

Variable	Description of variables
Gender	Either male or female
Age	Age of interviewees
Marital status	Single, married, divorced, etc.
Level of education	Informal, primary, secondary, post-secondary, etc.
Income of households	Average monthly income of household
Size of households	Number of family members in household
Occupation	Subsistence farmers, fishermen, public servant, small scale business, education, crafts, etc.
Accessibility to mangroves	Full access or access denied for harvesting mangroves
Household residence period	The number of years the household has lived in the area
Government policy	Community-based forest management or not

The results from the focus group discussions and key informant interviews were examined and processed using two qualitative data analysis methodologies. Firstly, constant comparison analysis was used, i.e., the data were grouped into small units, and then codes were attached to each of the units. Secondly, the codes were grouped into categories. Finally, themes expressing the content of each of the groups were developed (Strauss and Corbin, 1998; Phillips and Jorgensen, 2002). Discourse analysis was applied to understand the language used by the members of the focus group discussions and key informant interviews (Nyumba *et al*., 2018).

3.3 Results

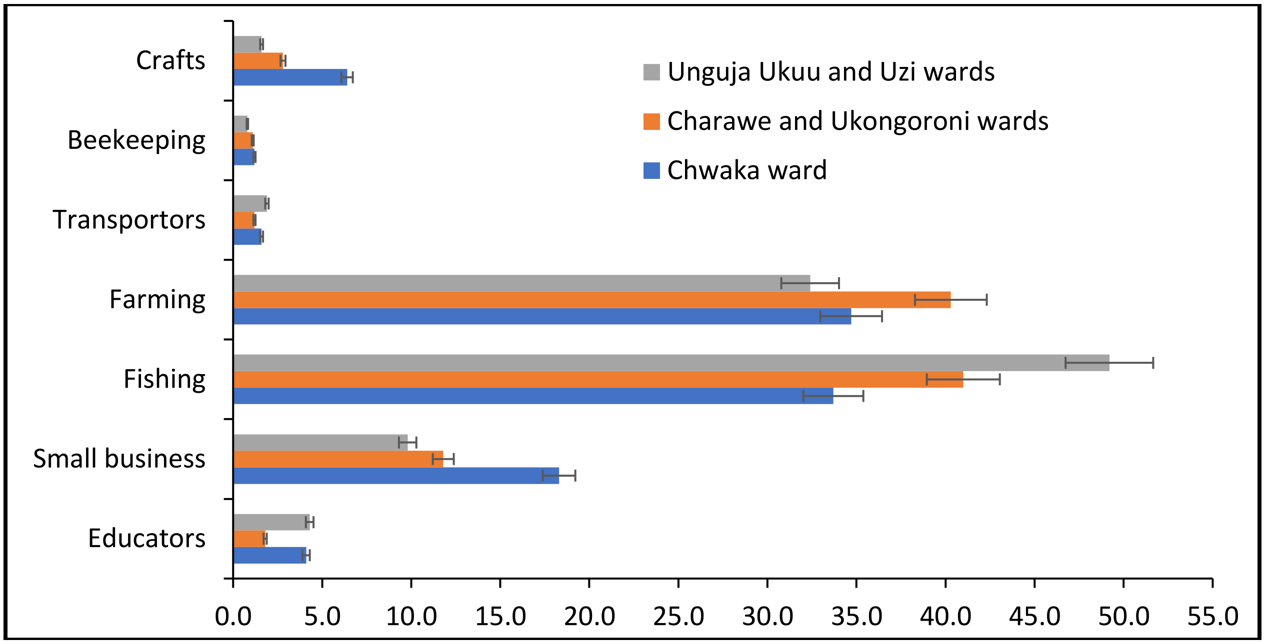
3.3.1 Demographics and socioeconomics of the respondents of the household survey

Overall, Muslims dominated the respondents to the household survey, i.e., 99.4%, while Christians comprised 0.6% (Table 3.2). Male participants comprised 55.7%, while the remainder were females. About 49%, 53%, and 60% of the participants in the Chwaka, Charawe/Ukongoroni, and Unguja Ukuu/Uzi wards were in the 50 to 59 age range, respectively. Overall, 87% of the participants were married. Only 4.9% of the respondents in the household survey had attained tertiary education. On average, about 62% of the households had from 6 to 10 family members. About 68% of the homes in the wards used mangroves as their primary fuel source.

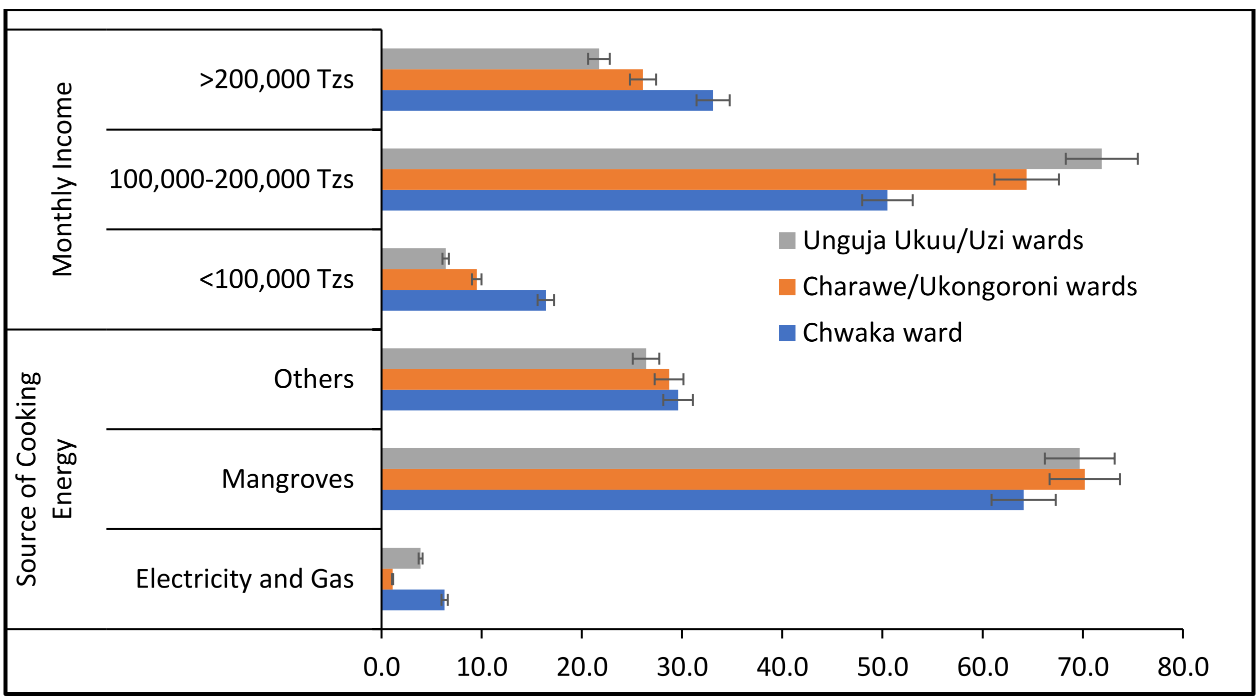
Table 3.2: *Demographic variables of participants in the household survey in Chwaka and Menai Bays, Unguja, Zanzibar.*

Variable	Sub-Category	Chwaka Ward (%)	Charawe/Ukongoroni Wards (%)	Unguja Ukuu/Uzi Wards (%)	Average
Religion	Muslims	99.1	99.4	99.6	99.4
	Christians	0.9	0.6	0.4	0.6
Gender	Male	61.1	49.1	56.9	55.7
	Female	38.9	50.9	43.1	44.3
Age	40–49	8.7	32.1	23.4	21.4
	50–59	48.8	52.6	59.7	53.7
	60+	42.5	15.3	16.9	24.9
Marital status	Married	88.2	81.7	93.1	87.7
	Widowed	9.0	4.6	5.2	6.3
	Divorced	2.8	13.7	1.7	6.1
Education level	Tertiary	4.1	3.4	7.3	4.9
	Secondary	41.5	31.8	38.1	37.1
	Primary	54.4	64.8	54.6	57.9
Household size	1–5	11	21.3	49.2	27.2
	6–10	69.8	66.8	48.7	61.8
	10+	19.2	11.9	2.1	11.1

The household survey showed that 41.3% of the participants were fishermen, 35.8% were subsistence farmers, and only 0.1% of the participants were beekeepers (Figure 3.1a). About 27% of the respondents earned >200,000 TZS (1 USD, 2504.76 TZS). The respondents who had a mean monthly income of about 100,000 to 200,000 TZS comprised 62.3% (Figure 3.1b).



(a)



(b)

Figure 3.1. (a) *Occupation of respondents (in percentage) in Chwaka, Ukongoroni, Charawe, Unguja Ukuu, and Uzi wards in Chwaka and Menai Bays, Unguja Island, Zanzibar. Error bars are 95% confidence intervals. (b) Average monthly income and source of cooking energy of the households in Chwaka, Ukongoroni, Charawe, Unguja Ukuu, and Uzi wards in Chwaka and Menai Bays, Unguja Island, Zanzibar. Error bars are 95% confidence intervals.*

3.3.2 Classification of mangrove ecosystem services

The focus group discussions and key informant interviews identified sixteen mangrove ecosystem services in the study area (Table 3.3), categorized into four classes, i.e., supporting, cultural, provisioning, and regulating services. Two supporting services (wild habitat and soil formation), four cultural services (ecotourism, spiritual activities, educational purposes, and scenic viewing), seven provisioning services (poles, firewood, medicine, honey, fruit, picnic sites, and fodder), and three regulating services (erosion control and sediment accretion, regulation of climate, and attenuation of waves) were identified by the respondents.

Table 3.3: *Mangrove ecosystem services identified in the study area through focus group discussions and key informant interviews.*

Mangrove Ecosystem Service	Use of Mangrove Ecosystem Services Identified in the Study Area
Wild habitat (SS)	Home to numerous shrimp, mollusks, fish, and crabs that serve as food sources.
Soil formation (SS)	Sediments are filtered by mangroves into soil; this soil is used to make bricks.
Ecotourism (CS)	Mangroves are popular tourist destinations because of their biodiversity.
Spiritual activities (CS)	Mangrove forests are used for ritual practices, e.g., to pray for rain and household protection, and they also contain ritual plants used for ritual healing.
Education (CS)	Source of information and knowledge regarding mangroves.
Scenic viewing (CS)	Viewing of the natural scenery of mangroves so as to feel relaxed and refreshed.
Poles (PS)	For building houses and boats and making furniture and fences, particularly *Rhizophora mucronata*, *Bruguiera gymnorhiza*, and *Ceriops tagal*.
Firewood (PS)	*Rhizophora mucronata* and *Ceriops tagal* are a source of cooking energy.
Medicine (PS)	Leaves of *Xylocarpus granatum* are used to treat stomachache.
Honey (PS)	Honey is used to disinfect wounds and heal burns. Also added to tea and porridge and spread on bread.
Fruits (PS)	The fruits of *Avicennia marina* are chewed to ease heartburn.
Picnic sites (PS)	Areas set aside inside mangrove forests where people can visit for outdoor activities
Fodder (PS)	Leaves of particularly *Heritiera littoralis* and *Avicennia marina* are fed to livestock.
Erosion control and sediment accretion (RS)	Minerogenic mangroves trap and consolidate sediment; this controls soil erosion and leads to improved soil fertility for farming.
Regulation of climate (RS)	Mangroves sequester carbon in soils and forest biomass and exchange carbon dioxide with and emit methane to the atmosphere.
Attenuation of waves (RS)	Mangrove vegetation causes wave attenuation because it acts as an obstacle by creating vegetation drag for the water flow in the waves.

3.3.3 Awareness of mangrove ecosystem services

The findings indicated that the participants in the household survey were aware of the benefits given by mangroves (Figure 3.2). Overall, 83.9% of the households knew provisioning services to be the most crucial, followed by supporting, regulating, and cultural services with 46.2%, 45.4%, and 21.0%, respectively. Chwaka ward was more aware of provisioning services, followed by supporting services, regulating services, and, lastly, cultural services, as they attained 90.4%, 39.4%, 36.6%, and 25.2%, respectively. Ukongoroni and Charawe wards were more aware of provisioning services, i.e., 92.6%, followed by regulating services with 41.3%, supporting services with 37.4%, and cultural services with 28.1%. The findings on the awareness of mangrove ecosystem services from Unguja Ukuu and Uzi households indicated that provisioning services attained the highest score of 68.7%, followed by supporting, regulating, and cultural services, which earned 61.8%, 58.4%, and 9.8%, respectively. The respondents in the focus group discussions in Unguja Ukuu and Uzi wards reported that several had attended training on mangrove ecosystems, which made them well-versed in the supporting and regulating services of mangroves. This study found that there were statistically significant differences between the Chwaka, Charawe, Ukongoroni, Unguja Ukuu, and Uzi wards in terms of household awareness of regulating services ($\chi^2 = 6.061$, $p = 0.014$) and supporting services ($\chi^2 = 6.006$, $p = 0.014$). There were no substantial differences between the wards in the identification of provisioning ($\chi^2 = 1.510$, $p = 0.919$) and cultural ($\chi^2 = 1.601$, $p = 0.901$) services.

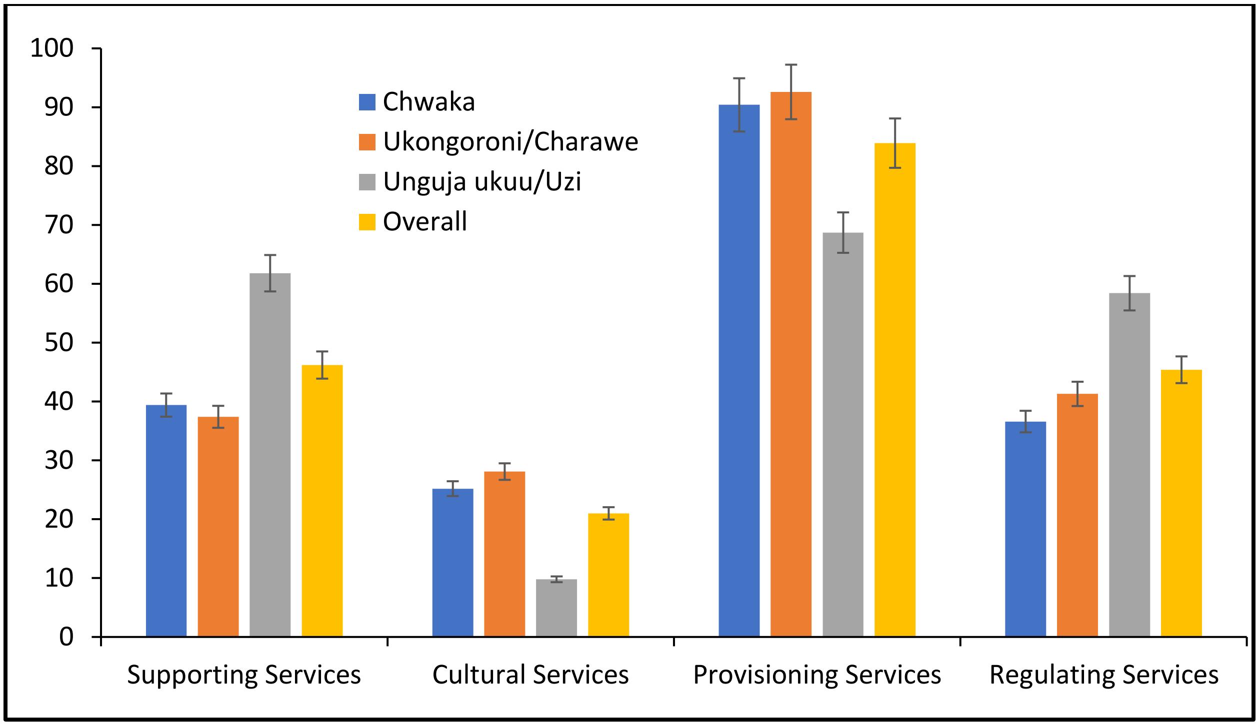


Figure 3.2. *Awareness of mangrove ecosystem services in Chwaka, Charawe, Ukongoroni, Unguja Ukuu and Uzi wards in Unguja, Zanzibar. Error bars are 95% confidence intervals.*

The following radar diagram analysis (Figure 3.3) shows that the residents of the Chwaka ward needed to be more aware of mangrove ecosystem services compared to those of the Ukingoroni, Charawe, Unguja Ukuu, and Uzi wards. The five mangrove ecosystem services that the Chwaka, Ukongoroni, and Charawe wards primarily identified were poles, firewood, medicine, spiritual activities, and educational purposes, as opposed to the Unguja Ukuu and Uzi wards' protection of shorelines, regulation of climate, wild habitats, soil formation, and sediment trapping. In contrast to supporting and regulating services, which were more recognized in the Chwaka, Ukongoroni and Charawe wards, the Unguja Ukuu and Uzi wards mostly recognized the mangrove ecosystem services in the form of cultural and provisioning services. The mangrove ecosystem services with the highest identification score were poles (91.4%), attenuation of waves (91.2%), and regulation of climate (89.6%), while fodder harvesting (9.4%) and spiritual activities (11.2%) were among the lowest-identified mangrove ecosystem services.

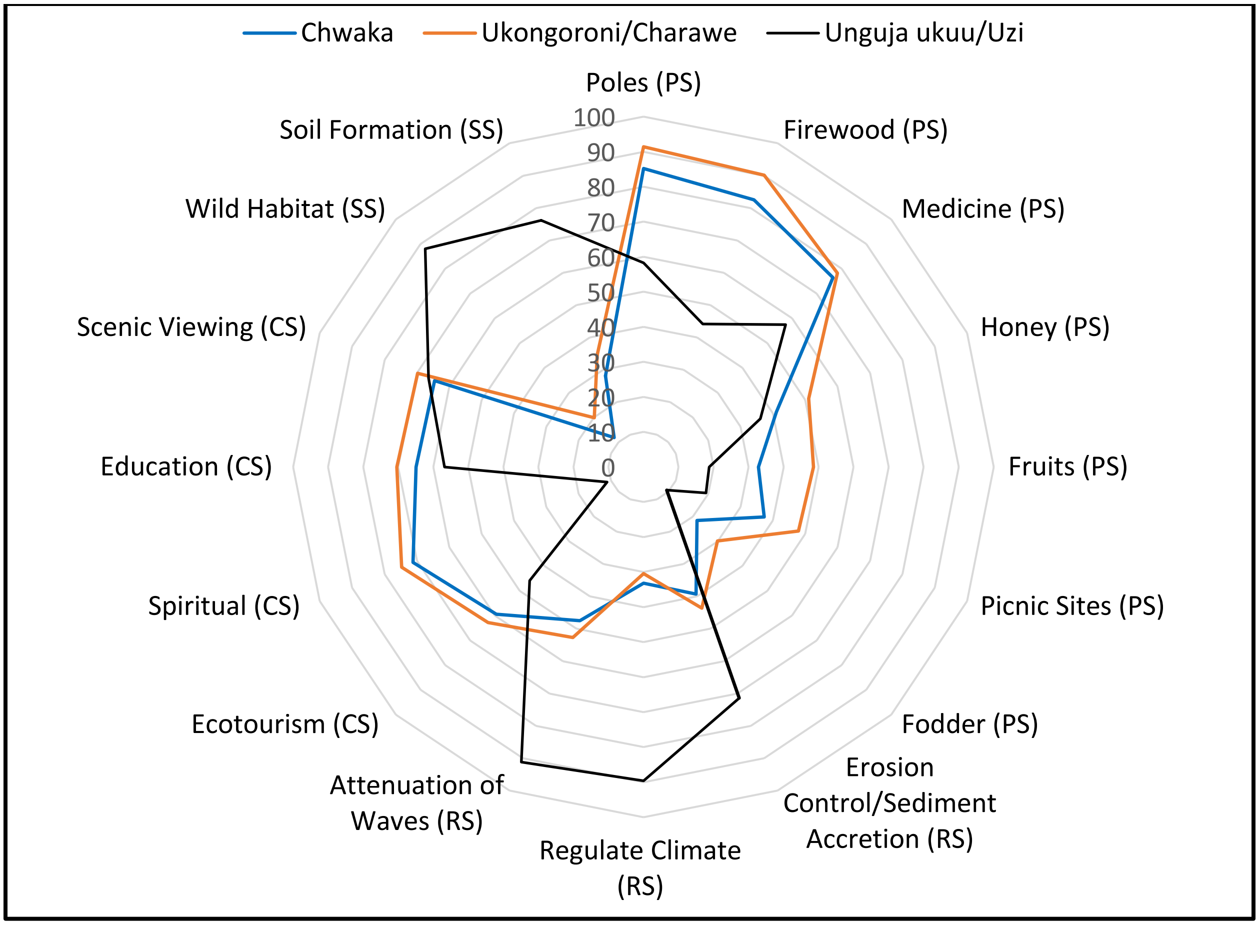


Figure 3.3. *Awareness (in percentage) of the identified mangrove ecosystem services by households in the study areas: PS (provisioning services), RS (regulating services), CS (cultural services), and SS (supporting services).*

3.3.4 Mangrove ecosystem services as perceived by household survey

There were notable disparities in the perception of mangrove ecosystem services between the wards (Table 3.4). The Chwaka, Ukongoroni, and Charawe wards considered provisioning and cultural services to be more critical compared to the Unguja Ukuu and Uzi wards, where regulating and supporting services were more significant. The average scores of provisioning services were 1.6, 2.4, and 1.9 in the Unguja Ukuu/Uzi, Ukongoroni/Charawe, and Chwaka wards, respectively. The results for regulating services showed 3.5, 1.5, and 1.5 for the Unguja Ukuu and Uzi, Ukongoroni and Charawe, and Chwaka wards, respectively. The cultural services for the Unguja Ukuu and Uzi, Ukongoroni and Charawe, and Chwaka wards scored 1.8, 2.4, and 2.2, respectively.

The household survey indicated that the Unguja Ukuu and Uzi, Ukongoroni and Charawe, and Chwaka wards attained mean scores of 3.3, 1.3 and 1.2, respectively.

Table 3.4: *The importance of mangrove ecosystem services in the study area according to the household survey: PS (provisioning services), RS (regulating services), CS (cultural services), and SS (supporting services).*

Category	Mangrove Ecosystem Services	Chwaka Ward	Ukongoroni/Charawe Wards	Unguja Ukuu/Uzi Wards	Overall
PS	Poles	3.4 (0.5)	3.9 (0.3)	2.4 (0.4)	3.2 (0.4)
	Firewood	2.5 (0.7)	3.8 (0.5)	1.5 (0.5)	2.6 (0.6)
	Medicines	2.5 (0.5)	2.8 (0.7)	2.3 (0.6)	2.5 (0.6)
	Honey	1.4 (0.6)	1.9 (0.6)	1.5 (0.3)	1.6 (0.5)
	Fruit	1.3 (0.6)	1.7 (0.4)	1.2 (0.3)	1.4 (0.6)
	Picnic sites	1.4 (0.7)	1.6 (0.2)	1.2 (0.4)	1.4 (0.4)
	Fodder	1.1 (0.4)	1.3 (0.3)	1.1 (0.2)	1.2 (0.3)
	Ave. PA	1.9 (0.6)	2.4 (0.4)	1.6 (0.3)	1.9 (0.4)
RS	Erosion control and sediment accretion (RS)	1.4 (0.6)	1.5 (0.4)	2.9 (0.6)	1.9 (0.5)
	Regulation climate	1.3 (0.5)	1.2 (0.4)	3.8 (0.4)	2.1 (0.4)
	Attenuation of waves (RS)	3.8 (0.6)	2.0 (0.7)	3.9 (0.3)	3.2 (0.5)
	Ave, RS	1.5 (0.6)	1.5 (0.5)	3.5 (0.4)	2.2 (0.4)
CS	Ecotourism	2.0 (0.6)	2.2 (0.3)	1.9 (0.6)	2.0 (0.5)
	Spiritual	2.3 (0.7)	2.7 (0.8)	1.1 (0.2)	2.0 (0.6)
	Education	2.2 (0.4)	2.5 (0.3)	1.9 (0.6)	2.2 (0.4)
	Scenic viewing	2.3 (0.5)	2.5 (0.4)	2.4 (0.3)	2.4 (0.5)
	Ave. CS	2.2 (0.6)	2.4 (0.4)	1.8 (0.4)	2.1 (0.5)
SS	Wild habitat	1.1 (0.4)	1.2 (0.6)	3.7 (0.4)	2.0 (0.5)
	Soil formation	1.2 (0.4)	1.4 (0.3)	2.9 (0.6)	1.8 (0.4)
	Ave, SS	1.2 (0.4)	1.3 (0.4)	3.3 (0.5)	1.9 (0.4)

Note: *means are represented by the values outside the parentheses, while the values inside the parentheses represent standard deviations. Likert scale: not important (1), least important (2), moderately important (3), most important (4), and not sure (5).*

Table 3.5 illustrates the perceptions of mangrove ecosystem services by occupation in the Chwaka, Ukongoroni, Charawe, Unguja Ukuu, and Uzi wards. The findings showed that mangrove ecosystem services were especially significant in some cases when they had a solid connection to occupation. For example, the importance of provisioning services, such as poles, was rated highly by small-scale farmers (3.6), servants in the public sector (3.5), small-scale businesses (3.5), and craftsmen/women (3.4) (Table 3.5). All occupations indicated less importance to honey. Regulating services such as soil erosion control and sediment accretion, regulation of climate, and attenuation of waves were highly rated by the educated and those in the teaching/research profession in particular. Cultural services, such as scenic viewing, were lowly perceived as a mangrove ecosystem service by subsistence farmers, fishermen, small-scale business owners, transporters, and craftsmen/women, yielding mean score values of 1.9, 1.7, 1.2, 1.4, and 1.5, respectively. There was a higher score in the perceptions of scenic beauty from civil servants and educators, as it had mean score values of 2.8 and 2.9, respectively. Supporting services, such as wild habitats, was highly important to fishermen and educators because they scored mean scores of 3.9 and 3.8, respectively. Soil formation attained a mean score value of 3.6 by educators. In contrast to small-scale business owners, craftsmen/women, and transporters, regulating and supporting services were highly perceived as mangrove ecosystem services, without a doubt, by those working in education-/research-related fields. This study found that no significant differences existed between the reliance on mangrove ecosystem services and household occupation, i.e., $\chi^2 = 8.015$ and $p = 0.1554$.

Table 3.5: *Perception of mangrove ecosystem services by occupation in Chwaka, Charawe, Ukongoroni, Unguja Ukuu and Uzi wards in Unguja, Zanzibar: PS (provisioning services), RS (regulating services), CS (cultural services), and SS (supporting services).*

	Occupation of Household Survey Participants						
Mangrove Ecosystem Services	Subsistence Farmers (*n* = 48)	Fishermen (*n* = 36)	Public Servants (*n* = 14)	Small-Scale Business (*n* = 28)	Transporters (*n* = 22)	Craftsmen/Women (*n* = 13)	Educators (*n* = 21)
PS							
Poles	3.6 (0.5)	3.4 (0.4)	1.5 (0.6)	3.5 (0.5)	2.0 (0.2)	3.4 (0.0)	1.1 (0.2)
Firewood	3.5 (0.7)	3.7 (0.5)	2.7 (0.4)	3.1 (0.6)	2.1 (0.4)	3.1 (0.2)	1.9 (0.0)
Medicines	2.8 (0.6)	3.2 (0.7)	1.2 (0.2)	2.3 (0.5)	2.1 (0.4)	2.4 (0.4)	1.6 (0.3)
Fodder	1.4 (0.4)	1.5 (0.5)	1.1 (0.3)	1.1 (0.4)	1.0 (0.5)	1.5 (0.6)	1.3 (0.7)
Fruit	1.3 (0.2)	1.6 (0.4)	1.2 (0.2)	1.1 (0.5)	1.0 (0.6)	1.1 (0.4)	1.0 (0.4)
Picnic sites	1.2 (0.2)	1.1 (0.3)	2.8 (0.6)	1.9 (0.4)	1.6 (0.2)	1.7 (0.2)	1.8 (0.0)
Honey	1.1 (0.3)	1.0 (0.4)	1.0 (0.2)	1.0 (0.3)	1.0 (0.2)	1.0 (0.4)	1.0 (0.2)
RS							
Erosion control and sediment accretion	2.9 (0.8)	3.3 (0.6)	3.0 (0.3)	2.2 (0.5)	1.7 (0.2)	1.5 (0.4)	3.8 (0.2)
Regulation of climate	2.7 (0.5)	2.6 (0.4)	2.8 (0.6)	2.6 (0.5)	1.2 (0.4)	1.6 (0.2)	3.6 (0.4)
Attenuation of waves	1.9 (0.3)	3.2 (0.5)	2.2 (0.0)	1.4 (0.4)	1.0 (0.2)	1.3 (0.6)	3.7 (0.6)
CS							
Scenic beauty	1.9 (0.7)	1.7 (0.5)	2.8 (0.0)	1.2 (0.4)	1.4 (0.6)	1.5 (0.2)	2.9 (0.0)
Spiritual	1.7 (0.5)	1.8 (0.4)	1.0 (0.0)	1.1 (0.5)	1.1 (0.2)	1.7 (0.4)	1.0 (0.2)
Ecotourism	1.3 (0.3)	1.9 (0.6)	1.4 (0.2)	1.4 (0.5)	1.2 (0.6)	1.6 (0.2)	2.6 (0.4)
Education	1.2 (0.2)	1.3 (0.4)	1.0 (0.0)	1.3 (0.4)	1.2 (0.2)	1.2 (0.0)	1.1 (0.6)
SS							
Wild habitat	2.6 (0.5)	3.9 (0.4)	2.0 (0.6)	1.1 (0.4)	1.1 (0.4)	1.9 (0.2)	3.8 (0.4)
Soil formation	1.3 (0.4)	1.7 (0.5)	1.1 (0.4)	1.2 (0.2)	1.0 (0.0)	1.0 (0.2)	3.6 (0.2)

Note*: means are represented by the values outside the parentheses, while the values inside the parentheses represent standard deviations. Likert scale: not important (1), least important (2), moderately important (3), most important (4), and not sure (5).*

3.3.5 Factors affecting perception towards mangrove ecosystem services

The findings from this study found that the perception and prioritization of respondents regarding mangrove ecosystem services were context-dependent and were determined by numerous factors such as engagement in mangrove conservation, age, education level, the socio-economic status of the local community, government policies related to the preservation of ecosystem services, the intensity and frequency of utilizing mangrove products, and the institutions responsible for managing them. During a focus group discussion in the Uzi ward, one participant reported that "the knowledge and experience on mangrove ecosystem service is based on my prolonged engagement in mangrove conservation and the periodic education on mangrove conservation I get from forest officers". The findings from the household surveys indicated that the most to the lowest influential factors that affected perceptions towards mangrove ecosystem services were education level, the intensity and frequency of utilizing mangrove products, engagement in mangrove conservation activities, the socio-economic status of the local community, and the institutions responsible for managing mangroves, as they recorded mean score values of 3.6, 2.7, 2.6, 2.4, and 2.3, respectively (Table 3.6). Two notable factors—the age of the respondents and government policies related to the conservation of ecosystem services—both attained a mean score of 1.2. Education level scored highest in the Chwaka, Ukongoroni/Charawe, and Unguja Ukuu/Uzi wards. After education level, Chwaka rated the intensity and frequency of utilizing mangrove products as the second significant factor with a value of 2.9, compared to the Ukongoroni/Charawe ward with a value of 2.8 for engaging in mangrove conservation activities. The Unguja Ukuu/Uzi ward rated the second significant factor as the intensity and frequency of utilizing mangrove products with a value of 3.3.

Table 3.6: *Factors affecting perceptions toward mangrove ecosystem services based on household survey in Chwaka, Charawe, Ukongoroni, Unguja Ukuu, and Uzi wards in Unguja, Zanzibar.*

Factors	Chwaka Ward	Ukongoroni/Charawe wards	Unguja Ukuu/Uzi Wards	Overall
Engagement in mangrove conservation activities	2.6 (0.9)	2.8 (0.8)	3.3 (0.7)	2.6 (0.8)
Age of respondents	1.1 (0.5)	1.4 (0.4)	1.1 (0.4)	1.2 (0.4)
Education level	3.4 (0.2)	3.7 (0.4)	3.8 (0.5)	3.6 (0.4)
Socio-economic status of the local community	2.4 (0.6)	2.6 (0.5)	2.2 (0.4)	2.4 (0.5)
Government policies related to the conservation of ecosystem services	1.2 (0.3)	1.3 (0.9)	1.1 (0.2)	1.2 (0.5)
Intensity and frequency of utilizing mangrove products	2.9 (0.7)	2.6 (0.2)	2.6 (0.3)	2.7 (0.4)
Institutions responsible for managing mangroves	2.6 (0.5)	2.1 (0.6)	2.3 (0.4)	2.3 (0.5)

Note: *means are represented by the values outside the parentheses, while the values inside the parentheses represent standard deviations. Likert scale: (1) strongly disagree, (2) disagree, (3) neither agree or disagree, (4) agree, (5) and strongly agree.*

3.3.6 Threats to mangrove ecosystem services

About 76% (*n* = 31) of the participants in the key informant interviews claimed that mangroves were degraded during the extraction of ecosystem services; the remaining 24% opined that severe degradation occurred during the extraction of mangrove-related resources. In the Unguja Ukuu ward, 74.5% of the participants claimed that they had witnessed illegal harvesting of mangrove products in the study area more than once. A participant in the focus group discussions stated that although it is unlawful to harvest mangrove products without a permit, locals do so covertly, endangering the regeneration of mangrove ecosystems. The participants in the focus group discussions and key informant interviews agreed that mangroves were more degraded in unprotected mangrove forests. The participants in the focus group discussions agreed that the amount of mangrove ecosystem services extracted in the study area was far more than the regeneration amount. According to the respondents in the focus group discussions, the rate at which mangrove ecosystem services are harvested, especially in Unguja Ukuu, is worrying; local loggers work in cahoots with corrupt community leaders and government officials.

3.3.7 Factors affecting the supply of mangrove ecosystem services

The factors affecting mangrove ecosystem services in the Chwaka and Menai Bays are shown in Table 3.7. During the focus group discussions in the Chwaka ward, one participant reported that “Mangroves’ natural beauty has been damaged, and fish breeding grounds have been severely affected”. An academic staff member at The State University of Zanzibar also stated that “Local communities around the bays are poor, and such areas have rapid population growth. Also, the lack of alternative livelihood opportunities drives them to rely on illegal mangrove harvesting. However, the forest department lacks adequately trained personnel due to insufficient funding from the government”. The strongest drivers identified by the household survey were lack of alternative livelihoods and unresponsive or faulty institutional structures in terms of forestry management, which achieved overall mean score values of 3.5 (Table 3.7). Insufficient resources to fund institutions and hire related expertise in managing forestry resources attained mean scores of 3.4, 3.3, and 3.1 for the Chwaka, Ukongoroni/Charawe, and Unguja Ukuu/Uzi wards, respectively. The unclear/faulty/discriminatory land tenure system also showed a relatively strong influence, with mean score values of 3.4, 2.9, and 3.2 for the Chwaka, Ukongoroni/Charawe, and Unguja Ukuu/Uzi wards, respectively. Flawed/unclear/opaque/poorly formulated forestry policy and legal framework attained an overall mean score of 1.2; Chwaka, Ukongoroni/Charawe, and Unguja ukuu/Uzi wards attained mean score values of 1.2, 1.0, and 1.3, respectively.

Table 3.7: *Factors affecting mangrove ecosystem services based on household survey in Chwaka, Charawe, Ukongoroni, Unguja Ukuu, and Uzi wards in Unguja, Zanzibar.*

Drivers of Changes in Mangrove Ecosystem Services	Chwaka Ward	Ukongoroni/Charawe Wards	Unguja Ukuu/Uzi Wards	Overall
Lack of alternative livelihood	3.5 (0.6)	3.4 (0.4)	3.6 (0.6)	3.5 (0.5)
Insufficient resources to fund institutions and hiring of adequate personnel to manage forestry resources	3.4 (0.5)	3.3 (0.9)	3.1 (1.1)	3.3 (0.8)
Unresponsive/faulty institutional structure in forestry management	3.6 (0.6)	3.7 (0.6)	3.3 (0.5)	3.5 (0.6)
Population growth	2.4 (0.8)	2.9 (0.2)	2.8 (0.6)	2.7 (0.5)
Climate change	2.1 (0.4)	2.8 (0.6)	2.5 (0.9)	2.5 (0.6)
Unresponsive/faulty government forestry policy	2.0 (0.5)	2.5 (0.7)	2.1 (0.5)	2.2 (0.6)
Agricultural development	1.3 (0.4)	1.3 (0.6)	1.8 (0.4)	1.5 (0.5)
Expanded aquaculture	2.0 (0.4)	1.4 (0.2)	1.1 (0.8)	1.5 (0.5)
Unchecked/uncontrolled coastal development	2.9 (0.3)	1.3 (0.7)	1.4 (1.0)	1.9 (0.7)
Underfunded judicial system	1.6 (0.6)	1.7 (0.9)	1.3 (0.3)	1.5 (0.6)
Weak government institutions	1.9 (0.6)	2.3 (0.2)	2.1 (0.4)	2.1 (0.3)
Flawed/unclear/opaque/poorly formulated forestry policy and legal framework	1.2 (0.4)	1.0 (0.5)	1.3 (0.8)	1.2 (0.7)
Lack of policy/laws specifically for mangroves	2.2 (0.5)	2.4 (0.2)	2.1 (0.6)	2.2 (0.2)
Local communities feel they are entitled to ownership of and access to mangrove ecosystem services	2.6 (0.4)	2.4 (0.8)	2.6 (0.2)	2.5 (0.7)
Lack of expertise and adequate staff in management of mangroves at local level	1.4 (0.5)	1.7 (0.3)	1.9 (1.0)	1.7 (0.6)
Poor public participation in design and decision-making involving mangrove ecosystem services	2.6 (0.8)	3.0 (0.5)	2.3 (0.5)	2.6 (0.6)
Unclear/faulty/discriminatory land tenure system	3.4 (0.9)	2.9 (0.6)	3.2 (0.6)	3.2 (0.7)
Corruption	2.8 (0.6)	2.5 (0.4)	2.7 (0.5)	2.7 (0.5)

Note*: means are represented by the values outside the parentheses, while the values inside the parentheses represent standard deviations. Likert scale: (1) not important, (2) least important, (3) second most important, and (4) most important.*

3.4 Discussion

3.4.1 Awareness of mangrove ecosystem services in Chwaka and Menai Bays

This study used focus group discussions, household surveys, and key informant interviews to assess the perception and contribution of mangrove ecosystem services to the well-being of communities in the Chwaka and Menai Bays. People's perceptions of ecosystem goods and services are essential to understanding the interaction between people and their environment (He *et al*., 2019). High levels of community awareness influence people's perceptions of environmental benefits and make it easier to recognize how ecosystems support their livelihoods and well-being (Su *et al*., 2020). Provisioning services were the most-identified mangrove ecosystem services, which was in line with the findings of Oteros-Rozas et al. (2014); provisioning services were mostly identified because of their high market value. Cultural services were second. Also, the results of this study showed that because forest-adjacent communities are sometimes involved in the conservation and restoration of mangrove ecosystems, they seemed to be aware of regulating and supporting services. Ruslan *et al*. (2022) reported that locals who participate in mangrove conservation activities are more likely to appreciate the provisioning and supporting services of mangroves.

3.4.2 Perception and importance of mangrove ecosystem services to the livelihoods and well-being of the communities in Chwaka and Menai Bays

In sustaining local livelihoods, firewood and poles were the highest-rated provisioning services by the focus group discussions, while the key informant interviews highly rated regulating services. Due to their accessibility, mangrove poles are used for building houses and making furniture, which is in line with Mensah *et al*. (2017), who found that when forest products and services are accessible, local communities recognize them. Most locals rely on mangroves for fuel; Makonese *et al*. (2018) noted that forest-adjacent communities use firewood for cooking since it is more readily available and less expensive. The Unguja Ukuu and Uzi wards had higher mean scores for supporting services, such as erosion control and sediment accretion, climate, and attenuation of waves, and regulating services such as wild habitats and soil formation. Recently, residents in both wards have been involved in workshops on the conservation and restoration of mangroves.

Educating community members on ecosystem protection makes them more knowledgeable about supporting and regulating services (Alam *et al*., 2022). Local communities explore the benefits of ecosystem services as awareness of the regulating and supporting services of mangroves grows (Su *et al*., 2020). Because it is challenging to keep bees in mangrove areas, the respondents placed minimal weight on honey production. Lee *et al.* (2014) reported that it is challenging to keep bees for honey in forests where there is considerable mangrove cutting. Fruits and fodder were among the provisioning services that were recognized by a small number of the respondents. According to Tanner *et al*. (2019) and Joshi and Negi (2011), farmers only graze livestock in mangrove wetlands whenever there is a shortage of fodder, especially during dry seasons. Farmers in the study area asserted that there was little usage of mangrove feed because animals frequently graze on coral rags, grasses, and bushes. Traditional medicine was mentioned by several respondents and was placed high among the provisioning services. Forest-adjacent communities frequently rely on conventional remedies over contemporary healthcare facilities (Moutouama *et al*., 2019).

The findings demonstrated that the Unguja Ukuu and Uzi wards valued the significance of regulating services, which include protecting shorelines and controlling climate. The household survey findings showed that local communities, particularly in the Unguja Ukuu and Chwaka wards, valued the attenuation of waves since they had severally experienced coastal flooding in the past, which caused significant marine erosion. The same conclusions were made by Damastuti and de Groot (2019), who demonstrated that the frequency of coastal threats, such as tsunamis and storms, makes coastal people appreciate mangrove ecosystem services, such as coastal protection. This is consistent with Joshi and Negi (2011); dense mangroves shield coastal areas from powerful storms and waves.

The medium scores for cultural services were for spiritual beliefs, which may be attributed to the transition of coastal communities from traditional spiritual beliefs to modern religious beliefs in Islam and Christianity (2017). Provisioning services, such as poles, firewood, and medicine, were given the highest scores by the Chwaka, Ukongoroni, Charawe, Unguja Ukuu, and Uzi wards, which was in contrast to honey, fruit, picnic sites, and fodder, which were given lower scores. The Chwaka, Ukongoroni, and Charawe wards gave cultural services, such as places for spiritual activities and scenic beauty, higher ratings than regulating services, which was likely due to their direct advantages that positively impact the communities' means of livelihood. Cultural services, e.g., education and ecotourism, also received high scores. These findings were similar to Lee *et al*.

(2014), who demonstrated that coastal communities have different perceptions of ecosystem services in their localities because of socioeconomic status. Fishing is one of the most vital sources of income on Zanzibar Island; therefore, the Unguja Ukuu and Uzi wards highly valued habitat-related services, but the Chwaka, Ukongoroni, and Charawe wards awarded wild habitats the lowest marks since they did not see the importance of mangroves as habitat grounds.

This study found that mangrove ecosystem services could be related to the residents' livelihood sources. For instance, small-scale farmers and fishermen/women highly ranked the importance of providing services like poles, firewood, and medicine. In contrast, educated respondents and those in the teaching and research professions gave the highest priority to regulating services such as soil erosion control and sediment accretion, climate regulation, and wave attenuation (Nyangoko *et al*., 2021). Ruiz-Frau *et al*. (2013) found that respondents' propensity to recognize ecosystem services depends on the types of employment they are engaged in. According to He *et al*. (2018), small-scale farmers and fishers strongly value provisioning and cultural services since they interact with and use them directly.

The results of this study showed that the respondents' perceptions of mangrove ecosystem services depended on the context and were influenced by a wide range of variables. Examples include the involvement of local communities in mangrove conservation, socioeconomic status, and government policies relating to the preservation of ecosystem services. Others include accessibility to mangrove ecosystem services and the institutions tasked with managing mangroves. According to Purida *et al.* (2020), various social and political elements can affect how a local population perceives ecosystem services. The results of this study are consistent with those of the Millennium Ecosystem Assessment (2005) and Marlianingrum *et al*. (2021), which revealed that respondents' education levels and involvement in mangrove protection are the two most important factors influencing how people perceive ecosystem services. The socioeconomic level of the local population, interaction with the environment, age, education, and interaction with the ecosystem have significant roles in shaping how local people perceive ecosystem services Tanner *et al*., (2019).

3.4.3 Extraction of mangrove ecosystem services and destruction of mangrove forests in Zanzibar

Due to rapid population growth and changes in land use, the mangroves in the Chwaka and Menai Bays have experienced a significant rate of deterioration in coverage and quality (Mohamed *et al*., (2023a). The respondents from the five wards agreed on the extensive illegal harvesting of mangroves, reducing mangrove ecosystem services. These findings are supported by Msangameno *et al*. (2017), who stated that the loss in mangrove coverage in these bays has resulted in low ecological benefits to the coastal people in Zanzibar. More significantly, this problem has endangered the culture of mangrove-dependent Zanzibar people (Lugomela, 2012). Furthermore, Zanzibar's mangrove ecosystem benefits are grossly undervalued (Lugomela, 2012), since most ecosystem services are illegally traded (Marlianingrum *et al*., 2021). The respondents knew of the adverse impacts, particularly coastal erosion, along the coastal shore as mangroves decline. The severe coastal erosion in the Zanzibar Islands has worsened due to ongoing massive coastal deforestation (Pitman, 2014). In particular, it has been noted that considerable erosion has been detected along the 113.5 km of sandy beaches in Unguja, which has been highly attributed to deforestation and tourism development (RGoZ., 1996). Since the 1980s, Zanzibar's unexpected increase in tourism and related development has increased the demand for forest products (Pitman, 2014). This trend has continued unabated up to date.

3.4.4 Drivers of changes in mangrove ecosystem services in Zanzibar

This study also documented several drivers of mangrove change in the Chwaka and Menai Bays. The household survey identified a lack of alternative livelihoods, insufficient resources to fund institutions and acquire adequate staff to manage forestry resources, unresponsive or faulty institutional structures in forestry management, and the unclear and/or discriminatory land tenure system in Zanzibar. The findings in this study agreed with Ruslan *et al*. (2022) in that a lack of alternative livelihoods, a lack of qualified labor force in mangrove conservation and management, ineffective management, and population pressure are the main drivers of mangrove forest change and ecosystem services. Kukkonen *et al*. (2014) found that mangrove forests in the Chwaka and Menai Bays have experienced illegal harvesting of their products. In general, illicit, unsustainable resource exploitation severely threatens numerous eastern African coastal resources (Nyumba *et* *al.*, 2018; Mangora, 2016). Also, the respondents reported climatic change as a threat to the ecosystem services provided by mangrove ecosystems (Nyangoko *et al*., 2021). Generally, changes in mangrove ecosystem services considerably impact ecosystems and the quality of human life.

3.4.5 Limitation of the study

This study experienced the limitations of qualitative research regarding subjectivity and researcher bias. The sampling design, the interview guide, deciding which interviewees to contact, the coding process, systematizing the study results, and interpreting them all involve some bias (Norris, 1997). The snowballing sampling approach used to sample the interviewees in this study is biased because interviewees may share a similar perception (Parker *et al.,* 2019). The discourse analysis used in this study can be subjective, and its findings are often specific to a particular context, limiting the findings' generalizability. As much as the study aimed to achieve a more heterogeneous perception of mangrove ecosystem services, some interviewees were not directly responsible for the sustainable management of mangroves. Also, convincing the local communities to participate in the study took work, as they were skeptical and wondered how it would benefit them. They complained that researchers come to them asking for information but have not seen any benefit.

Generally, the smaller the population, the larger the sampling ratio required; for populations below 1000, a minimum ratio of 30 percent, i.e., 300 individuals, is needed to ensure the sample's representativeness (Neuman, 2007). For larger populations, such as 10,000, a relatively small minimum ratio of 10 percent, i.e., 1000 individuals, is required (Neuman, 2007). This study's comparatively small sample size was due to the fact that the target groups were small and hard to access; navigating through the dense mangroves using a canoe was challenging and time-consuming.

Additionally, navigating through the dense mangrove trees using a canoe was challenging and time-consuming. Also, some respondents' comprehension of the questionnaires took a lot of work; therefore, collecting the data took time and effort. The acquisition of a research permit from the Department of Forestry took longer than anticipated and affected every other aspect of the study.

3.5 Conclusions

This study aimed to assess how people in the Chwaka and Menai Bays perceive ecosystem services and the contribution of mangrove ecosystem services to their well-being. The respondents perceived the ecosystem services differently according to focus group discussions, key informant interviews, and household surveys. Perceptions about mangrove ecosystem services are an essential communication and decision-support tool for policies on managing and conserving mangrove ecosystems. Generally, understanding preferences for mangrove ecosystem services can strengthen the links between local stakeholders and conservation actors for the sustainable management of mangroves. Overall, provisioning services were the most commonly recognized as supporting local livelihoods due to their direct value. The comparatively lower rating of regulating, cultural, and supporting services highlights the need for current management initiatives to increase awareness about mangrove forests' value, significance, and multifaceted functionality. Such initiatives can motivate local communities and management institutions to relook at the various benefits of mangroves; this could contribute to more sustainable use/management of mangrove ecosystem services to benefit posterity.

The value of ecosystem services cannot be ignored. There is still a need for further research into mangrove ecosystem services. Future research will aim to study the economic value of mangrove ecosystem services in Zanzibar.

CHAPTER FOUR

The spatial and temporal distribution of mangrove forest cover from 1973 to 2020 in Chwaka Bay and Menai Bay, Zanzibar

This chapter is based on:

Mohamed, M.K.; Adam, E.; Jackson, C.M. (2023). The Spatial and Temporal Distribution of Mangrove Forest Cover from 1973 to 2020 in Chwaka Bay and Menai Bay, Zanzibar. *Appl. Sci. 13*, 7962. https://doi.org/10.3390/app13137962.

Abstract

Mangroves in Zanzibar have a high value for biodiversity and scenic beauty; however, mangroves are susceptible to anthropogenic and natural environmental disturbances. The purpose of this study was to examine the change in the mangrove cover in Chwaka and Menai Bays, between the years 1973 and 2020, using Landsat satellite data. The transformed divergence (TD) index and Jeffries-Matusita (J-M) distance were used to calculate the separability of the land cover classes before classification. The overall accuracies in 1973, 1990, 1995, 2000, 2009 and 2020 were 82.5%, 85.4%, 86.6%, 89.3%, 91.7% and 92.7%, respectively, for Chwaka Bay, and 85.5%, 85.5%, 85.4%, 93.1%, 91.0% and 94.5%, respectively, for Menai Bay. The kappa coefficients (κ) were in the range of 0.72—0.90, while the producer's and user's accuracies were between 72 and 100%. Chwaka Bay's annual decrease in mangrove cover between 1973 and 2020 was 48.5 ha, compared to Menai's 6.8 ha. The loss of mangroves in Zanzibar could be linked to high population density - i.e., 712 persons per km2, which has led to overexploitation of man-groves. These findings could allow forest managers to improve methods for prediction and timely detection of mangrove loss, and inform future restoration of mangrove forests in Zanzibar.

Keywords: Mangroves. Maximum-likelihood classifier. Landsat data. Transformed divergence (TD) index. Jeffries-Matusita (J-M) distance. Change detection. Zanzibar.

4.1 Introduction

Mangrove forests are among the most valuable ecosystems on earth - they were previously estimated to cover c. 20,100,000 ha of the world's coastline (Spalding, 2002), but they have suffered large-scale deforestation and degradation. According to (Giri, 2010), and (Hamilton *et al*., 2016), mangroves covered c. 13,776,000 ha and 8,349,500 ha, respectively. Mangroves, which occur at the land-ocean interface in the tropics and subtropics, have significant ecological, economic, and social benefits (Scarnecchia and Saenger, 2004; Kirui *et al*., 2013). Mangroves and related marine resources are essential to the social and economic opportunities offered by activities such as tourism, fishing and agriculture in Zanzibar (Nagelkerken *et al*., 2000; Kukkonen *et al*., 2004; Mkumbukwa, 2014). Mangroves are crucial in protecting coastlines from storm surges, and also able to regulate local climate (Nagelkerken *et al*., 2000; Kukkonen *et al*., 2004). The coastal marine environment and communities depend heavily on mangroves and related coastal wetland ecosystems—e.g., seaweed, seagrass, and coral reefs. Mangrove habitats offer coastal and marine organisms a place to feed, breed, and flourish (Lobban and Harrison, 2004; Dromard *et al*., 2017). In addition to accumulating living biomass, mangroves also act as carbon sinks by accumulating litter and dead wood, as well as act as biofilter by trapping sediment and inorganic substances (Abal and Dennison, 1996; Laegdsgaard and Johnson, 2001; Nagelkerken *et al*., 2000). Mangroves store more carbon per unit area than any other forest on Earth - it stores c. 3–5 times as much organic carbon as tropical upland forests (Donato *et al.,* 2011). A high productivity and the slow pace of soil decomposition makes mangroves able to acquire and retain organic carbon, especially in their soils (Alongi, 2012). Mangrove ecosystems significantly increase atmospheric oxygen levels and remove CO2 through photosynthesis (Donato *et al.,* 2011). Mangroves supply essential ingredients to the chemical, pharmaceutical, and cosmetic industries (El-Gamal, 2009). However, mangroves are vulnerable to human activities (Parks and Bonifaz, 1994; Duke *et al*., 2007; Donato *et al.,* 2011; Liu *et al*., 2013; Nfotabong-Atheull, *et al*., 2013; Polanía *et al*., 2015), and environmental changes (Alongi, 2002; Alongi, 2008; Asbridge *et al.*, 2015; Ellison, 2015). Like many other parts of the world, the loss of mangroves in Zanzibar is linked to human activities such as timber cutting, pole cutting, firewood collection, charcoal burning, and crop cultivation (Mangora *et al*., 2016). This is due to intense population growth coupled with poverty and lack of alternative livelihoods (Macintosh and Ashton, 2002).

Mangrove establishment, restoration, and conservation have all received increased attention in Zanzibar (RGoZ., 2008). However, national and regional-scale strategies and solutions for mangrove management and rehabilitation have been significantly hampered by the lack of up-to-date, reliable, and consistent large-scale spatial data on mangrove forests (Leskinen *et al*., 1997; Defries *et al*., 2010). The spatial and temporal information about the dynamics of mangroves in Zanzibar is vital in advising on their management and conservation, and their sustainable use thereof. Information gathered from monitoring and evaluating mangroves offer an understanding of the mangrove forests for future planning and decision making (Mchenga and Ali, 2015). The assessment of Zanzibar's mangrove cover using ground-based methods is difficult because of the expertise and expenses required—in many cases areas covered by these surveys are small and not spatially contiguous (Gao, 1999). Therefore, ground-based approaches are unreliable to estimate mangrove cover/degradation. Satellite remote sensing technique has been used to track mangrove changes (Gullström *et al*., 2006; Eslami-Andargoli *et al*., 2010; Carle *et al*., 2014) and is essential for managing natural resources and preserving the environment (Garcia *et al*., 2015; Hoang *et al*., 2016). The Landsat imagery has been extensively utilized to track historical changes in mangrove distribution and extent at local (Kovacs *et al*., 2001; Hoang *et al*., 2016), regional (Bunting *et al*., 2023), national (Leimgruber and Kelly, 2005), and global (Giri, 2010) scales. This is made possible by the free and open data Landsat data policy, imagery archive—going as far back as 1972, consistent revisit period, and global coverage (Heumann, 2011a). Mangroves in Zanzibar have been studied since the 1990s. However, these studies were themed around calculating the total mangrove volume (Lugomela, 2012), the mapping of mangrove flora and fauna (Machiwa and Hallberg, 2005), the inventorying of wood biomass (RGoZ, 1997), the impact of the deforestation of mangroves on the nutrition, ecology, and genetic diversity of *Uca annulipes* (Lubida *et al*., 2019), a review of the status of mangrove ecosystems (Mchenga and Ali, 2015) the exploitation and regeneration of mangroves (Hamad *et al*., 2014), and the management strategy for mangrove habitats (RGoZ, 2008).

Past policies and regulatory frameworks in Zanzibar have significantly influenced the dynamics of mangrove forest change, often exacerbating degradation and loss. Historically, the management of mangroves has been fragmented and reactive rather than proactive, with limited emphasis on conservation and sustainable use. For instance, the Zanzibar Land Policy of 1992 did not sufficiently address the protection of coastal ecosystems, leading to unsustainable practices such as timber extraction from mangroves and charcoal production (RGoZ, 2008). Furthermore, the lack of enforcement of existing laws, such as the Fisheries Act and the Environmental Management for Sustainable Development Act, has allowed for illegal activities like overharvesting of mangrove products and land conversion for agriculture to persist (Macintosh and Ashton, 2002). Additionally, the absence of comprehensive spatial data on mangrove ecosystems has hampered effective planning and management, as noted by Leskinen *et al*. (1997), making it challenging to develop strategies that balance economic development with ecological conservation. Consequently, these policy shortcomings have contributed to a decline in mangrove coverage, with studies indicating a reduction of mangrove areas due to human-induced pressures (Mangora *et al*., 2016; Lubida *et al*., 2019). Therefore, revisiting and strengthening regulatory frameworks to incorporate integrated coastal management and community participation is crucial for the restoration and sustainable management of Zanzibar's mangrove forests.

Studies on mangrove forests reveals both their immense ecological and economic value and the significant threats they face, particularly in regions like Zanzibar. Studies by Spalding (2002) and subsequent assessments by Giri (2010) and Hamilton *et al*. (2016) illustrate the alarming decline in global mangrove cover, dropping from an estimated 20.1 million hectares to approximately 8.35 million hectares. This degradation is linked to various anthropogenic activities, as noted by Duke *et al*. (2007) and Mangora *et al*. (2016), highlighting how population growth, poverty, and unsustainable practices such as timber cutting and charcoal burning exacerbate mangrove loss. In contrast, the ecological benefits of mangroves, such as their role in carbon sequestration and coastal protection, are underscored by research from Donato *et al*. (2011) and Alongi (2012), which emphasize their capacity to store more carbon than any other forest type, alongside their critical role in supporting marine biodiversity. However, despite recognizing these ecological benefits, significant gaps persist in the availability of up-to-date spatial data necessary for effective management, as outlined by Leskinen *et al*. (1997) and Mchenga and Ali (2015). The shift towards using remote sensing techniques, as suggested by Gullström *et al*. (2006) and Eslami-Andargoli *et al*. (2010), presents a promising avenue for monitoring mangrove dynamics over time. Nonetheless, areas requiring further research include the application of remote sensing technologies with traditional ground-based methods to enhance accuracy, and a deeper exploration of mangrove dynamics in the context of the socio-economic and climate change on mangrove ecosystems. Addressing these research gaps will be essential for the sustainable management and conservation of mangrove forests in Zanzibar and globally.

Therefore, this study aimed to use a supervised classification approach and remote sensing data to analyse the patterns and dynamics of Zanzibar's mangrove forests in two major mangrove-protected bays, over 47 years, from 1973 to 2020.

4.2 Materials and Methods

4.2.1 Data acquisition and pre-processing

This study used satellite data (Table 4.1) to monitor the mangrove changes between 1973 and 2020. Landsat images acquired in 1973, 1990, 1995, 2000, 2009, and 2020 were downloaded from the US Geological Survey Global Visualization Viewer (USGS Glovis) site. Persistent clouds cover the study areas all year round. The Landsat MSS (Multispectral Scanner) collected data from Landsats 1–5. Landsat TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper Plus) have 7 spectral bands with a spatial resolution of 30 m for bands 1–5 and 7, while band 6, a thermal infrared, is acquired at 120 m and 60 m resolution, respectively. The Landsat 8 data have 9 spectral bands with a spatial resolution of 30 m for bands 1–7 and 9. Both Landsat 7 and 8 acquire the panchromatic band, i.e., band 8 at a pixel size of 15 m. Google Earth images and topographical maps and aerial data obtained from the Department of Forestry and the Department of Land Surveying Zanzibar was used as a reference dataset to determine the accuracy of the classified results. The uneven interval acquisition of Landsat images over Zanzibar is primarily due to the persistent cloud cover that affects the region throughout the year. Zanzibar, located in a tropical zone, experiences frequent cloudiness and rainfall, significantly reducing the availability of clear satellite images. Clear images remained inconsistent even with the higher resolution of the thermal infrared bands (120 m and 60 m for band 6). Landsat 8, featuring 9 spectral bands and a spatial resolution of 30 meters for most, provided more advanced imaging capabilities, but the region's persistent clouds still hampered the frequency of usable data. Thus, the uneven acquisition intervals over the years reflect the challenges posed by cloud cover, which limits the availability of cloud-free imagery, despite advances in satellite technology and sensor resolution.

Table 4.1: *The Landsat data used to analyse the patterns and dynamics of mangroves in Chwaka and Menai Bays, Zanzibar.*

Landsat					Google Earth		Topographical Maps		Aerial Data	
Year	Bands	Landsat Type	Sensor	Resolution (m)	Year	Resolution (m)	Year	Scale	Year	Resolution (m)
1973	1–4	Landsat 1	MSS	60	---	---	1982	10,000	1975	5
1990	1–5, 7	Landsat 5	TM	30	---	---	1990	1:9500	1991	5
1995	1–5, 7	Landsat 5	TM	30	---	---	1996	1:7500	1996	3
2000	1–5, 7	Landsat 7	ETM+	30	---	---	2001	1:7500	2001	3
2009	1–5, 7	Landsat 7	ETM+	30	2010	0.3	2010	1:7500	2010	3
2020	1–7	Landsat 8	OLI	30	2020	0.3	2020	1:2500	2017	0.5

The Landsat module tool in the TerrSet IDRISI software version 18.1 was used to radiometrically correct the Landsat images. The raw DN (digital number) values were converted to surface reflectance. Using the dark-object subtraction algorithm, atmospheric correction was carried out to remove atmospheric haze. All images were projected onto the UTM zone 30 North projection system. The Landsat images were resampled to a 15 m spatial resolution using the nearest neighborhood resampling technique (Leimgruber and Kelly, 2005; Aziz *et al*., 2015).

4.2.2 Acquisition of field data

Ground control points were acquired using a portable Global Positioning System (eTrex® 20 GPS Receiver; Garmin, Olathe, KS, USA), Landsat OLI imagery, topographical maps, and aerial photographs covering the two study sites. Ground truth points were gathered in June 2021. Greater details and color contrasts were obtained by the false color (rgb—754) Landsat OLI composite. Within the study sites, appropriate transect lines were placed to sample the different class types, i.e., mangroves, other forests, bare ground, agriculture, and water—where the classes were more homogenous. Thirty-two coordinates with an accuracy of 3 to 5 m were gathered for each of the five classes in each of the two study areas. The coordinates were then overlaid on the resampled Landsat images. The points were converted into polygons using the TerrSet software 2020 v. 19.0 by following the edges of the respective pixels. The polygons were then used as reference data to generate regions of interest (ROIs) which represented the land cover classes.

Ground truth data for historical analysis of mangrove ecosystem dynamics were obtained through a multifaceted approach that integrate aerial imagery, and historical records. Aerial surveys, including drone imagery, complement this by providing a broader perspective on mangrove cover and conditions. Additionally, leveraging historical records—such as land use maps, and photographs from the Department of Forestry - allowed to reconstruct past mangrove ecosystem's long-term trends. Furthermore, reviewing scientific literature and governmental reports helped contextualize findings and establishes a baseline for understanding mangrove dynamics.

4.2.3 Spectral separability

An analysis of the multispectral response patterns of the land cover types was used to determine their spectral separability. Spectral separability computes the statistical distance between signatures; therefore, it determines the overall classification accuracy (Jackson and Adam, 2021). The transformed divergence (TD) index and Jeffries-Matusita (J-M) distance separability measures were used in this study. Divergence (D) is calculated from the mean and variance–covariance matrices of data representing feature classes (Kavzoglu and Mather, 2000):

$$D_{ij} = \frac{1}{2} tr\left[(\Sigma_i - \Sigma_j)(\Sigma_j^{-1} - \Sigma_i^{-1})\right] + \frac{1}{2} tr\left[(\Sigma_i^{-1} + \Sigma_j^{-1})(\mu_i - \mu_j)(\mu_i - \mu_j)^T\right] \quad (1)$$

The TD is used to lessen the effect of well-separated classes, which may increase the average divergence value and make the divergence measure misleading (Kavzoglu and Mather, 2000):

$$TD_{ij} = c\left[1 - e^{\frac{-D_{ij}}{8}}\right] \quad (2)$$

where tr[·] is the trace of a matrix, which is the sum total of the diagonal elements of the matrix, and Σ_i and Σ_j are the variance-covariance matrices of classes i and j; μ_i and μ_j are the corresponding mean vectors; c is a constant value defining the range of TD values.

The J-M distance between distributions of two classes ω_i and ω_j has been defined as follows (Jia *et al*., 1999):

$$\boldsymbol{JM_{ij} = 2\left(1 - e^{-B_{ij}}\right),} \quad (3)$$

where B_{ij} is the Bhattacharyya distance computed as (Kailath, 1967):

$$B_{ij} = \frac{1}{8}(\mu_i - \mu_j)^T \left(\frac{\Sigma_i + \Sigma_j}{2}\right)^{-1} (\mu_i - \mu_j) + \frac{1}{2} ln\left(\frac{1}{2}\frac{|\Sigma_i + \Sigma_j|}{\sqrt{|\Sigma_i||\Sigma_j|}}\right) \quad (4)$$

where μ_i and μ_j are the mean reflectance of species *i* and *j*; Σ_i and Σ_j correspond to their covariance matrices; and $|\Sigma_i|$ and $|\Sigma_j|$ are the determinants of Σ_i and Σ_j, respectively. *ln* is the natural logarithm function, while *T* is the transposition function.

As a general rule, classes are separable if the result is greater than 1.9, fairly separable if it is between 1.7 and 1.9, and not separable if it is below 1.7 (Jensen, 2005).

4.2.4 Pairwise feature comparison

The pairwise comparison technique was used to compute similarity scores between each pair of Landsat bands (Li *et al*., 2016). If the similarity score is greater than a predefined threshold, then the two bands are co-referent. Pairwise comparisons are in the form of a matrix: $C = [c_{kp}]n \times n$; where c_{kp} is pairwise comparison rating for kth and pth criteria. The matrix C is reciprocal—i.e., $c_{pk} = c_{kp}^{-1}$, and all its diagonal elements are unity—i.e., $c_{kp} = 1$, for k = p (Li *et al*., 2016). Table 4.2 shows a correlation matrix calculated from the Landsat 8 bands.

Table 4.2: *Spectral separability as calculated by TD index (Equation (2)) and J-M distance (Equation (3)); W—water, OF—other forests, MF—mangrove forest, BL—bare land, and A—agriculture.*

	MSS (1973)		TM (1990)		TM (1995)		ETM+ (2000)		ETM+ (2009)		OLI (2020)	
LULC Pairs	TD Index	J-M Distance	TD Index	J-M Distance	TD Index	J-M Distance	TD Index	J-M Distance	TD Index	J-M Distance	TD Index	J-M Distance
W/OF	1.90	1.91	1.97	1.98	1.99	1.98	2.00	2.00	2.00	2.00	2.00	2.00
W/MF	1.93	1.93	1.97	1.97	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
W/BL	1.91	1.98	1.98	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
W/A	1.91	1.90	1.99	1.98	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
OF/MF	1.36	1.34	1.89	1.87	1.96	1.90	1.96	1.91	1.95	1.90	1.99	1.92
OF/BL	1.75	1.74	1.91	1.98	1.99	1.99	2.00	2.00	2.00	2.00	2.00	2.00
OF/A	1.50	1.45	1.89	1.90	1.90	1.89	1.92	1.83	1.92	1.83	1.94	1.85
MF/BL	1.88	1.85	1.89	1.87	1.99	2.00	2.00	2.00	1.99	2.00	2.00	2.00
MF/A	1.88	1.86	1.90	1.89	1.99	1.99	2.00	2.00	2.00	2.00	2.00	2.00
BL/A	1.84	1.82	1.83	1.80	1.97	1.92	1.98	1.97	1.98	1.97	1.98	1.98

4.2.5 Image classification

The maximum likelihood classification algorithm was also used to classify the Landsat images. This algorithm is widely used in remote sensing because of its strong theoretical foundation and can accommodate varying data, land use and land cover (LULC), and satellite systems (Foody, 2002). Therefore, this study used TerrSet's hybrid classification technique, which combines segment-based and pixel-based categorization (Jia and Richards, 1999). SEGMENTATION, SEGCLASS, and SEGTRAIN are the three modules that make up the technique [52]. Image segmentation was applied using the SEGMENTATION module to group pixels according to their spectral similarity, i.e., using a watershed delineation approach, the input images were segmented based on the variance similarity of pixel values. The SEGTRAIN module was then used to convert the image segments into training sites and signature classes. Finally, the SEGCLASS module was used to categorize segments based on a classified image created using pixels.

4.2.6 Accuracy assessment

Accuracy assessment quantitatively evaluates how well the pixels were sampled into the appropriate land cover groups. The performance of the classifier was evaluated using ground truthing. Confusion matrices with the user's, producer's, and overall accuracies as well as kappa statistics were generated. The producer's accuracy (PA) is the likelihood that a specific land cover of a location on the ground will be labeled as such. How frequently the class shown on the map will actually be present on the ground depends on the user's accuracy (UA). The kappa coefficient (κ) was used to assess if one error matrix differs significantly from another (Cohen, 1960).

4.2.7 Change detection analysis

The CROSSTAB module in the TerrSet Geospatial Monitoring and Modeling Systems was used to track the mangrove forest changes from 1973 to 2020. The product of the CROSSTAB is a cross-classification image or a table, or both (Pontius and Cheuk, 2006). In this study, the CROSSTAB module was instructed to generate both a statistical table and a change detection image. The tabular matrix generated after cross-tabulation shows the number of pixels corresponding to each combination of categories in the two classified maps. Additionally, CROSSTAB provides the tabular matrix in terms of the proportion of the total number of pixels and summary statistics (Pontius and Cheuk, 2006). The image output produces an image which represented a category combination from each of the two images under comparison. The image output produces an image in which each pixel shows the combination of categories in the two images.

4.3 Results

4.3.1 Spectral separability between land cover classes

The mean spectral reflectance curves extracted from the pixels of the respective LCLU classes in the two study areas are plotted with their standard deviations (SDs) (Figure 4.1). Overall, within 1 SD, the seven Landsat bands recorded considerable spectral overlaps of the five LULC classes. More spectral overlaps were exhibited by the visible bands (bands 1 to 4, i.e., coastal aerosol, blue, green, and red). The lowest reflectance values were recorded by the visible bands, followed by band 7 (Short-wave 2), 6 (Short-wave 1), and 5 (Near Infrared), respectively. Near Infrared (band 5) showed the largest difference in reflectance values between water and non-water bodies. Only Near Infrared and Short-wave 1 (bands 5 and 6, respectively) were helpful in separating water and the other classes, beyond 1 SD of uncertainty.

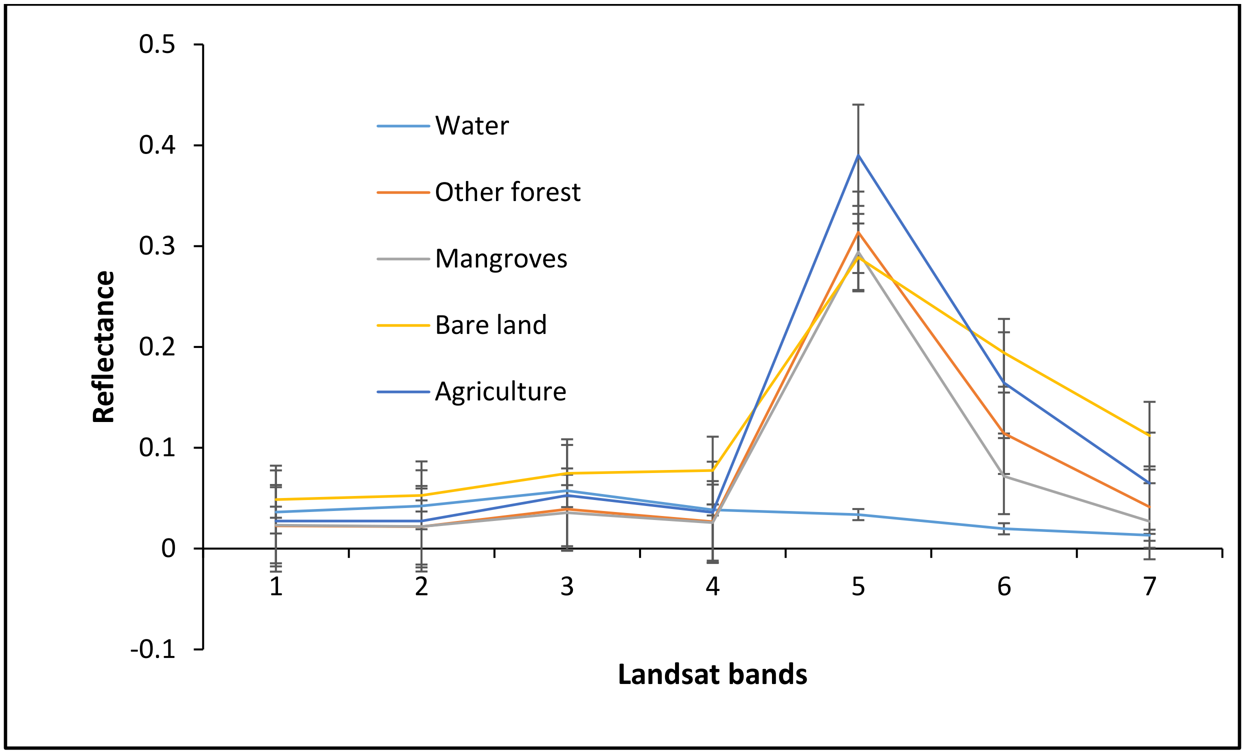


Figure 4.1. *Mean spectral response—extracted from the Landsat OLI imagery—of land cover and land use classes in Chwaka and Menai study areas.*

Table 4.2 shows the spectral separability of the five LULC classes, i.e., water, other forests, mangrove forests, bare land, and agriculture, calculated from bands 1–7 of the Landsat OLI imagery using transformed divergence (TD) and the Jeffries–Matusita (J-M) distance. According to the results, for the Landsat OLI, ETM+ (2009), ETM+ (2000), and TM (1995) images, the TD index showed that all classes attained values higher than 1.9; therefore, they were all separable. The same applied to the J-M distance except for agriculture/other forests, which reported a separability value < 1.9. The Landsat TM (1990) image shows that, according to the TD index, other forests/mangrove forests and other forests/agriculture and J-M's other forests/mangrove forests, other forests/agriculture, and mangrove forests/agriculture did not attain the 1.9 separability threshold. The Landsat MSS image showed that for both the TD index and J-M distance, other forests/mangrove forests, other forests/bare land, other forests/agriculture, mangrove forests/bare land, mangrove forests/agriculture, and bare land/agriculture were not separable.

4.3.2 Pairwise band comparison

The bands of the Landsat scenes covering the two study areas were found to be significantly correlated. For the Landsat OLI, the pairwise comparison showed that the bands with the highest correlation coefficients were bands 1 and 2 (0.99), 1 and 4, 2 and 4, and 3 and 4, all of which are visible bands (Table 4.3). Correlation values > 0.7 are considered significant—pairs of Landsat bands with such values are known to be correlated. Therefore, they provide redundant information, i.e., the recorded reflectance in one channel could be used to predict the value in the other. Therefore, with the exception of bands 5 and 1, and 5 and 2 which reported the least correlation coefficient values of 0.68 and 0.66, respectively, the Landsat bands of the image are significantly correlated.

Table 4.3: *Pairwise correlations between Landsat bands for the scene covering Chwaka and Menai Bays in Unguja, Zanzibar.*

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7
Band 1	-----	0.999	0.980	0.994	0.681	0.790	0.902
Band 2		-----	0.979	0.993	0.662	0.776	0.893
Band 3			-----	0.985	0.783	0.868	0.936
Band 4				-----	0.707	0.820	0.925
Band 5					-----	0.963	0.869
Band 6						-----	0.961
Band 7							-----

4.3.3 Image classification

The classification maps for the years 1973, 1990, 1995, 2000, 2009, and 2020 show the LULC changes in Chwaka Bay in the last 47 years (Figure 4.2). Figure 4.2 depicts the percentage area covered under each class, i.e., water, bare land, mangroves, agriculture, and other forests in Chwaka Bay in 1973, 1990, 1995, 2000, 2009, and 2020. Significant LULC changes can be observed from one period to another, e.g., bare land, mangrove forests, agricultural land, and other forests in 1973 occupied, c., 8%, 24%, 19%, and 22%, respectively, but by 2020, they occupied, c., 9%, 12%, 35%, and 17%, respectively. Therefore, by the year 2020, only a portion of the mangrove forests remained, which is about half the area covered by mangroves in 1973. Between 1973 and 2020, the area covered by water increased by, c., 3%.

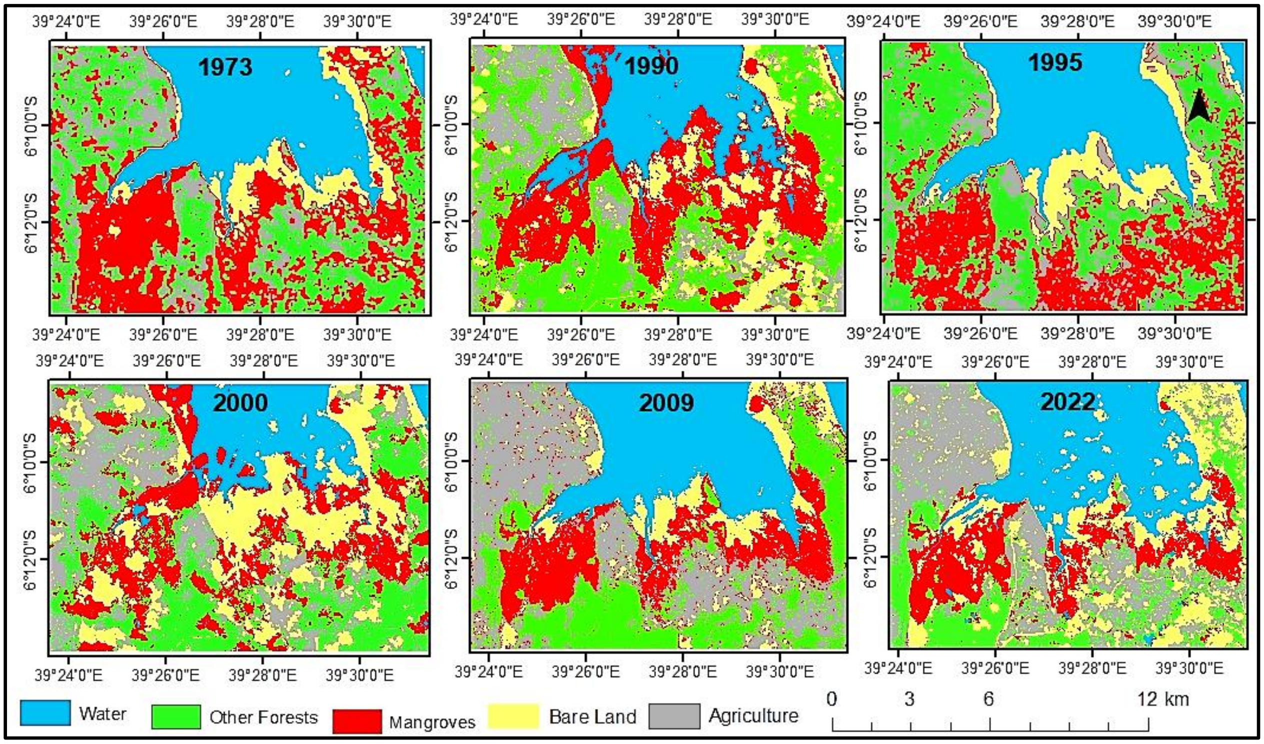


Figure 4.2. *Classified land use and land cover maps for the years 1973, 1990, 1995, 2000, 2009, and 2020—Chwaka bay, Unguja, Zanzibar.*

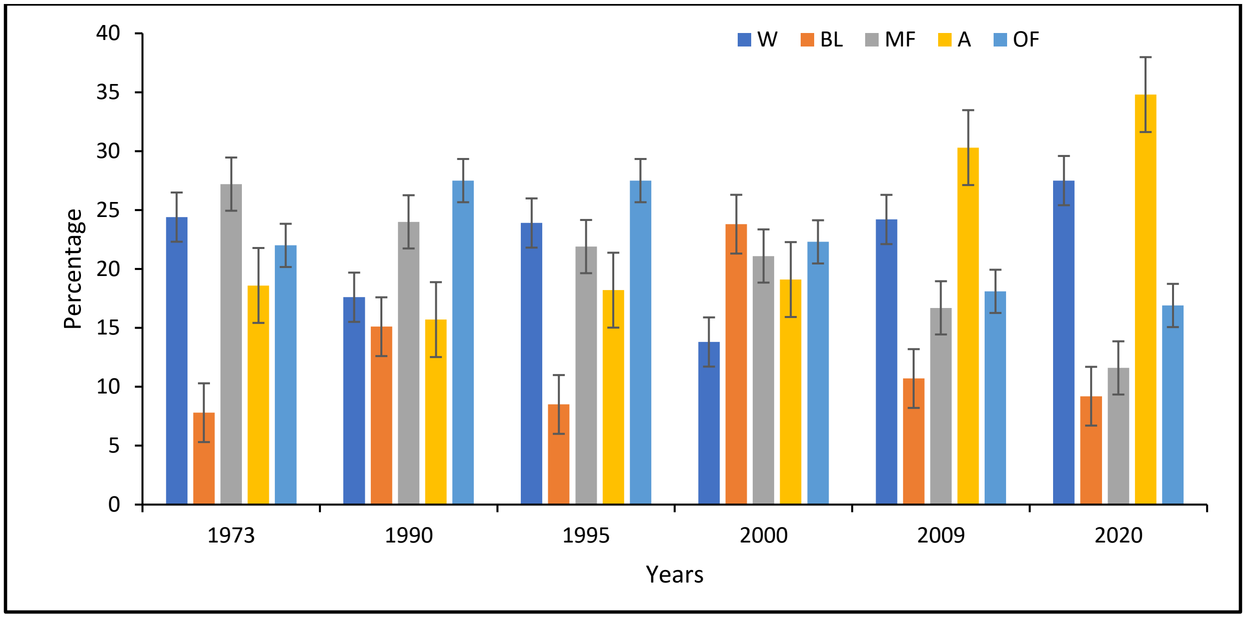


Figure 4.3. *Percentage coverage of land use and land cover in Chwaka bay in 1973, 1990, 1995, 2000, 2009, and 2020; W—water, OF—other forests, MF—mangrove forest, BL—bare land, and A—agriculture. Error bars are 95% confidence intervals.*

Figure 4.4 shows the distribution of LULCs in Menai Bay between 1973 and 2020. It can be observed from the 1973 land cover map that mangroves and other forests were distributed over the study area, but in 2010 and 2020, mangroves and other forests were cleared. The 2020 map shows that only a narrow strip of mangroves remained in a southwest–northeast direction. Only a handful of other forests remained in the northern part of the study area.

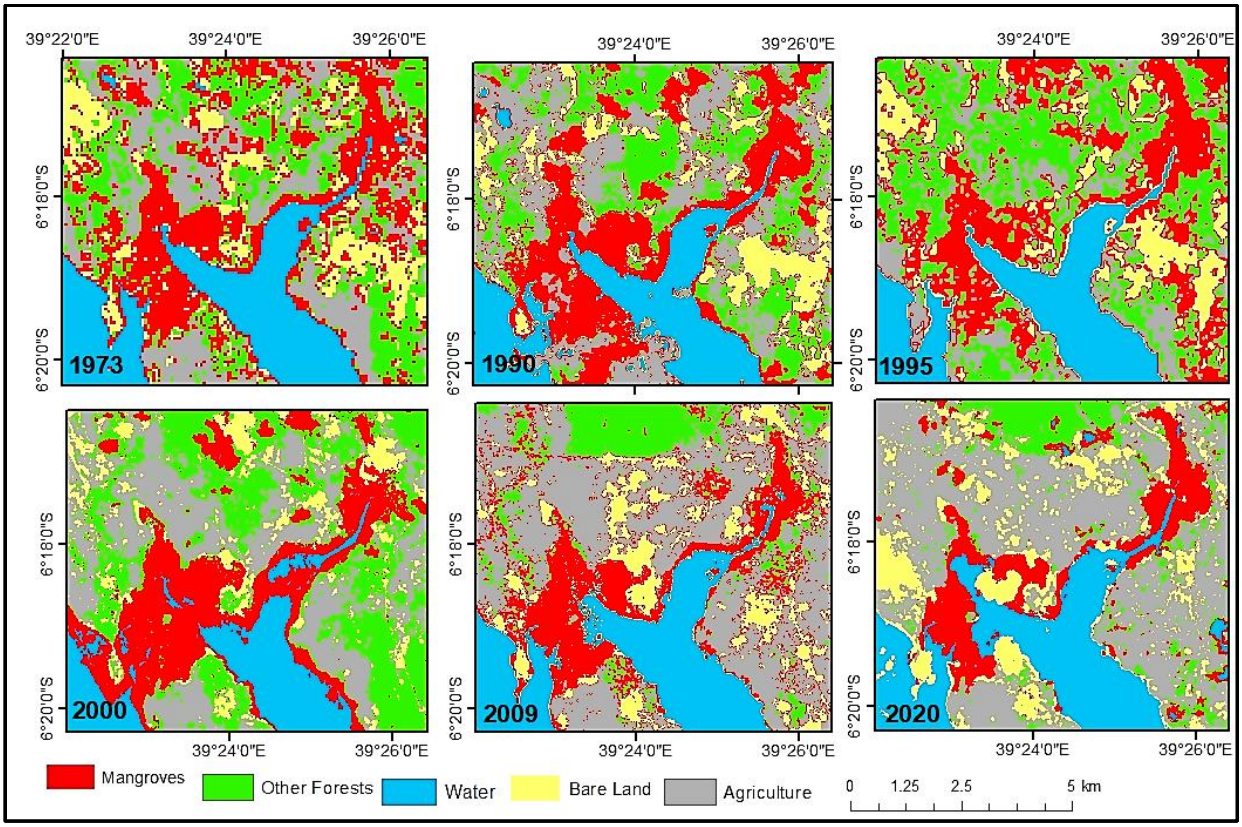


Figure 4.4. *Classified land use and land cover maps for the years 1973, 1990, 1995, 2000, 2009, and 2020—Menai Bay, Unguja, Zanzibar.*

The dynamics of the LULCs in Menai Bay, for the years 1973, 1990, 1995, 2000, 2009, and 2020, are shown in Figure 4.5. In 1973, mangrove forests occupied 18.4% of the study area, but by 2020, only 13.2% remained. Agricultural land and bare land increased from 21.5% to 43.8% and 12.4% to 15.3%, respectively, while water and other forests declined from 27.4% to 19.6% and 20.3% to 8.1%, respectively. Mangrove forests showed a decrease of 5.2%.

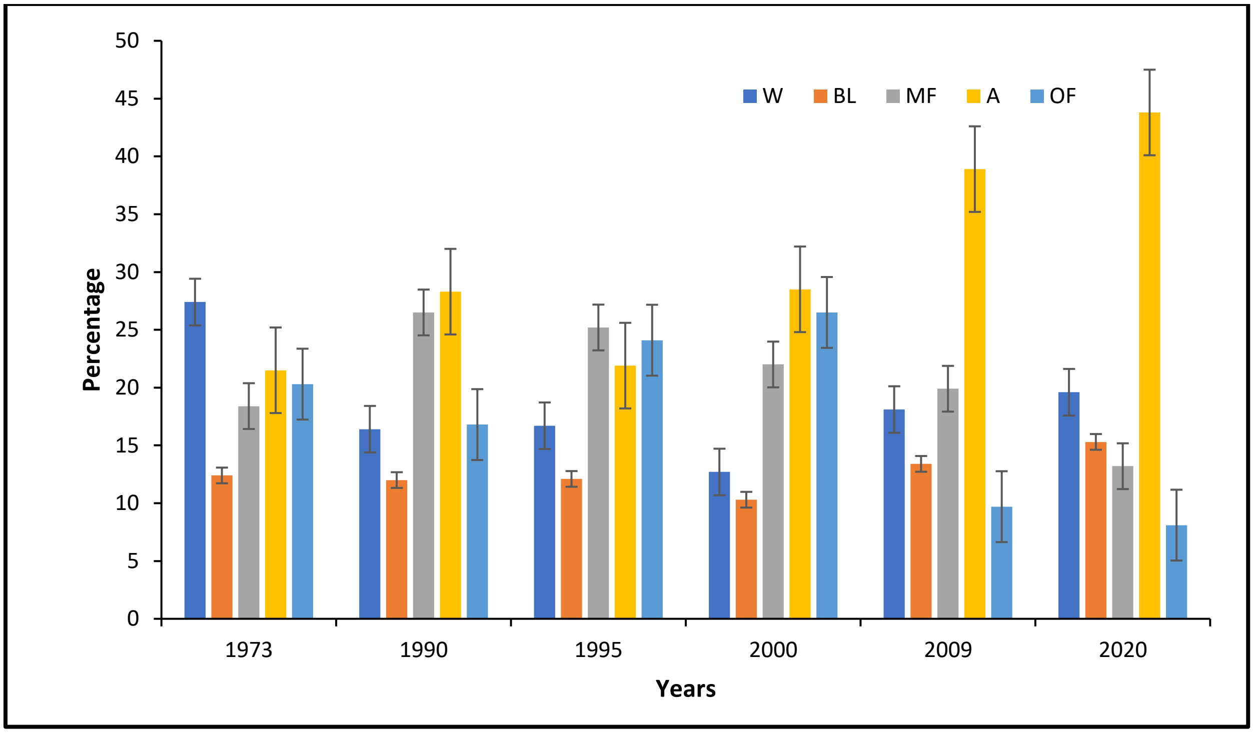


Figure 4.5. *Percentage coverage of land use and land cover in Menai Bay in 1973, 1990, 1995, 2000, 2009, and 2020); W—water, OF—other forests, MF—mangrove forest, BL—bare land, and A—agriculture. Error bars are 95% confidence intervals.*

4.3.4 Accuracy assessment

The overall accuracies for Chwaka Bay in 1973, 1990, 1995, 2000, 2009, and 2020 were 82.5%, 85.4%, 86.6%, 89.3%, 91.7%, and 92.7, respectively. The kappa coefficients (κ) were 0.72, 0.76, 0.79, 0.81, 0.86, and 0.89, respectively. In Menai Bay, the overall accuracies were 85.5%, 85.5%, 85.4%, 93.1%, 91.0%, and 94.5, respectively. The κ values were 0.77, 0.77, 0.78, 0.87, 0.88, and 0.90, respectively. The producer's and user's accuracies were in the range of 72–100% (Table 4.).

Table 4.4: *The overall accuracies and kappa coefficients for Chwaka Bay and Menai Bay in Unguja, Zanzibar.*

	Chwaka Bay					Menai Bay			
	Ground Data	Classification Results	Overall Accuracy	Kappa Coefficients		Ground Data	Classification Results	Overall Accuracy	Kappa Coefficients
1973	160	142	82.5%	0.72	1973	160	138	85.5%	0.77
1990	160	136	85.4%	0.76	1990	160	141	85.5%	0.77
1995	160	136	86.6%	0.79	1995	160	134	85.4%	0.78
2000	160	146	89.3%	0.81	2000	160	149	93.1%	0.87
2009	160	139	91.7%	0.86	2009	160	141	91.0%	0.88
2020	160	153	92.7%	0.89	2020	160	156	94.5%	0.90

4.3.5 Change detection analysis

4.3.5.1 Spatio-temporal mangrove distribution in Chwaka Bay

The 1973–2020 period shows that mangrove cover reduced from 3988.0 ha to 1706.6 ha, i.e., a 57.2% decrease. This is equivalent to a deforestation rate of 1.2% per annum. The 1973–1990 period shows that mangrove forests reduced from 3988.0 ha to 3529.9 ha, i.e., an 11.4% decrease. This is equivalent to a deforestation rate of 26.9 ha per annum. The mangrove forest cover lost 783.5 ha to sea water, probably due to rising sea levels, 473.3 ha were converted into bare land, 291.3 ha into agricultural land use, and 303.4 ha into other forests. During this period, mangroves gained 6.7 ha initially occupied by sea water, 508.6 ha from bare land, 420.5 ha from agriculture, and 1373.8 ha from other forests. From 1990 to 1995, mangrove forests decreased from 3529.9 ha to 3222.0 ha, i.e., an 8.7% decrease, a decrease of, c., 62 ha per annum. About 2.7 ha of the mangrove forest cover was covered by sea water, 327.8 ha were converted into agricultural land, 1369.8 ha were converted into other forests, and 426.7 ha were degraded to bare land. Mangroves gained 774.2 ha from the area formerly occupied by the sea, 529.0 ha from bare land, 602.7 ha from agricultural land, and 528.9 ha from other forests. Between 1995 and 2000, mangrove forests decreased from 3222.0 ha to 3092.0 ha, i.e., c., a 4% decrease, translating to a loss of about 26 ha per annum. The mangroves lost 768.4 ha to water, 149.5 ha to bare land, 556.2 ha to agriculture, and 676.3 ha to other forests. During this period, mangrove forests gained 9.5 ha from water, 585.7 ha from bare land, 465.1 ha from agricultural land, and 1220.2 ha from other forests. From 2000 to 2009, the mangroves decreased from 3092.0 ha to 2449.2 ha, i.e., a 28.2% decrease, translating to a rate of change of 71.4 ha per annum. About 3.0 ha of the mangrove forest cover was covered by sea water, 134.4 ha were converted into agricultural land use, 343.3 ha were converted into other forests, and 620.6 ha were degraded to bare land. The mangroves gained an area of about 766.4 ha from the sea, 147.4 ha from bare land, 490.4 ha from agricultural land, and 340 ha from other forests. In the 2009 to 2020 period, there was a decrease of mangrove forests by about 32.5%, at a deforestation rate of 67.5 ha per annum. The mangrove area was turned into other land use, i.e., 23.6 ha were covered by sea water, 115.2 ha were transformed into bare land, 193.6 ha were transformed into agricultural land use, and 227.8 ha were converted into other forests. The mangrove forest cover gained about 82.0 ha from the sea, 165.8 ha from bare land, 343.6 ha from agricultural land, and 711.1 ha from other forests.

Figure 4.6 shows the mangrove forest gain and loss (in ha) from 1973 to 2020. The amount of mangrove change differed from one period to another. The green color shows the area (in ha) that the mangrove forest cover gained from the other LULC classes, while the yellow color indicates the area of the mangrove forest lost to the other LCLU classes, i.e., water, bare land, agriculture, and other forests. Overall, mangroves lost, c., 2797 ha to water, bare land, agriculture, and other forests and gained, c., 515 ha. The overall destruction of the mangroves was, c., 2281 ha. Change in the area covered by mangrove forests was lowest between 1995 and 2000 and highest between 2009 and 2020. Therefore, the general trend shows that the area of mangrove forests lost to the other LULC classes increased with time.

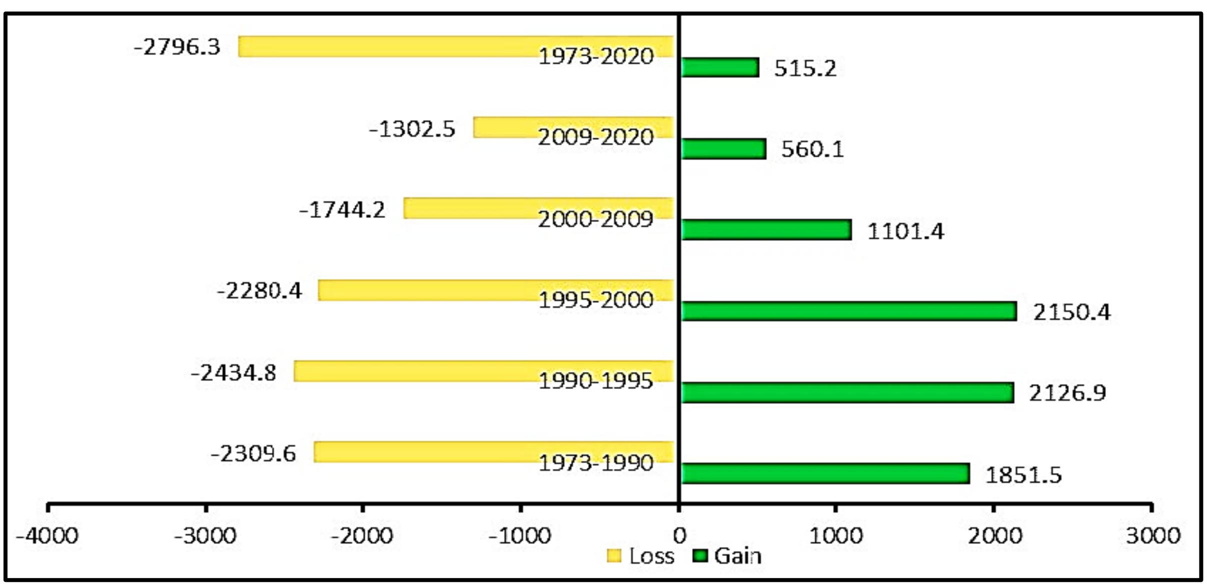


Figure 4.6. *Mangrove forest loss/gain (ha) from 1973 to 2020, Chwaka Bay in Unguja, Zanzibar.*

Figure 4.7 shows the spatiotemporal mangrove distribution in Chwaka Bay, Unguja, Zanzibar, Tanzania from 1973 to 2020.

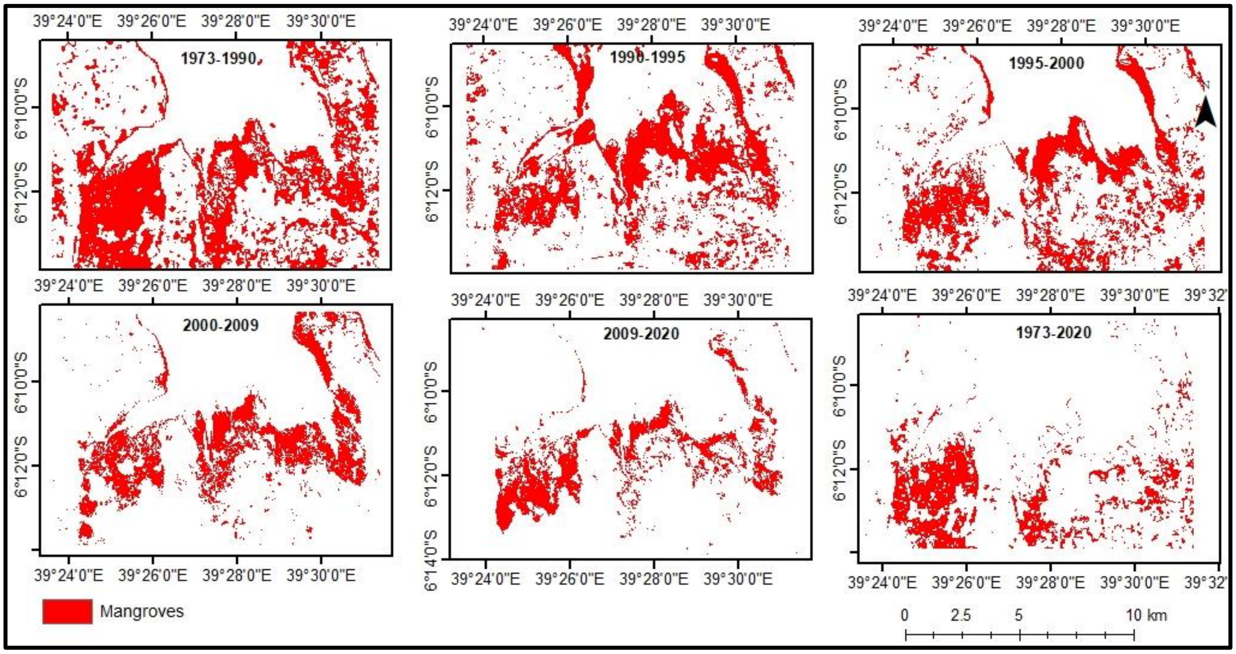


Figure 4.7. *The dynamics of mangrove forests along the coast of Chwaka Bay in Unguja, Zanzibar from 1973 to 2020.*

4.3.5.2 Spatio-temporal mangrove distribution in Menai Bay

The 1973 to 2020 period shows that the mangrove cover reduced from 1694.6 ha to 819.2 ha, i.e., a 51.7% decrease. This is equivalent to a deforestation rate of 1.1% per annum. During the 1973–1990 period, there was a 3.4% decrease of the mangrove forest cover, i.e., from 1694.6.0 ha to 1637.2 ha, equivalent to a degradation rate of 3.4 ha per annum. In the 17-year period, 34.2 ha of mangroves were covered by sea water, 164.3 ha were degraded to bare land, 404.3 ha were converted into agricultural land use, and 266.4 ha into other forests. In the same period, the mangrove forest cover gained an area equivalent to 95.7 ha originally covered by sea water, 194.8 ha from bare land, 247.1 ha from agricultural land use, and 274.2 ha from other forests. Between 1990 and 1995, the mangrove forest cover reduced from 1637.2 ha to 1561.9 ha, i.e., a 4.4% loss. The mangrove forest cover gained 15.4 ha of land earlier occupied by sea water, 135.2 ha by bare land, 332.4 ha by agricultural activities, and 277.6 ha by other forests. About 37.7 ha of mangroves were covered by sea water, 184.3 ha were converted into bare land, 321.2 ha into agricultural land, and 292.7 ha into other forests. The 1995–2000 period saw mangroves decrease from 1561.9 ha to

1358.9 ha, i.e., a reduction equivalent to 12.0%. About 3.9 ha of mangrove were covered in water, 179.7 ha turned into bare land, 169.9 ha into agricultural land use, and 550.3 ha into other forests. In this period, mangrove gained 261.2 ha from an area initially covered by water, 107.8 ha from bare land, 192.8 ha from agricultural land, and 139.0 ha from other forests. In the 2000–2009 period, mangrove forest cover fell by 125.6 ha (7.4%), i.e., from the initial 1358.9 ha to 1233.4 ha. The fall is equivalent to a mangrove degradation rate of 14.0 ha per annum. About 341.3 ha of mangroves were occupied by sea water, 146.8 ha transformed into bare land, 94.6 ha into agricultural land, and 108.3 ha into other forests. The mangrove forest cover gained 6.8 ha originally occupied by sea water, 113.8 ha by bare land, 141.0 ha by agricultural activities, and 303.9 ha by other forests. From 2009 to 2020, the area covered by mangroves declined by 414.2 ha (24.4%), i.e., from 1233.4 ha to 819.2). The mangrove degradation rate was 37.7 ha per year. In this period, mangrove forest cover increased by 12.0 ha, an area initially covered in water, 92.3 ha from bare land, 128.7 ha from agricultural land, and 62.1 ha from other forests. About 76.2 ha of mangrove forest cover was covered by sea water, 240.3 ha turned into bare land, 349.3 ha lost to agricultural land use, and 43.4 ha to other forests.

Mangrove forest gain and loss (in ha) from 1973 to 2020 is shown in Figure 4.8. Generally, mangroves gained, c., 295 ha from the other LULC classes, but lost 709 ha to water, bare land, agriculture, and other forests. In the period from 1973 up to 1990, about 57.4 ha of mangrove forest cover was destroyed, while between 1990 and 1995, about 75.4 ha were cleared. The next three periods recorded massive destruction of mangroves. The highest change in the area covered by mangroves was between 2009 and 2020. The overall destruction of mangrove forests was, c., 875 ha.

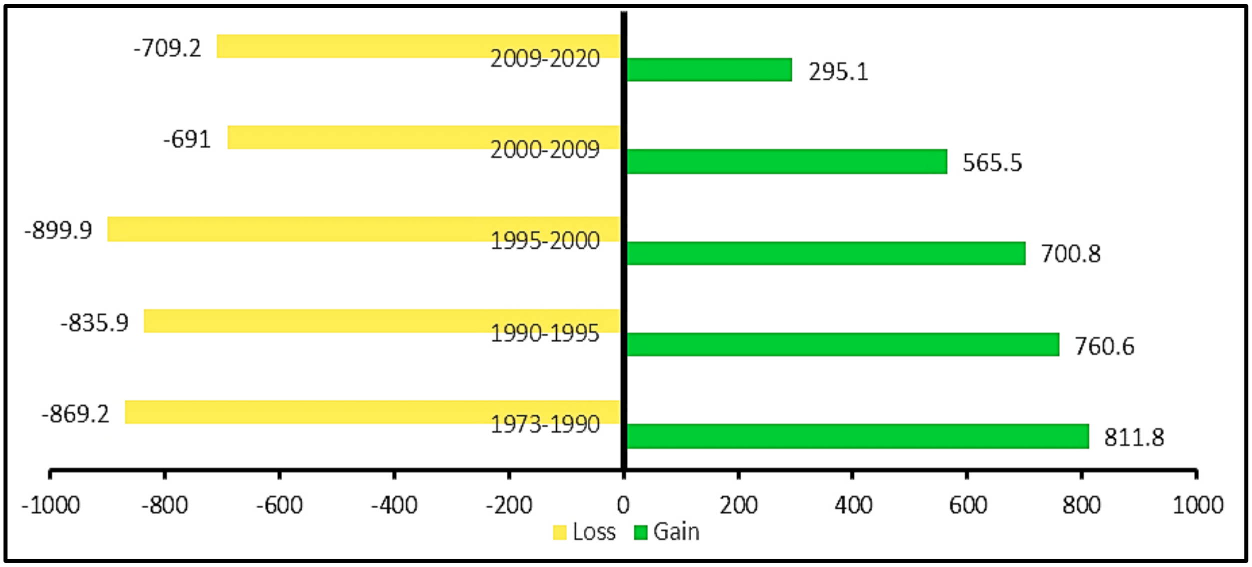


Figure 4.8. *Mangrove forest loss and gain (ha) from 1973 to 2020, Menai Bay in Unguja, Zanzibar.*

Figure 4.9 shows the spatio-temporal mangrove distribution in Menai Bay, Unguja, Zanzibar, Tanzania between 1973 and 2020.

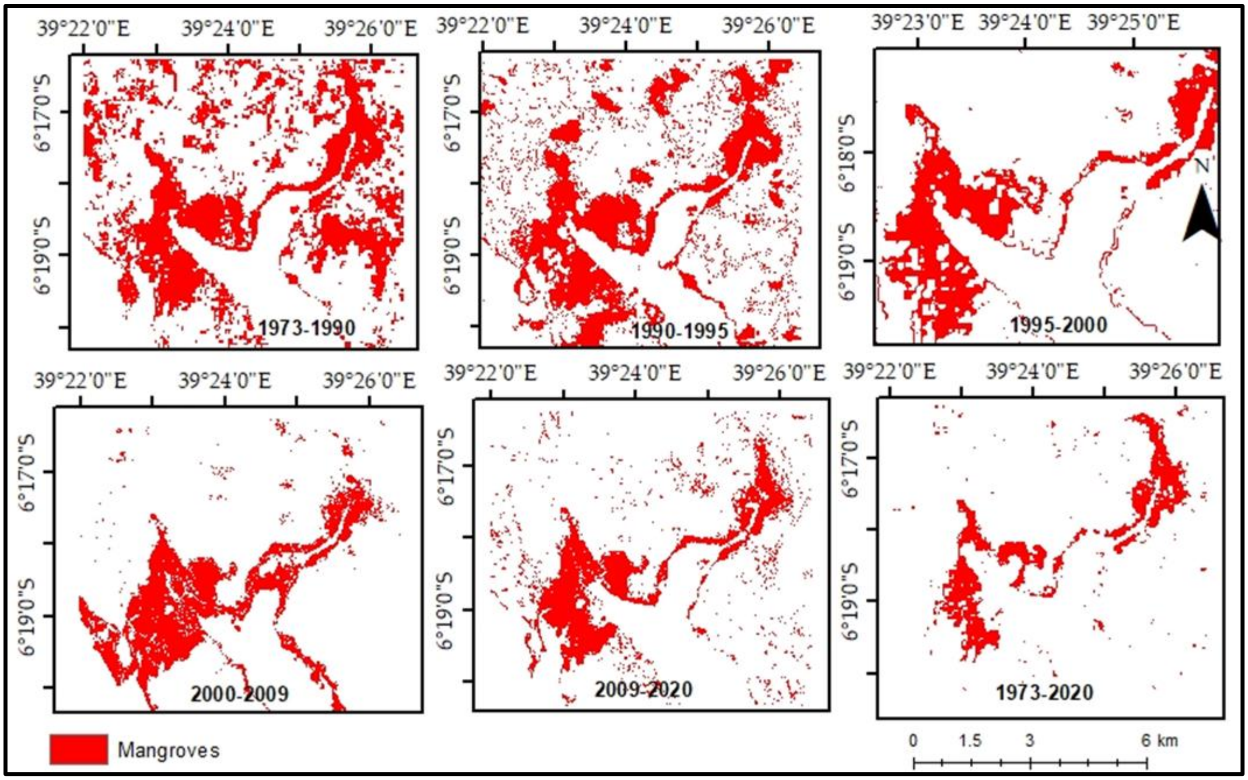


Figure 4.9. *The dynamics of mangrove forests along the coast of Menai Bay in Unguja, Zanzibar from 1973 to 2020.*

4.4 Discussion

This study aimed to detect and analyze the patterns and dynamics of mangroves in Zanzibar over 47 years—i.e., from 1973 to 2020, using a Landsat earth observation dataset. Since the eighteenth century, mangroves and their products have been extensively exploited (Mohamed *et al*., 2023a). Mangrove wood was a valuable resource that the Sultan of Zanzibar harvested, utilized for construction, and transported to the Middle East, Europe, and America (Msangameno *et al*., 2017). During that time, mangroves were exploited without any binding management plans in place; therefore, they were severely degraded (Msangameno *et al*., 2017). This study found that the areal mangrove forest cover has been decreasing over the past 47 years, although the rates of change varied spatially and temporally, in both the Chwaka Bay and Menai Bay. In eastern Chwaka Bay, i.e., the Charawe, Chwaka, and Ukongoroni Villages, mangrove degradation is more severe compared to western Chwaka. The protected Jozani Forest in the southwest of Chwaka Bay may have promoted the conservation of mangrove forests in the area. Since Jozani was designated as a forest reserve in 1952, most of the island's wildlife is found here, as similar habitats elsewhere have been destroyed to make room for human habitation. Chwaka Bay and Jozani Forest were placed under a single management system in 1995 under the name Jozani-Chwaka Bay Conservation Project (JCBCP). In Menai Bay, the areas experiencing the most degradation of mangroves are those closest to villages such as Unguja Ukuu, Pete, and Uzi. Therefore, Menai's mangrove degradation is more prevalent in the western part than in the eastern part. Zanzibar's rate of mangrove degradation is alarming, despite the availability of the current policy and regulatory frameworks to check their degradation. The most affected mangrove species are *C. tagal*, *R. mucronata*, and *B. gymnorrhiza* (Othman, 2005; RGoZ, 2019; Käyhkö *et al*., 2021).

The observed decrease in mangrove forest cover over the past 47 years in Zanzibar, particularly in Chwaka Bay and Menai Bay, highlights the challenges in the effectiveness of mangrove management policies and regulatory frameworks. In Chwaka Bay, degradation is more severe in eastern areas such as Charawe, Chwaka, and Ukongoroni villages, while western Chwaka, adjacent to the protected Jozani Forest, shows better conservation outcomes. The Jozani Forest, designated as a reserve in 1952, has played a crucial role in preserving local ecosystems by limiting human encroachment, as similar habitats elsewhere have been destroyed for settlement. The establishment of the Jozani-Chwaka Bay Conservation Project (JCBCP) in 1995 further strengthened conservation efforts by bringing the forest and bay under a unified management framework, reflecting the importance of coordinated and legally backed management strategies in halting environmental degradation (Semesi, 1998; Richmond, 2002).

However, despite such frameworks, the rate of mangrove degradation remains alarming, particularly in Menai Bay, where villages like Unguja Ukuu, Pete, and Uzi experience the highest levels of degradation, especially in the western areas. This indicates that existing policies, while present, may suffer from weak enforcement and insufficient local engagement. Socio-economic pressures from nearby communities, such as the demand for mangrove wood for construction and fuel, exacerbate unsustainable use, undermining the effectiveness of current regulatory frameworks. The continued degradation in both Chwaka Bay and Menai Bay underscores the need for stronger implementation of policies, enhanced community-based management approaches, and alternative livelihood strategies to address the human pressures that drive illegal harvesting and ecosystem destruction (Shao, 2017; Spalding *et al*., 2010).

Like many other parts of the world, the loss of mangroves in Zanzibar is linked to human activities such as timber/pole cutting, firewood collection, charcoal burning, and crop cultivation (Bunting *et al*., 2023). This is due to rapid population growth coupled with poverty and a lack of alternative livelihoods (Macintosh and Ashton, 2002). The majority of the population in rural Zanzibar are poor, and they rely on firewood for cooking (RGoZ., 2020; Käyhkö *et al*., 2021). According to Mohammed (2004) and Saunders (2011), residents in rural Zanzibar majorly depend on mangroves for their livelihood, resulting in massive mangrove destruction. Coastal communities have been relying on mangroves and their products due to a lack of diversification of livelihood opportunities (Saunders, 2011). According to the National Bureau of Statistics and the Zanzibar Bureau of Statistics, Unguja's population was, c., 250,000 in 1975, doubled to, c., 500,000 in 1996, and reached, c., 800,000 in 2009 (RGoZ, 2020). The 2022 census shows that Zanzibar has 1,889,773 residents (URT, 2022). With an average population density of 712 people per km^2 and an annual growth rate of 3.1%, the island has one of the densest rural populations in the world. A total of 13.0% of homes cannot afford to eat three meals a day, and around half of the households struggle to meet their basic needs (WB, 2022). Therefore, forests in Zanzibar, including mangrove forests, have been cleared for their products and also to create more space for agricultural land, especially in the coastal areas, to meet the rising demand for food and the burgeoning urban centers (Othman, 2005). The demand for mangrove wood products in Zanzibar was 66,702 m^3 in 1996 and was predicted to rise to about 940,630 m^3 by 2006 (Mchenga and Ali, 2015) With the current population growth rate, the demand for mangrove was expected to be at, c., 3,240,934 m^3 in 2022. Some mangrove areas have been overexploited to an extent that without human intervention, natural regeneration would not occur and, therefore, they would not regain their ecological functions (RGoZ, 1996). Despite increasing management interventions by the Revolution Government of Zanzibar (RGoZ) to conserve mangroves, biodiversity losses continue unabated (Mangora *et al*., 2016). Compared to national figures from the FAO and related research from the East African countries, Zanzibar has reported comparatively low deforestation (FAO, 2010). However, this study found that since 2000, mangrove deforestation in Zanzibar has increased dramatically. Global data suggest an average annual mangrove loss rate of 0.21% (Benjaminsen, 2017), which is lower than the average mangrove decline in Zanzibar of 1.2%. Farms upstream overuse and/or improperly manage pesticides, animal waste, fertilizers, and other toxic agrochemicals, which eventually enter the water supply (RGoZ, 2009). The problem is made worse by irrigation systems that reduce the amount of freshwater flowing to the wetlands. Mangroves are tolerant of saltwater, but they need the right balance of freshwater to survive, otherwise they dry/die (RGoZ, 2009). After many years of uncontrolled/unsustainable coastal development and infrastructure, wetlands, as well as mangrove forests have been cleared to make way for roads, industry, city expansion, harbors, and resorts (RGoZ, 2009; Othman, 2015). Overfishing, another threat to mangroves, can eradicate links in the marine food chain. In addition, fish farming can add extra nutrient waste to the marine ecosystems. Both overfishing and fish farming in Zanzibar have led to a shift in the delicate balance of marine ecosystems through, e.g., algae blooms that have affected mangroves (RGoZ, 2009). The rise in sea level remains the biggest climate-related threat to mangroves in Zanzibar (RGoZ, 2009; Käyhkö *et a*l., 2021). Some mangrove species cannot tolerate the influx of saltwater or escape the surging tides (RGoZ, 2009). Although mangroves can keep pace with the sea-level rise, changes in climate and intense weather can cause them to shift or disappear, leading to lasting changes to the coastlines they protect (RGoZ, 2009), such as erosion along creeks. Drier conditions have slowed/stopped the natural buildup of organic peat soils (RGoZ, 2009). Lessened water flow has caused the peat soils to collapse, undercutting the mangroves (RGoZ, 2009). Sometimes storms damage trees, temporarily raising seawater levels and carrying sediment inland where it smothers the above-ground roots that provide mangroves with oxygen (RGoZ, 2009). In places where mangroves have been degraded/cleared and reforestation activities have not taken place, other forest types have grown, but if the local weather conditions are not favorable, such places remain dry and bare. Afforestation activities initiated by the RGoZ and other stakeholders have led to the occurrence of mangrove forest cover where there was none.

In order to save mangroves in Zanzibar, the following should be implemented:

- The government should consult the relevant stakeholders for sustainable coastal development and infrastructure.
- Optimal practices for responsible seafood should be developed and implemented.
- Work should be carried out at all levels to prevent the worst impacts of climate change.
- Sustainable agricultural practices should be applied.
- Free-flowing rivers should be advocated for.
- The population growth rate should be controlled.

- A policy specifically targeting conservation/management of mangrove forests in Zanzibar (the current policy does not separate mangrove forests from the other forest types) should be formulated.
- A concerted effort in reafforestation and afforestation activities should be implemented.
- The forest management capacity should be improved.
- Zanzibar's economy should be diversified.

Taking these actions will not only secure a future for mangrove forests alone, but it will also bolster the entire coastal ecosystem.

A method used in restoring mangroves in Zanzibar is through natural regeneration, where mangroves occupy the shoreline and natural succession takes over (Hamad *et al*., 2014). The *R. mucronate* and *B. gymnorrhiza* are successful regeneration species in most areas of Zanzibar (Benjaminsen, 2017). The regeneration of *R. mucronata* on the Island of Pemba is 9549 seedlings/ha, compared to the 1592 seedlings/ha on Unguja Island (RGoZ, 1997; Mchenga and Ali, 2015). The poor regeneration of *R. mucronata* on Unguja may be caused by the cutting and removal of the mangrove root system (Benjaminsen, 2017; Quinn *et al*., 2017). The mangrove forest cover in places such as Kisakasaka, Pete, Muungoni, and Muwanda in Unguja as well as Gawani, Mkoani, Kisiwa Panzaa, Makoongwe, and Micheweni in Pemba has significantly increased—this could be attributed to increased community participation in the conservation and management of mangroves (Shunula, 2002). Since the mid-1990s, the Department of Forestry in association with the local communities joined hands to rehabilitate the mangroves of Zanzibar (Kovacs *et al*., 2001).

Landsat imagery is highly useful for tracking the spatial changes in mangroves, although it is limited in terms of spatial resolution and was unavailable before the 1970s. What the extent of mangroves was before the use of satellites is unknown; however, satellite images revealed broad variations in mangrove extent over a short period of time, i.e., 47 years. This study found that mangrove forests in Zanzibar could be distinguished from other LCLUs using Landsat Earth observation data. This could be attributable to Landsat's higher spectral resolution, compared to other satellites such as SPOT XS.

A crucial step in the processing of remote sensing data is the assessment or validation of accuracy. Previously, studies on satellite images' categorization did not place a high importance on accuracy evaluation (Anderson, 1976). Yet, accuracy assessment has become a crucial step due to the increased potential for inaccuracy that digital imaging presents. An important step in evaluating the results of the classification process is the accuracy assessment (Anderson, 1976). In order to properly use the data, the user of land-cover results must be aware of how accurate the result is (Anderson, 1976). The minimum degree of interpretation accuracy in the identification of land use and land cover classes (LULC) using remote sensing data should be at least 85% (Anderson, 1976; Jensen, 2005; Li *et al*., 2016). Furthermore, this study's overall accuracies (OA) in both study areas were above 85%, except the 1973 image for Chwaka Bay which recorded an overall accuracy of 82.5%. Overall accuracies in both study bays seem to improve from 1976 to 2020. For instance, the overall accuracies improved from 82.5% to 92.7% in Chwaka Bay and from 85.5% to 94.5% in Menai Bay from 1976 to 2020, respectively. Furthermore, the kappa coefficients improved in Chwaka Bay from 0.72 to 0.89 and from 0.77 to 0.90 in Menai Bay from 1976 to 2020, respectively. According to (Anderson, 1976), there are variations between image resolutions in the relative disparities in overall accuracy and kappa coefficients. More precision will be achieved with higher quality images than with lower resolution ones (Anderson, 1976).

The commission error is higher in the case of forest-related classes (mangroves, other forests, and agricultural land), which resulted in the classification of a greater number of points that do not fall into a specific category because of the confusion during classification (Thomlinson, 1999). Equally, the number of points that are incorrectly excluded from a category despite really being a part of that category is also reflected by the omission mistake. In comparison with water, the commission error was less because the nature of water bodies is quite different from other land covers. The average overall kappa coefficient for this study was 0.805 for Chwaka Bay and 0.828 for Menai Bay, which is considered to be significant. Therefore, the ability to accurately discriminate between mangroves, agricultural land, and other vegetation was one of the main hurdles we faced while classifying the Landsat images.

This study encountered several obstacles, including the need to collect ground truth data in muddy and watery mangrove forests, and due to frequent cloud cover in Zanzibar, this study was not able to acquire equal study periods between the years, which are appropriate for comparison purposes. The problem is further exacerbated by cloud and cloud shadow detection algorithms that are not reliable (Masiliunas, 2017); therefore, more research is needed in this area. Still, other data sources, such as synthetic aperture radar (SAR) which can capture images of the Earth's surface regardless of smoke, darkness, or cloud cover, can be explored to detect mangrove loss (Jackson and Adam, 2021). Moreover, data integration and more sophisticated data fusion techniques will contribute to the measurement and mapping of forest attributes (Jackson and Adam, 2021). Finally, error matrices only estimate the classification accuracy using the samples collected from the field; therefore, only biased conclusions can be drawn from such data (Jackson and Adam, 2021). Therefore, the measurement of model performance should be tried using other metrics, e.g., balanced accuracy, bias score, Matthew's Correlation Coefficient, among others (Jackson and Adam, 2021).

4.5 Conclusions

Mangroves in the Menai and Chwaka Bays are extremely important. The mangrove forests of Zanzibar serve as "safe" havens for the diversity of plants and animals. In order to map and comprehend the spatial and temporal evolution of mangrove forests, remote sensing has proven to be an invaluable tool. The overall change in the mangrove forests in both bays is about half of what they were in 1973. The annual rate of change in the mangrove forest cover varied over time and space. The primary factors thought to have contributed to the destruction of mangroves in Chwaka Bay and Menai Bay include rampant illegal anthropogenic activities, unsustainable crop cultivation, urban development and infrastructure, weak forest management policies, as well as environmental and climatic changes. The methodology used in this study could avail new insights for guiding mangrove ecosystem conservation and management in Zanzibar.

In the future, research will be carried out to compare the results obtained here with other types of remote sensing data, especially higher resolution datasets and other metrics of accuracy assessment, to monitor mangroves in the study area. The proposed methodology in this research will be applied to forested areas in other regions to advance a more comprehensive monitoring and mapping of the mangrove forest changes across Zanzibar.

CHAPTER FIVE

Mangrove species mapping in Menai Bay, Zanzibar, using Landsat 9 OLI-2 and machine learning algorithms

This chapter is based on:

Mohamed, M.K., Adam, E., and Jackson, C.M. (under review, *Estuarine, Coastal and Shelf Science*). Mangrove species mapping in Menai Bay, Zanzibar, using Landsat 9 OLI-2 and machine learning algorithms. Remote Sensing.

Abstract

Remote sensing is vital for biomass management and vegetation mapping because it offers a robust reservoir of fundamental data at various spatial resolutions and spectral areas. Over the years, satellites have primarily been utilized for mapping vegetation, resource analysis, and conservation monitoring. This study aimed to map mangrove species in Menai Bay using metrics extracted from the Landsat 9 OLI-2 dataset, i.e., vegetation indices (VIs) and gray-level co-occurrence matrices (GLCMs). Therefore, it a critical to understand the contribution of vegetation indices and texture features to classify mangroves species. Training data was derived from very high-resolution (VHR) unmanned aerial vehicle (UAV) data covering parts of the study area. Results showed that five major mangrove species are found in the study area, i.e., *Rhizophora mucronata*, *Ceriops tagal*, *Sonneratia alba, Avicennia marina, and Bruguira gymnorrhiza*. In addition, results showed that textural features attained overall classification accuracy of 68.29% (kappa = 0.62) and 67.07% (kappa = 0.60) for random forest (RF) and support vector machine (SVM), respectively. Vegetation indices (VIs) recorded overall accuracy of 72.64% (kappa = 0.67) and 67.78% (kappa = 0.61) for RF and SVM, respectively. The results of this study could help natural resource managers, policymakers, and other stakeholders with better assessments of mangrove forest resources and management plans in the face of anthropogenic and natural threats.

Keywords: Mangrove species, Machine learning, Support Vector Machine, Random Forest, Vegetation index, gray-level co-occurrence matrix, Zanzibar.

5.1 Introduction

Mangrove forests are a special ecosystem found along tropical and subtropical intertidal zones and comprise a variety of biodiversity, therefore, mangrove forests are highly productive ecosystems (Bunting *et al*., 2022). Mangrove forest habitats provide a variety of purposes, including ecological, chemical, physical, and economic ones, that significantly impact nearby coastal ecosystems (Zeng, *et al*. 2023). Coastal societies have long used mangroves in a variety of ways. However, projects involving coastal development have led to unsustainable extraction of mangrove forests, posing a major threat to their existence and the survival of the biodiversity they support (Li, *et al*., 2022). Due to urbanization, population expansion, water diversion, the creation of salt ponds, and aquaculture, mangrove habitats are being degraded and cleared globally (Cherrington, *et al*., 2020). Mangroves are among the most vulnerable environments in the world despite the growing understanding of their socioeconomic advantages to coastal populations (Zhao, *et al*., 2023). As a result, it is becoming more important to monitor and evaluate the dynamics and structure of mangrove forests to direct conservation and restoration initiatives (Mingming *et al*., 2023). In order to keep an eye on mangroves, many global mangrove distribution maps were created, including the Global Mangrove Watch (GMW), the Global Atlas of Mangroves-1 (WAM-1), and the World Atlas of Mangroves-2 (WAM-2). The global mangrove maps may be most helpful in mapping the national and regional coverage (Arimatéa *et al*., 2023). However, they may be limited to relatively small/ protected areas containing mangrove forests. Currently, a significant number of local monitoring projects are underway, e.g., Gasi Bay mangrove conservation in Kenya, Papua New Guinea’s mangrove conservation preprogramme, Karnataka mangrove conservation project in India, mangrove conservation project in Kampot, Cambodia, mangrove conservation project in Niger delta, and Manila Bay mangrove conservation project in the Philippines (Mingming *et al*., 2023). However, effective protection of mangroves would be attained if losses were recognized at the species level (Chen *et al*. (2023). The advancement of satellite imagery and sophisticated classification algorithms has led to notable advancements in monitoring mangrove forests (Chen *et al*. (2023). The mapping of mangrove species is crucial because it gives precise information on which mangroves are the most threatened (Wang *et al*., 2024).

The most popular method for mapping and discriminating mangrove species is the visual analysis method based on high-resolution spatial images combined with field surveys (Xin *et al*., 2018). However, field surveys require are cumbersome and not appropriate especially submerged dense mangrove forests and mangrove forests on mudflats (Zheng *et al*., 2024). Furthermore, mangrove's prop roots, make it challenging to enter mangrove forests for in-depth field surveys (Zheng *et al*., 2024). Consequently, mapping and monitoring mangroves have extensively relied on remotely sensed data (Kumar *et al*., 2020). Mangrove distinctive hues and tones in remote sensing imagery, along with their correlation with coastal regions, allow for mangrove species classification (Kumar *et al*., 2020)). Green chlorophyll-rich, healthy mangroves have low spectral reflectance in the red and blue bands, high reflectivity in the green band, and noticeably high reflectance in the near-infrared band; as the water content in the leaves decreases, so does the reflectance (Kumar *et al*., 2020)). Because mangrove substrates absorb light in the near-infrared spectrum, true-color composite images of mangroves appear visually darker than images of vegetation in general. Spectral reflectance in satellite data enables laboratory-scale species-level differentiation of tropical mangroves (Ou *et al*. (2023). High spatial and spectral resolution images are necessary for properly mapping mangrove species, and field measurements of each species' spectral reflectance pattern are also necessary (Wang *et al*., 2024).

Machine learning (ML) algorithms, e.g., random forest (RF) (Boateng *et al*., 2020), gradient boosting machine (GBM), Neural network (NN), classification and regression trees (CART), Naive Bayes, and support vector machine (SVM) (Van *et al*., 2014) have been frequently used for mapping mangrove species. Because ML can be applied to enormous datasets and produce more consistent and precise findings, they have gained popularity in remote sensing in recent years (Maung *et al*. 2024). The RF, CART, SVM, multi-layer perception (MLP), convolution neural network (CNN), adaptive boosting (AdaBoost), rotation forest (RoF), and K-Means are frequently applied at small scales with good outcomes in mangrove species mapping (Chicco *et al.,* 2020). The most developed ML techniques, RF, SVM, GBM, and NN, are frequently employed for mapping mangrove species (Boateng *et al*., 2020; Tian *et al*., 2023). When classifying mangrove species from remote sensing data, ML techniques can perform better than parametric classifiers, especially when dealing with massive amounts of currently available data (Behera *et al*., 2021). Artificial neural networks (ANNs) demand a lot of processing power but produce good results (Quang *et al*., 2020). Nonetheless, parametric algorithms enable intriguing outcomes across vast, homogeneous regions (Li *et al*., 2013). Machine Learning Classifiers (MLC) can be applied to map mangrove species to achieve the desired outcomes (Cohen *et al*., 2020). For instance, with an overall accuracy of 85.1%, Das and Singh (2013) identified four mangrove species using Landsat TM (Thematic Mapper) data. Using Landsat OLI (Operational Land Imager) imagery, Noviar *et al.* (2017) identified mangrove species with an overall accuracy of 97%. Elhag *et al*. (2017) managed to classify mangrove species using OLI imagery and attained a 98.1% accuracy rate.

Several spectral indices have been established in remote sensing and applied to classify mangrove species (Tran *et al*., 2022). Tran *et al*. (2022) conducted a thorough analysis of the use of vegetation indices (VI) in classifying mangroves. In addition to mapping species of mangroves, VIs have been applied to map mangrove extent, distribution, and above-ground mangrove parameters, e.g., carbon density, biomass, canopy height, and estimates of leaf area index (LAI) (Zhen et al., 2021). Vegetation indices (VIs) have also been used to track changes in mangroves over time (Bathmann *et al*., 2021). The normalized difference vegetation index (NDVI), which was used in numerous research from 1996 to 2021 of the papers assessed by Tran *et al*. (2022), was determined to be the most extensively applied index in mangroves. Recently, there has been a rise in the development and utilization of potential indices for mapping mangrove species (Faridah-Hanum *et al*., 2019).

Numerous research works, e.g., Zhang *et al*. (2017) and Adeli *et al.* (2022), have demonstrated the significance of texture features in classifying mangrove species. While spectral bands offer data for the same objects in various spectra, these textures offer information about various things with the same spectral (Zhang *et al*., 2017). The accuracy of mapping mangrove species is increased by using VIs and GLCM texture features (Mohammadpour *et al*., 2022). The significance of GLCM texture features for enhancing the RF classifier's predictability was illustrated by Adeli *et al*. in 2022. Mangrove species classification is improved and the Overall Accuracy (OA) increased by the use of GLCM textural features (Mohammadpour *et al*., 2022). GLCM texture features allow for more precise mapping of plant species and their class discrimination (Zhang *et al*. (2017). Costa *et al*. (2018) state that GLCM texture features result in improved overall classification accuracy and are significant for mangrove species.

Two main obstacles must be addressed when mapping marsh vegetation with remote sensing techniques (Yang *et al*., 2022). First, because of the great spectral and geographical diversity, it is challenging to demarcate the boundaries of vegetation communities accurately.

Second, the spectral reflectance values of water and wet soil beneath wetland vegetation are frequently combined (Cohen *et al*., 2020). The near-infrared to mid-infrared bands' signal will be attenuated by underlying wet soil and water (Cohen *et al*., 2020). This will reduce the accuracy of map classification due to confusion between mangroves, other types of vegetation, urban areas, and mudflats (Quang *et al*., 2020). Therefore, applying remote sensing data and techniques that have successfully identified terrestrial vegetation communities to mangrove species mapping is not possible. Additional difficulties arise when mapping mangroves at the species level using remote sensing. Fu *et al.* (2022) examined several conventional methods for satellite remote sensing of the mangrove ecosystems. After examining data from multiple sources, the study found that the type of data can have an impact on the mapping of mangroves. The limits of employing high-resolution data from remote sensing to map the species compositions of mangroves were illustrated by Heumann (2011a). Many studies have explored the possibilities of employing hyperspectral imagery from remote sensing for wetland vegetation, yet regarding mangrove species classification, the findings remain equivocal (Kamal, 2011).

Many studies including Zeng *et al*. (2020) and Mohammadpour *et al*. (2022) applied texture analysis and vegetation indices derived from high-resolution satellite imagery, showing that the combined use of these two features enhanced the accuracy of mangrove species classification. The research gap lies in the limited application of Landsat 9 OLI-2 data for mangrove species classification, especially when combined with advanced textural features and vegetation indices. Although several studies have used these methods for mangrove species mapping, they typically relied on high-resolution or hyperspectral data. More research is needed to evaluate the performance of these techniques with medium-resolution sensors like Landsat 9 OLI-2, considering the challenges of spectral confusion and environmental variability in dense mangrove ecosystems. This study addresses the gap by assessing the effectiveness of Landsat 9's spectral and textural features in improving classification accuracy for mangrove species, which is crucial for local-scale conservation efforts. Additionally, higher spatial resolution datasets such as WorldView 2/3/4 and Sentinel-2 are often unavailable due to persistent cloud cover in Zanzibar. Thus, this study aims to strike a balance between the readily available remote sensing data and suitable spatial resolution.

This study's primary goal was to map mangrove species in Menai Bay, Zanzibar using textural features and VIs extracted from Landsat 9 OLI-2 data and RF and SVM classification algorithms. So far, no attempts have been made to map mangrove species in Zanzibar using remote sensing technology. Landsat is freely available and its spatial and temporal resolution makes Landsat 9 OLI-2 suitable to the nature of this study in comparison to Sentinel 2 which is not available in the study areas.

5.2 Materials and methods

5.2.1 Acquisition and pre-processing of Landsat 9 satellite data

One Landsat 9 OLI-2 imagery, obtained on December 26, 2023, covered the study site. In Zanzibar, the dry season, which corresponds to summer, typically occurs from June to October. During this period, there is minimal rainfall, lower humidity, and more stable weather conditions, making it ideal for ground data collection. Another shorter dry season also occurs from late December to February. The imagery distributor pre-processed and orthorectified the image used in this investigation (DigitalGlobe, 2019). The Landsat 9 OLI-2 was georeferenced to the Universal Transverse Mercator (UTM) zone 37S projection and the World Geodetic System (WGS) 1984 datum. Landsat 9 OLI-2 was successfully launched on Monday, Sept. 27, 2021 (Malings, 2023). Landsat 9 OLI-2, similar to Landsat 8 OLI-1, possesses an increased imaging capability compared to previous Landsat satellites, enabling the inclusion of more valuable data in the Landsat global land archive (Malings, 2023). The Landsat 9 OLI-2 architecture is a replication of the OLI from Landsat 8, and it offers imagery that is in line with the spectral, spatial, radiometric, and geometric characteristics of Landsat 8 OLI-1 missions (Malings, 2023). Except for the panchromatic band, which has a GSD of 15 meters (49 feet), all nine spectral bands covered by OLI-2 will have data with a maximum ground sampling distance (GSD) of 30 meters (98 feet), for both in-track and cross-track. To guarantee radiometric stability and precision, Landsat 9 OLI-2 offers both internal calibration sources and the capability to carry out lunar and solar calibrations (Malings, 2023). According to Chung *et al*. (2021), detailed feature extraction theoretically requires radiometric correction and calibration of image data. Fine-spectral difference-based landscape features may have more difficult spectral separability due to atmospheric impacts (Chung *et al*., 2021). To extract features as best as possible, this study used Landsat 9 OLI-2 collection Level 2 data which is atmospherically calibrated by translating the digital numbers (DN) to the reflectance at the top of the atmosphere (Table 5.1). Zhang *et al*. (2017) and Adeli *et al.*

(2022) have recommended the use of Landsat 9 OLI-2 for mapping mangrove species. Whereas the spatial resolution of Landsat (30m) is considered coarse for detailed species-level mapping, it can still be effective when combined with additional data processing techniques. For example, the combination of spectral indices and advanced textural features can enhance the discrimination of mangrove species at the pixel level. Specifically, the incorporation of GLCM (Gray Level Co-occurrence Matrix) texture features would allow the capture of variations in mangrove canopy structure and spatial patterns, improving species separability. As well, the relatively homogeneous distribution and large patches of dominant mangrove species in the study area makes it feasible to distinguish species using Landsat 9 OLI data.

Table 5.1: Characteristics of Landsat 9 Operation Land Imager-2

Band	Band Name	Wavelengths	Center Wavelength (nm)	Spatial Resolution
B1	Visible Coastal Aerosol	0.43 - 0.45 µm	0.44	30
B2	Visible Blue	0.450 - 0.51 µm	0.48	30
B3	Visible Green	0.53 - 0.59 µm	0.56	30
B4	Red	0.64 - 0.67 µm	0.655	30
B5	Near-Infrared	0.85 - 0.88 µm	0.865	30
B6	Shortwave Infrared (SWIR) 1	1.57 - 1.65 µm	1.61	30
B7	Shortwave Infrared (SWIR) 2	2.11 - 2.29 µm	2.2	30
B8	Panchromatic	0.50 - 0.68 µm	0.54	15
B9	Cirrus	1.36 - 1.38 µm	1.385	30
B10	Thermal Infrared (TIRS) 1	10.6-11.19 µm	10.895	100 (resampled to 30)
B11	Thermal Infrared (TIRS) 2	11.50-12.51 µm	12.005	100 (resampled to 30)

5.2.2 *Ground control points*

Reference data was collected from September to December 2023. Due to relatively dense forest cover and high-water levels, only a few areas were accessible. Therefore, the field campaign randomly selected mangrove species along channels traversing the study area. A portable Global Positioning System (Garmin eTrex® 20 GPS Receiver) was used to help collect the data. A boat was used to access inaccessible areas by foot. A total of 613 GPS locations were gathered as training and validation points. *Rhizophora mucronata, Ceriops tagal, Bruguira gymnorrhiza, Avicennia marina,* and *Sonneratia alba* were the five main mangrove species identified by field observation in the study area (Figure 5.1). *Lumnitzera racemosa, Heritiera littoralis*, and *Xylocarpus granatum* are rare species in the study area.

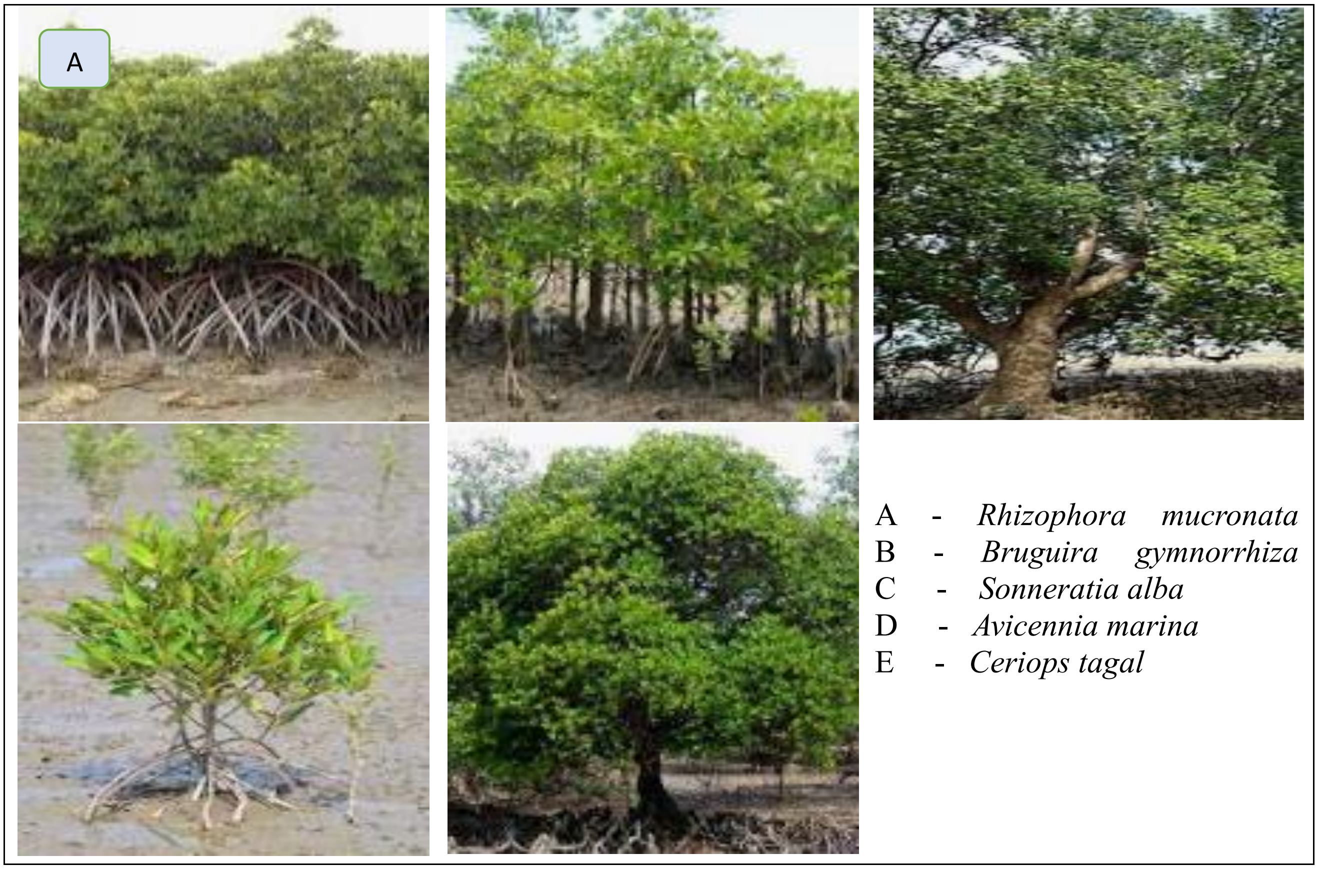


Figure 5.1. *Samples of dominant mangrove species in Menai Bay, Zanzibar.*

Using a GIS (ArcGIS v. 10.3®, ESRI, Redlands, CA, USA), points were set on all relevant (spectrally homogeneous) Landsat 9 OLI-2 imagery pixels. The points were made into polygons by following the edges of the pixels. The dominance of mangrove species identified in the study area determined the number of field samples per species. *Rhizophora mucronate, Sonneratia alba,* and *Ceriops tagal* were the predominant mangrove species (Table 5.2). The reference data were then divided into 30% (188) for the testing data set and 70% (425) for the training data set. Other reference data were collected through Google Earth, UAV, and expert opinions. Reference information from unmanned aerial vehicles (UAVs) was acquired from the Department of Forestry in Zanzibar in 2017.

Table 5.2. Training and validation points used for each mangrove species

Species	Training Points	Validation Points
Ceriops tagal	70	30
Rhizophora mucronata	89	38
Bruguiera gymnorhiza	41	18
Sonneratia alba	74	32
Avicennia marina	43	28
Othe mangrove species	52	18
Water	56	24
Total	425	188

Othe species comprised *Lumnitzera racemosa, Heritiera littoralis*, and *Xylocarpus granatum*.

The mean spectral reflectance curves derived from the pixels of the mangrove species in Menai Bay are displayed along with their standard deviations (SDs) in Figure 5.2. Overall, within one standard deviation, the seven Landsat bands exhibit significant spectral overlaps among the mangrove species. The visible bands (bands 1 to 4, which include coastal aerosol, blue, green, and red) showed the most substantial overlaps. Notably, the Near Infrared band (band 5) displayed the greatest difference in reflectance values between water bodies and mangrove species. Therefore, this study utilized a combination of spectral indices and advanced textural features derived from the Landsat 9 OLI-2 imagery to enhance the discrimination of mangrove species at the pixel level. Specifically, the incorporation of GLCM (Gray Level Co-occurrence Matrix) texture features allows the capture of variations in mangrove canopy structure and spatial patterns, improving species separability. Incorporating the water class improves the contextual understanding of mangrove distribution, since water bodies are integral to mangrove ecosystems. Thus, including water allows for better spatial delineation of mangrove boundaries, enhances the accuracy of classification, and provides a comprehensive overview of the landscape.

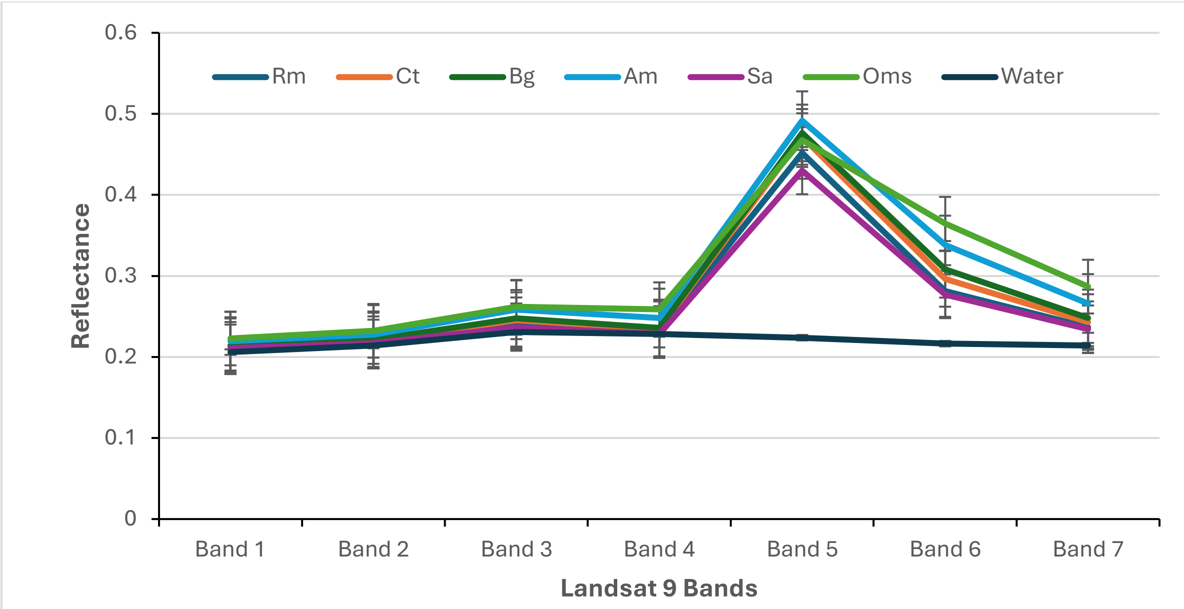


Figure 5.2. *Mean reflectance curves—extracted from the Landsat 9 OLI imagery—using reference points of mangrove species in Menai Bay.*

5.2.3 *Texture Analysis*

A remote sensing method that quantitatively represents the textural properties of different tree species is called the gray-level co-occurrence matrix (GLCM) (Matsushita *et al*., 2007). The GLCM produces texture information by taking the relationship between pixels into account. GLCM has been extensively utilized in the classification of land cover using texture and tree species (Rahmandhana *et al*., 2022). A particular area of an image of a given size is represented by the distance and angle relationship using GLCM. The quantitative expression of texture was achieved by quantifying the frequency of grayscale pixel brightness value pairs occurring simultaneously within a moving window that the user defines. Statistics were used to choose which five types of GLCM to extract, i.e., homogeneity, contrast, correlation, entropy, and angular second moment (Table 5.3).

Table 5.3. The Grey-Level Co-occurrence Matrix-based texture measure used

Texture Measure	Function	Formula
Homogeneity	It gives a measure of the similarity in the image	$HOM = \sum_{i,j=0}^{N-1} \frac{P_{ij}}{1+(i-j)^2}$
Contrast	Measure of the local variations present in an image	$CON = \sum_{i,j=0}^{N-1} P_{i,j}\,(i-j)^2$
Correlation	Measures the joint probability occurrence of the specified pixel pairs	$CO = \sum_{i,j=0}^{N-1} P_{i,j}\left[\frac{(i-MEA_i)\,(j-MEA_j)}{\sqrt{(VAR_i)(VAR_j)}}\right]$
Entropy	Statistical measure of randomness	$ENT = \sum_{i,j=0}^{N-1} P_{i,j}\left(-InP_{i,j}\right)$
Angular Second Moment	Represents the uniformity of distribution of grey level in the image	$SEM = \sum_{i.j=0}^{N-1} P_{i,j^2}$

Note: $P_{i,j} = V_{i,j} \quad \sum_{i,j=0}^{N-1} V_{i,j}, where\ V_{i,j}$ is the value in the cell (i,j) (row i and column j) of the moving window and N is the number of rows and columns.

Using the Random Forest (RF) variable importance feature, Landsat 9 OLI-2's bands 3, 5, and 6 were the best performing in the classification of mangrove species (Figure 5.3). The decision to apply both Random Forest (RF) and Support Vector Machines (SVM) for mangrove classification was driven by several factors: RF and SVM are well-established techniques in remote sensing classification due to their robustness. These methods are known for delivering high accuracy, especially in handling the complex and nonlinear relationships often found in vegetation classification, such as in mangrove ecosystems (Rodriguez-Galiano *et al*., 2012; Gislason *et al*., 2006). Random Forest is an ensemble learning technique particularly suited for managing large datasets with numerous variables, like the Landsat 9 OLI-2 bands utilized in this research. Its structure reduces the risk of overfitting by incorporating random sampling and averaging (Breiman, 2001). Additionally, RF is proficient at identifying key features (or bands) for classification, a critical function for assessing the spectral importance of various bands in distinguishing mangroves, as shown in Figure 5.3 (Liaw & Wiener, 2002). Conversely, Support Vector Machines are known for their capability to form high-dimensional hyperplanes that effectively differentiate between classes. This feature is especially useful when dealing with complex and overlapping categories, such as various types of mangroves and other vegetation (Cortes & Vapnik, 1995). Additionally, SVMs perform well with small training datasets, making them a valuable complement to RF because of their solid theoretical basis (Mountrakis *et al*., 2011). This study employed both RF and SVM to capitalize on their complementary strengths and improve classification accuracy. RF is effective at identifying the significance of various bands, while SVM excels in generalization, especially when class boundaries are complex and not linearly separable. By combining RF and SVM, the study ensures a more thorough evaluation of mangrove classification, enabling result validation across different machine learning methods, which ultimately enhances both accuracy and generalizability.

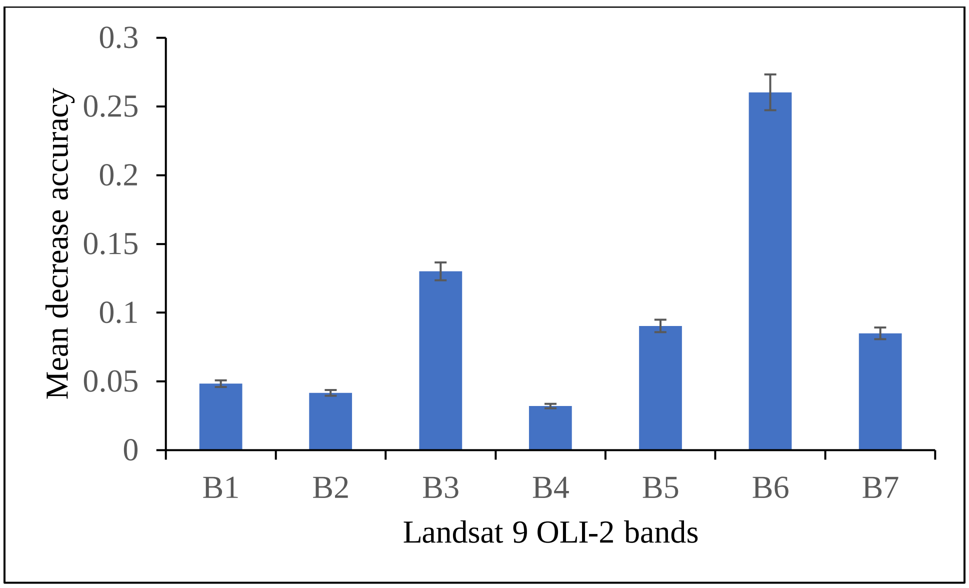


Figure 5.3. *The relative importance of Landsat 9 OLI-2 bands in discriminating mangroves by random forest. Error bars are 95% confidence intervals; B1 (Coastal Aerosol), B2 (Blue), B3 (Green), B4 (Red) B5 (Near-Infrared), B6 (SWIR 1), and B7 (SWIR 2)*

Therefore, GLCM features were extracted from bands 3, 5, and 6 as shown in Table 5.4.

Table 5.4. Grey-level co-occurrence matrix (GLCM) features

Contrast_B3	Contrast_B5	Contrast_B3
Correlation_B3	Correlation_B5	Correlation_B3
Entropy_B3	Entropy_B5	Entropy_B6
Homogeneity_B3	Homogeneity_B5	Homogeneity_B6
Second moment_B3	Second moment_B5	Second moment_B6

5.2.4 *Vegetation Indices*

Landsat 9 OLI-2 multispectral data was used to generate ten (10) vegetation indexes (VIs). Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Combined Mangrove Recognition Index (CMRI), Modified Normalized Difference Water Index (MNDWI), Wetland Forest Index (WFI), Normalized Difference Mangrove Index (NDM1), Mangrove Discrimination Index 1 (MDI 1), Mangrove Discrimination Index 2 (MDI 2), Mangrove Vegetation Index (MVI), and Optimized Soil Adjusted Vegetation Index (OSAVI). The VIs were selected based on their ability to capture the characteristics of mangrove ecosystems and separate them from other vegetation, water bodies, and surrounding land cover types. Each index was specifically chosen based on its sensitivity to vegetation health, water content, soil, and wetland dynamics, which are critical for accurately identifying and delineating mangrove forests (Cortes and Vapnik, 1995). The ten (10) vegetation indices were used to create a composite image which was used to classify mangroves in the study area. Details on the vegetation indices utilized in this study are given in Table 5.5.

Table 5.5. *Vegetation Indices Derived from Landsat 9 OLI - 2*

Indices	Formula	Sources
Normalized Difference Vegetation Index (NDVI)	(NIR-R/NIR+R)	Rouse *et al*., 1974
Normalized Difference Water Index (NDWI)	(G-NIR/G+NIR)	McFeeters, 1996
Combined Mangrove Recognition Index (CMRI)	(NDVI-NDWI)	Gupta *et al*., 2018
Modified Normalized Difference Water Index (MNDWI)	(G - SWIR1)/ (G + SWIR1)	Xu, 2006
Wetland Forest Index (WFI)	(NIR - R)/SWIR2	Wang *et al*., 2018
Normalized Difference Mangrove Index (NDM1)	(SWIR2-G/SWIR2+G)	Shi *et al*., 2016
Mangrove Discrimination Index 1 (MDI 1)	(NIR-SWIR1/SWIR1)	Gupta *et al*., 2018
Mangrove Discrimination Index 2 (MDI 2)	(NIR-SWIR2/SWIR2)	Gupta, *et al*., 2018
Mangrove Vegetation Index (MVI)	(NIR-G/SWIR1-G)	Baloloy *et al*., 2020
Optimized Soil Adjusted Vegetation Index (OSAVI)	(NIR-R/NIR+R+0.16)	Rondeaux *et a*l., 1996

Note: NIR = Near Infra-Red, R= Red, G = Green, SWIR1 = Short Wave Infra-Red 1 and SWIF2 = Short Wave Infra-Red 2.

Before performing the classification on the composite image comprising GLCM features and vegetation indices, the Jeffries-Matusita (J-M) distance separability measure was used to assess the separability of the mangrove species in the study area.

5.2.5 *Training of random forest and support vector machine classifiers*

A pixel-based supervised classification was used by applying random forest (RF) and support vector machine (SVM) algorithms using the R software's RStoolbox. Using bagged samples and randomly selected feature subsets, the RF algorithm clusters decision trees. (Breiman, 2001). The number of predictor variables (*mtry*) randomly picked at each node and the number of decision trees (*ntree*) in the ensemble must normally be defined before the RF model can be applied (Li *et al*., 2021). A 10-fold grid search technique was used to identify the top-performing parameters that would be used to train the algorithm (Li *et al*., 2021). By combining the predictions from every decision tree, RF combines a large number of weak learners, or decision trees, into a stronger predictor (Breiman, 2001). A final class was assigned based on the majority "vote" of all the trees. Breiman (2001) employed the mean decline in accuracy (MDA) as a metric to assess the explanatory power of the input variables. As each variable is removed from the model, the MDA displays the amount of accuracy that is lost (Breiman, 2001). A variable's importance in the model increased with its MDA value. The classification models additionally assessed the spectral bands of Landsat 9's capacity to identify the mangrove species.

5.2.6 Accuracy assessment

Any technique aimed at classifying images must include accuracy assessment (Sinha *et al*., 2014). According to Taureau *et al*. (2019), accuracy assessment is achieved by using the error matrix. Therefore, this study used overall, user's, and producer's accuracies, and Kappa coefficient to assess classification of mangroves in the study area (Li *et al*., 2019). Overall accuracy indicates how many of the reference sites were accurately mapped. The total accuracy is typically given as a percentage, where 100% accuracy denotes a flawless classification in which every reference site was properly identified (Taureau *et al*., 2019). Although overall accuracy is the easiest to compute and comprehend, it only offers the map producer and user the most basic accuracy information. Producer's accuracy is the likelihood that a particular ground feature will be designated as such (Li *et al*., 2019). It is the outcome of dividing the total number of pixels in each category that were correctly identified by the total number of sample pixels used for that category. User accuracy is the likelihood that a pixel on the map designated as a particular class actually belongs to that class

(Li *et al*., 2019). It is calculated by dividing the number of pixels correctly classified in the category by the total number of pixels classified in that category.

5.3 Results

5.3.1 Separability between mangrove species

The results of the Jeffries-Matusita (JM) distance analysis for species separability are summarized in Table 5.6. Classes are deemed separable if the JM distance is greater than 1.9, fairly separable if it falls between 1.7 and 1.9, and not separable if it is below 1.7. Among the *Rhizophora mucronata* and other mangrove species, *Rhizophora mucronata* was most distinguishable from water (JM = 11.24), followed by its separation from *other species (Lumnitzera Racemosa, Xylocarpus Granatum, Heritiera Littoralis)* (JM = 4.47) and *Avicennia marina* (JM = 3.73). The lowest separability for *Rhizophora mucronata* was observed against *Ceriops tagal* (JM = 1.12) and *Sonneratia alba* (JM = 1.28). *Ceriops tagal* showed the highest separability from water (JM = 11.57), while its lowest separability occurred against *Bruguira gymnorrhiza* (JM = 1.05). Similarly, *Bruguira gymnorrhiza* was highly distinguishable from water (JM = 13.69), but less so from *Ceriops tagal* (JM = 1.05) and *Avicennia marina* (JM = 1.68). *Avicennia marina* displayed considerable separation from water (JM = 18.39) and relatively high separability from *Sonneratia alba* (JM = 4.76). However, it was more challenging to differentiate *Avicennia marina* from other species *(Lumnitzera Racemosa, Xylocarpus Granatum, Heritiera Littoralis)* (JM = 1.36) and *Bruguira gymnorrhiza* (JM = 1.68). *Sonneratia alba* had a JM distance of 14.36 when compared to water, while its lowest value was against *Ceriops tagal* (JM = 1.69). Overall, other species *(Lumnitzera Racemosa, Xylocarpus Granatum, Heritiera Littoralis)* demonstrated significant separability from water (JM = 24.33), the highest value recorded among the class comparisons. The results highlight that water and other species *(Lumnitzera Racemosa, Xylocarpus Granatum, Heritiera Littoralis)* are generally well separated from most mangrove species classes, whereas separability between closely related species (e.g., *Rhizophora mucronata* and *Ceriops tagal*) remains lower. These findings suggest the potential challenges in accurately distinguishing between mangrove species using spectral data when their JM distances are below 2, which may necessitate additional band combinations or advanced classification techniques for improved discrimination.

Table 5.6. *Separability between mangrove species in Menai Bay, Zanzibar.*

	Rm	Ct	Bg	Am	Sa	OMS	Water
Rm		1.16	1.41	1.93	1.24	3. 78	4.47
Ct			1.05	1.81	1.91	3.10	5.05
Bg				1.51	1.91	2.58	4.09
Am					2.35	1.76	5.05
Sa						5.06	4.82
OMS							6.93
Water							

5.3.2 *Optimization of random forest and support vector machine*

In all models, the best-performing *ntree* and *mtry* parameters used in training the Random Forest (RF) algorithm were extracted using repeated 10-fold Cross-Validation (CV) technique. The SVM parameters were optimized using a similar approach. For RF and SVM models, the best parameter combinations are summarized in Table 5.7. For the RF model, the default *mtry* value of 10 and *ntree* value of 500 produced the lowest out-of-bag (OOB) error of 0.335 for the grey-level co-occurrence matrix (GLCM), while for vegetation indices the *mtry* and *ntree* values were also 10 and 500, respectively, with an OOB error of 0.341. The SVM for GLCM yielded a gamma value of 0.1 and a cost value of 1000, with a cross-validation error of 0.341, while the SVM model for VIs yielded a gamma value of 1 a cost value of 1000, and a cross-validation error of 0.343.

Table 5.7. *Parameters of model optimization for the random forest (RF) and support vector machine; GLCM (grey-level co-occurrence matrix), VIs (vegetation indices), OOB (out-of-bag), CV (cross-validation).*

Model	RF			SVM		
	mtry	*ntree*	OOB error	Gamma	Cost	CV error
GLCM	10	500	0.335	0.1	1000	0.341
VIs	10	500	0.341	1	1000	0.343

5.3.3 *Relative importance of variables*

In the analysis of mangrove species classification, the classification models were assessed using the Mean Decrease Accuracy (MDA) metric. This metric evaluates the relative importance of various textural features derived from the Landsat 9 OLI-2 dataset. Figure 5.4 presents the MDA values for these textural features, emphasizing their role in differentiating between various mangrove species. The analysis identified the most significant textural features as entropy, second moment, correlation, and contrast. Entropy represents the amount of information or randomness present in the texture of the imagery, indicating variability and complexity within the mangrove structure. Higher entropy values imply a more heterogeneous texture, often linked to diverse mangrove species and varying canopy structures. The importance of entropy in the classification process highlights its effectiveness in capturing the intricate patterns of mangrove ecosystems. The second moment, commonly referred to as angular second moment (ASM), assesses the uniformity or smoothness of the texture. A higher second moment signifies greater uniformity within the mangrove stands, which may be associated with particular species characteristics, including canopy density and overall health. Correlation, which evaluates the relationship between pixel values in the texture, is another important feature that played a significant role in the classification. High correlation values suggest that neighboring pixels exhibit similar values, indicating homogeneity in species composition or structural characteristics within mangrove regions. Contrast, which reflects the intensity difference between neighboring pixels, also had a significant impact on the classification process. Higher contrast values can signify more pronounced differences in texture, facilitating the differentiation between mangrove species with varying structural attributes. In summary, Figure 5.4 illustrates the relative significance of various textural features obtained from bands 3, 5, and 6 of the Landsat 9 OLI-2 dataset in distinguishing between mangrove species. The important contributions of entropy, second moment, correlation, and contrast emphasize the complexity and variability of mangrove ecosystems. Conversely, the lesser impact of homogeneity suggests a need for further investigation of texture features to enhance classification accuracy. These insights are vital for comprehending mangrove dynamics and can guide management practices focused on preserving these essential ecosystems. After running the classification models, the Mean Decrease Accuracy (MDA) provided the relative importance of the textural feature extracted from the Landsat 9 OLI-2 dataset (Figure 5.4). The most important textural features as depicted by the highest MDA values were entropy, second moment, and correlation, and contrast, while homogeneity recorded the lowest contribution to the classification of mangrove species.

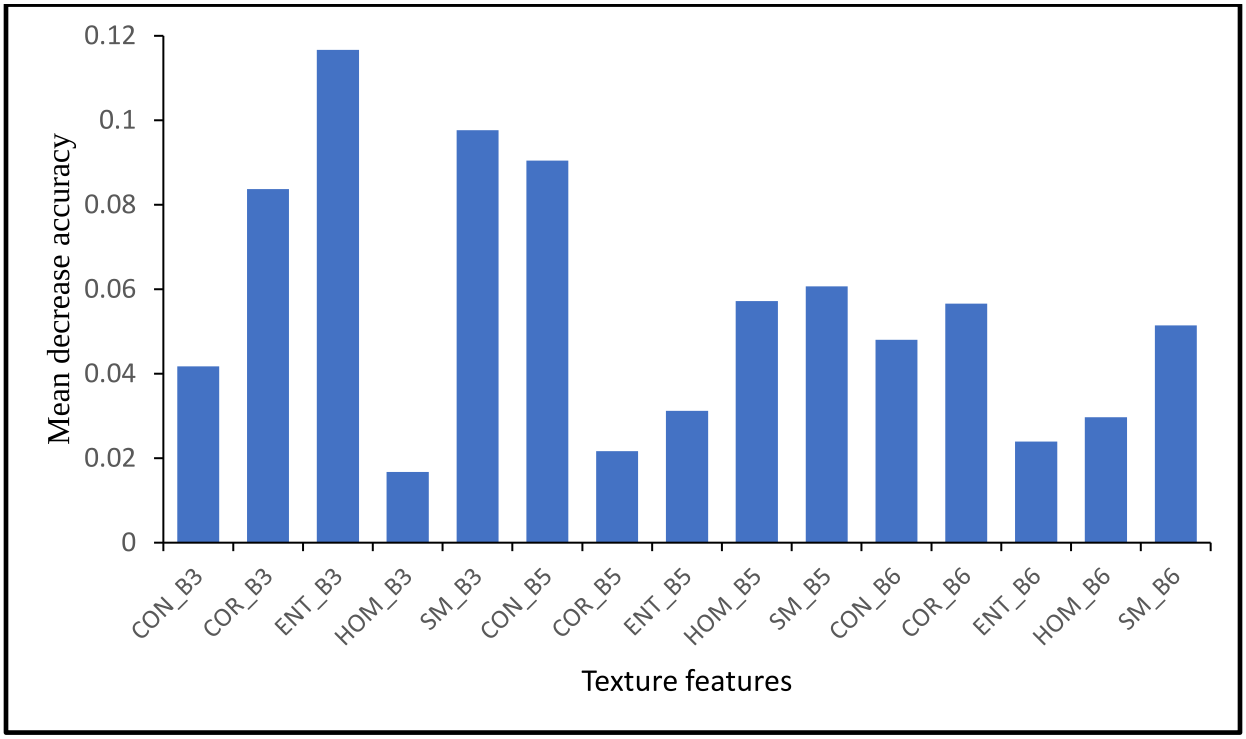


Figure 5.4. *The relative importance of texture features extracted from bands 3, 5, and 6 of the Landsat 9 OLI-2 dataset to discriminate between mangrove species.*

Figure 5.5 depicts the relative importance of various vegetation indices (VIs) derived from the Landsat 9 OLI-2 dataset for classifying mangrove species in Menai Bay. Among the VIs evaluated, the Modified Normalized Difference Water Index (MNDWI) stood out as the most significant factor in mangrove classification. MNDWI is particularly effective at distinguishing between water bodies and land areas, making it ideally suited for identifying mangrove habitats that frequently experience fluctuating water levels due to tidal changes. Its strong performance underscores the importance of accurately capturing the hydrological conditions of mangroves, which are essential for their growth and health. After MNDWI, the Normalized Difference Mangrove Index (NDMI) was also important in the classification process. NDMI is specifically designed to improve the detection of mangrove vegetation by using the reflectance properties of near-infrared and shortwave infrared bands. Its effectiveness in distinguishing between mangrove species highlights its capability to capture the unique spectral signatures of different mangrove types that thrive in moist, saline environments. The Normalized Difference Water Index (NDWI) contributed to the classification but to a lesser extent than MNDWI and NDMI. While NDWI is useful for assessing surface water and vegetation health, its broad application limits its effectiveness in distinguishing between different mangrove species, especially in areas where water and mangrove vegetation are closely integrated. In contrast, other vegetation indices (VIs) examined, such as the Combined Mangrove Recognition Index (CMRI), Mangrove Discrimination Index 1 (MDI-1), Mangrove Discrimination Index 2 (MDI-2), Mangrove Vegetation Index (MVI), Normalized Difference Vegetation Index (NDVI), Optimized Soil Adjusted Vegetation Index (OSAVI), and Wetland Forest Index (WFI), showed relatively insignificant contributions to the classification. Notably, MDI-1 had the least impact, suggesting it may not effectively capture the unique spectral characteristics needed to differentiate mangrove species, potentially due to its design not fully addressing the complexities of mangrove ecosystems in Menai Bay. The results in Figure 5.5 highlight the importance of specific vegetation indices, particularly MNDWI and NDMI, in improving the accuracy of mangrove classification. Selecting appropriate VIs is crucial for effectively capturing the unique characteristics of mangrove habitats, enhancing our understanding of their distribution and dynamics in coastal ecosystems. These insights can guide future research and management strategies for preserving and restoring mangrove ecosystems, which are vital for coastal protection, biodiversity, and climate resilience.

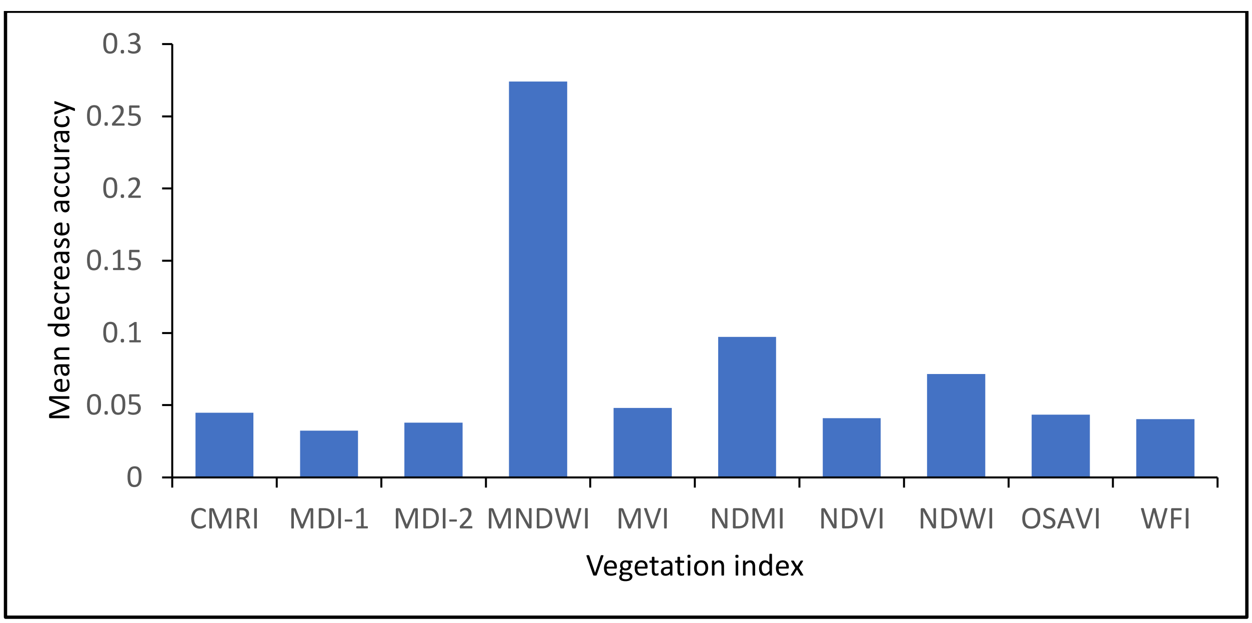


Figure 5.5. *Relative importance of vegetation indices (VIs) extracted from the Landsat 9 OLI-2 dataset to discriminate between mangrove species as measured by random forest (RF); combined mangrove recognition index (CMRI), mangrove discrimination index 1 (MDI 1), mangrove discrimination index 2 (MDI 2), modified normalized difference water index (MNDWI), mangrove vegetation index (MVI), normalized difference mangrove index (NDM1), normalized difference vegetation index (NDVI), normalized difference water index (NDWI), optimized soil adjusted vegetation index (OSAVI), wetland forest index (WFI).*

Figure 5.6 shows the Mean Decrease Accuracy (MDA) values, highlighting the relationship between mangrove species and textural features from Bands 3, 5, and 6 of the Landsat 9 OLI-2 dataset. Band 3's entropy feature was particularly important in identifying key mangrove species such as *Avicennia marina, Bruguiera gymnorrhiza, Sonneratia alba, Ceriops tagal*, and *Rhizophora mucronata*. The importance of entropy highlights its ability to capture the complexity and variability of mangrove ecosystems. High entropy values often reflect diverse canopy structures and leaf arrangements, key traits of various mangrove species. This feature's effectiveness in species differentiation underscores the role of texture and spatial arrangement in understanding mangrove habitat composition. Along with entropy, Band 3's second moment and correlation were also important in detecting *Avicennia marina, Bruguiera gymnorrhiza, Sonneratia alba, Ceriops tagal*, and *Rhizophora mucronata*. The second moment reflects texture uniformity, indicating structural consistency, while correlation measures pixel similarity in neighboring areas. Together, these features offer insights into the spatial and structural characteristics of these mangrove species. Band 5's contrast feature was crucial for identifying *Avicennia marina, Bruguiera gymnorrhiza, Sonneratia alba, Ceriops tagal*, and *Rhizophora mucronata*, as it highlights intensity differences between pixels, helping distinguish species with varied reflectance. Additionally, Band 5's second moment was effective for detecting all species except *Rhizophora mucronata*, possibly indicating unique textural properties or less uniform spectral responses for this species.

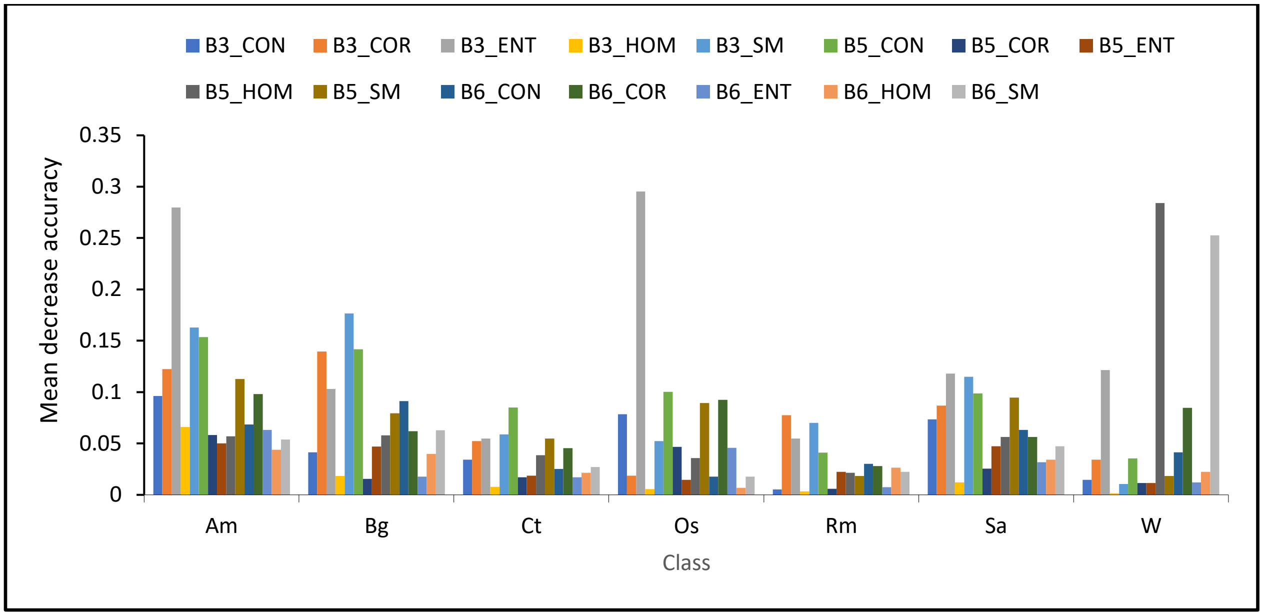


Figure 5.6. *Mean decrease accuracy (MDA) values showing the relationship between each mangrove species and textural features extracted from bands 3, 5 and 6 of Landsat 9 OLI 2 as measured by the RF: Am– Avicennia marina, Bg– Bruguira gymnorrhiza, Ct– Ceriops ta gal. Os– Other species, Rm– Rhizophora mucronata, Sa– Sonneratia alba, W–Water.*

Figure 5.7 shows the Mean Decrease Accuracy (MDA) values, highlighting the importance of Vegetation Indices (VIs) from Landsat 9 OLI-2 in distinguishing mangrove species. The modified normalized difference water index (MNDWI) and normalized difference mangrove index (NDMI) were especially effective in identifying key species like *Avicennia marina, Bruguiera gymnorrhiza, Sonneratia alba, Ceriops tagal,* and *Rhizophora mucronata*, capturing critical spectral characteristics for accurate classification. The MNDWI played a key role in distinguishing mangrove species from surrounding water and land by enhancing water features, especially for species like *Avicennia marina* and *Sonneratia alba* in coastal areas. Its high MDA values indicate strong discriminatory power. The NDMI was effective in detecting *Bruguiera gymnorrhiza, Ceriops tagal*, and *Rhizophora mucronata* by enhancing mangrove-specific spectral responses. Additionally, NDWI contributed to identifying several species by capturing moisture-related features, crucial in wetland environments. The use of MNDWI, NDMI, and NDWI together improved the accuracy of mangrove classification and provided insights into species distribution, health, and ecosystem structure.

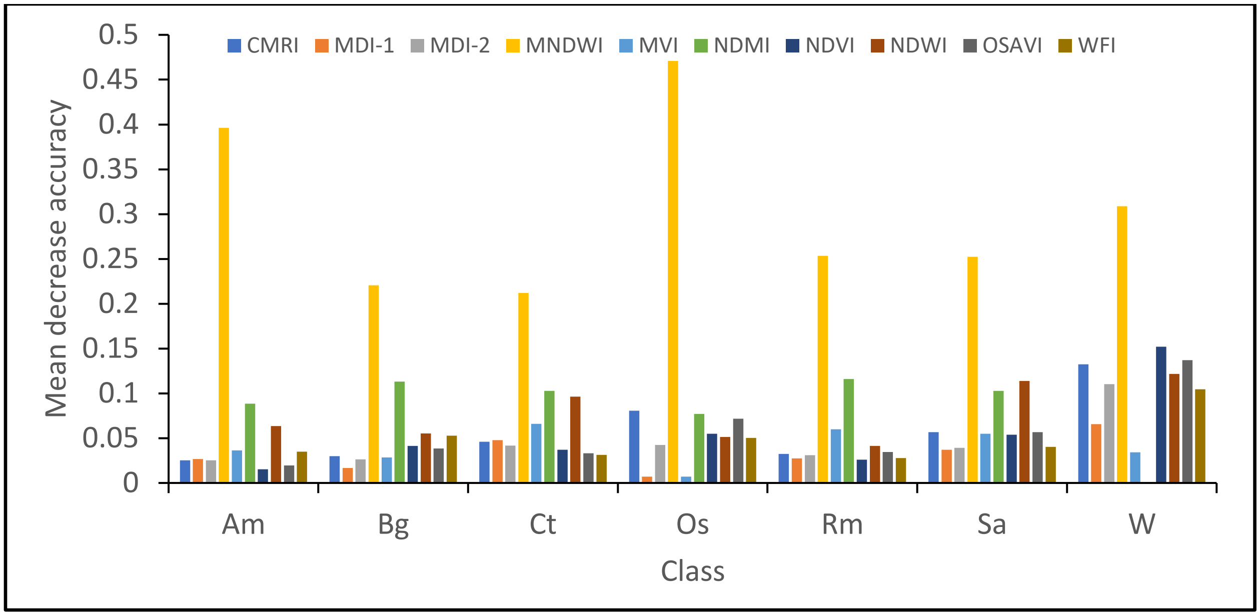


Figure 5.7. *The mean decrease accuracy (MDA) values show the relationship between each mangrove species and Vegetation Indices extracted from Landsat 9 as measured by the RF classifier. Am– Avicennia marina, Bg– Bruguira gymnorrhiza, Ct– Ceriops tagal. Os– Other species, Rm– Rhizophora mucronata, Sa– Sonneratia alba, W– Water.*

5.3.4 Accuracy assessment

Table 5.8 and 5.9 shows random forest (RF) and support vector machine (SVM) classification results using grey-level co-occurrence matrix (GLCM). The RF attained an overall accuracy (OA) of 68.29% and a kappa value of 0.62. The SVM reported OA of 67.07% (kappa = 0.60). The lowest and highest producer's accuracy (PA) was obtained for other species (*Os*) and water (W), respectively. Water showed the highest PA in both RF and SVM, i.e., 85.0% and 95.0% respectively. *Rhizophora mucronata and Ceriops tagal* attained high PA, i.e., more than 70% by RF. Only *Rhizophora mucronata* reported PA of over 70% when using SVM. *Sonneratia alba* attained the highest user's accuracy of 66.67% for RF and the lowest (56.25%) for *Bruguera gymnorrhiza*. Using SVM, *Sonneratia alba* also attained the highest user's accuracy of 75.00%, while other species *(Lumnitzera Racemosa, Xylocarpus Granatum, Heritiera Littoralis)* attained the lowest (50.00%).

Table 5.8. *Accuracy assessment of textural features extracted from Landsat 9 OLI-2 dataset to map mangrove species using for random forest (RF).*

Species/class	AM	BG	CT	RM	SA	OT	W	Total
AM	36	6	5	1	1	5	0	54
BG	4	27	6	6	3	2	0	48
CT	3	4	47	7	7	0	0	68
RM	1	7	6	60	8	1	1	84
SA	0	2	1	9	30	1	2	45
OT	1	1	1	1	0	7	0	11
Water	0	0	1	0	0	0	17	18
Total	45	47	67	84	49	16	20	328
OE	20.00%	42.55%	29.85%	29.57%	38.78%	56.25%	15.00%	
PA	80.00%	57.45%	70.15%	71.43%	61.22%	43.75%	85.00%	
Overall Accuracy = 68.29%				Kappa = 0.62				

Table 5.9*. Accuracy assessment of textural features extracted from Landsat 9 OLI-2 dataset to map mangrove species using Support Vector Machine*

Species/class	AM	BG	CT	RM	SA	OS	Water	Total
AM	35	5	6	1	0	4	0	51
BG	4	25	8	6	3	1	0	47
CT	4	5	44	8	9	0	0	70
RM	2	6	5	57	10	1	1	82
SA	0	1	2	7	33	1	0	82
OS	2	2	3	0	0	7	0	14
Water	1	0	0	0	0	0	19	20
Total	48	44	68	79	55	14	20	328
OE	27.08%	43.18%	35.29%	27.85%	40.00%	50.00%	5.00%	
PA	72.92%	56.82%	64. 71%	72.15%	60.00%	50.00%	95.00%	
Overall Accuracy = 67.07%				Kappa = 0.60				

Accuracy assessment of vegetation indices (VIs) using RF and SVM showed different results. The RF classification recorded OA of 72.64% (kappa = 0.67) compared to SVM's OA of 67.78% (kappa = 0.61). The lowest and highest PA for RF were obtained for other species *(Lumnitzera Racemosa, Xylocarpus Granatum, Heritiera Littoralis)* and water (W), i.e., 57.14% and 100%, respectively. The SVM classification depicted a similar trend, i.e., *Os* attained the lowest (53.33%)

while W attained the highest (90%) PA (Tables 5.10 and 5.11). Using Vegetation Indices (VIs) for Random Forest (RF) and Support Vector Machine, water (W) attained the highest (100%) user's accuracy. *Bruguera gymnorrhiza* attained the lowest user's accuracy of 65.91% and 60.00% for RF and SVM respectively.

Table 5.10. *Accuracy assessment of vegetation indices extracted from Landsat 9 OLI-2 dataset to map mangrove species using random forest (RF).*

Species/Class	AM	BG	CT	RM	SA	OS	Water	Total
AM	39	6	9	0	0	3	0	57
BG	3	29	4	7	0	1	0	44
CT	4	3	49	7	8	2	0	73
RM	0	4	8	62	8	0	0	82
SA	0	0	0	9	32	0	0	41
OS	1	2	0	1	0	8	0	12
Water	0	0	0	0	0	0	20	20
Total	47	44	70	86	48	14	20	329
OE	17.02%	34.09%	30.00%	27.91%	33.33%	42.86%	0.0%	
PA	82.98%	65.91%	70.00%	72.09%	66.67%	57.14%	100.00%	
Overall Accuracy = 72.64%				Kappa = 0.67				

Table 5.11. *Accuracy assessment of vegetation indices extracted from Landsat 9 OLI-2 dataset to map mangrove species using support vector machine (SVM).*

Species/class	AM	BG	CT	RM	SA	OS	Water	Total
AM	36	7	7	0	0	4	0	54
BG	3	27	4	8	2	1	0	45
CT	4	4	46	7	9	0	0	70
RM	0	5	9	59	11	0	2	86
SA	0	1	2	9	29	2	0	43
OS	2	2	0	1	0	8	0	13
Water	0	0	0	0	0	0	18	18
Total	45	46	68	84	51	15	20	329
OE	20.00%	41.30%	32.35%	29.76%	43.14%	46.67%	10.0%	
PA	80.00%	58.70%	67.65%	70.24%	56.86%	53.33%	90.00%	
Overall Accuracy = 67.78%				Kappa = 0.61				

5.3.5 *Mangrove species classification maps*

The spatial distribution of mangrove species in the study area was not haphazard. *Avicennia marina* occupied the edges of the mangrove forest – indicating that it does not flourish in deep water. *Bruguira gymnorrhiza and Ceriops tagal* mostly predominantly occupied on the seaward side of the bay in mud, i.e., in places that are well watered. *Rhizophora mucronata* covered the central part of the bay and was mostly found in the intermediate zone in the lower to mid-intertidal areas and more to the seaward side. *Sonneratia alba* is found near the tidal water where the sea water is shallow. Other minor species were found rarely in some places only and in isolation (Figure 5.8).

2.1

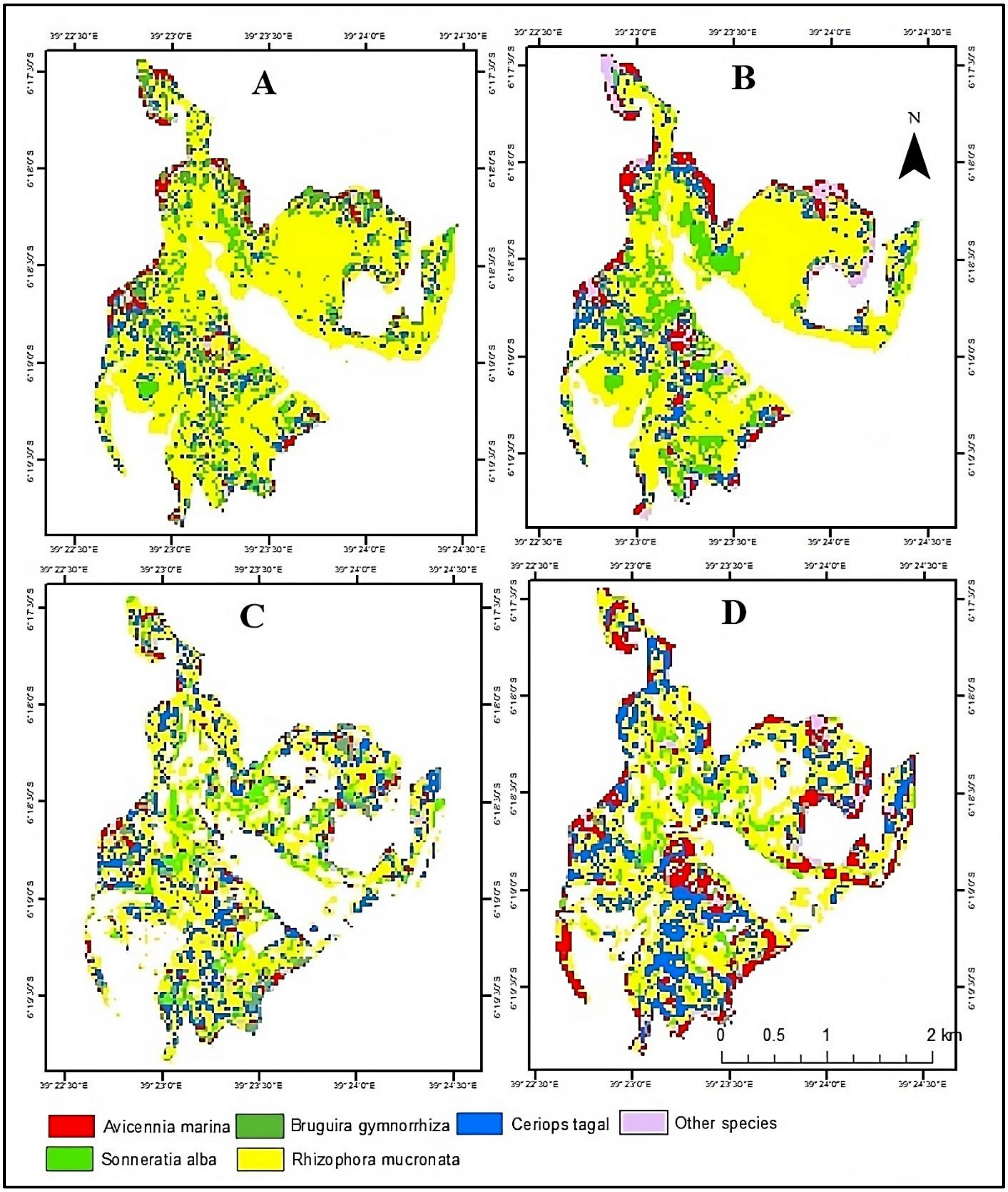


Figure 5.8. *Spatial distribution of mangrove species in Menai Bay. (A) Results of support vector machine (SVM) classification using vegetation indices (VIs), (B) Results of random forest (RF) classification using VIs, (C) Results of SVM classification using grey-level co-occurrence matrix (GLCM), and (D) Results of RF classification using GLCM.*

The RF and SVM classifiers showed differences in the coverage size of each mangrove species. The RF and SVM classifier for textural features indicated that *Rhizophora mucronate* is the most abundant species in the bay, covering approximately 8 and 7.6 ha, respectively (Table 5.12). *Bruguera gymnorrhiza* covered 0.8 and 1.8 ha. In some cases, differences between the two classifiers, i.e., RF and SVM were observed. For example, a 1.9 ha difference between RF and SVM classifications was recorded for *Avicennia marina*.

Table 5.12. *Area coverage in hectares and percentage of the classes of random forest (RF) and support vector machine (SVM) classification using textural features.*

Species/class	Grey-level co-occurrence matrix				Difference between Classifiers
	RF Classifier		SVM Classifier		
	Area (ha)	Percent (%)	Area (ha)	Percent (%)	
Avicennia marina	3.1	17.0	1.1	7.0	1.9
Bruguira gymnorrhiza	0.8	4.6	1.8	11.3	1.0
Ceriops tagal	3.8	21.1	3.0	18.7	0.8
Other species	1.0	5.4	0.7	4.5	0.2
Rhizophora mucronata	8.0	44.3	7.6	46.7	0.4
Sonneratia alba	1.4	7.6	1.9	11.9	0.6

The RF and SVM classification using VIs indicated that *Rhizophora mucronate* was the most abundant species in the bay (Table 5.13). The least abundant species were the other species *(Lumnitzera Racemosa, Xylocarpus Granatum, Heritiera Littoralis)* class. The RF and SVM classifiers showed that, *Rhizophora mucronate* covered 10.8 and 12.5 ha, respectively, which is equivalent to 56.8% and 62.6%, respectively. The highest difference in species area coverage observed between RF and SVM classification was 1.7 ha for *Rhizophora mucronata*.

Table 5.13. *Area coverage in hectares and percentage of the classes of random forest (RF) and support vector machine (SVM) classification using vegetation indices (VIs).*

Species/class	Vegetation Indices				Difference between Classifiers
	RF Classifier		SVM Classifier		
	Area (ha)	Percent (%)	Area (ha)	Percent (%)	
Avicennia marina	1.4	7.2	0.9	4.3	0.5
Bruguira gymnorrhiza	0.5	2.9	1.8	9.1	1.3
Ceriops tagal	2.4	12.8	2.0	10.2	0.4
Other species	1.0	5.4	0.5	2.4	0.5
Rhizophora mucronata	10.8	56.8	12.5	62.6	1.7
Sonneratia alba	2.7	14.2	2.2	10.9	0.5

5.4 Discussion

The classification of mangrove species using satellite imagery presents significant challenges due to the complexity of mangrove ecosystems and the unpredictability of remote sensing data (Deur et al., 2020). However, recent advancements in satellite technology—including multispectral data, high-resolution spatial and temporal data, and machine learning approaches—have improved classification accuracy (Zagajewski *et al*., 2021). This study focused on mapping key mangrove species in Menai Bay, Zanzibar, utilizing machine learning algorithms such as Random Forest (RF) and Support Vector Machine (SVM) in conjunction with textural features and vegetation indices derived from the Landsat 9 OLI-2 dataset. The use of textural features, particularly the Gray-Level Co-occurrence Matrix (GLCM), is vital for classification, with an optimal window size of 10 × 10 identified as effective for capturing relevant patterns in the imagery (Zhang *et al*., 2021). It is important to note that the performance of GLCM can be influenced by window size; smaller sizes may introduce noise, while larger sizes could overlook fine details (Costa, 2018). Additionally, even with a consistent window size, GLCM values can vary based on the spatial context of the image, highlighting the significance of contextual analysis in classification efforts.

Despite advancements, many studies in mangrove mapping have underutilized the potential of various spectral indices. This research incorporated ten vegetation indices (VIs) alongside RF and SVM algorithms to enhance mangrove species mapping in Menai Bay. While over 40 VIs are available, many studies focus on only a select few. The importance of VIs in classifying mangrove species has been underscored in recent literature, notably by Wang *et al*. (2019), which identified a gap in developing optimal spectral indices for this purpose. For instance, Tran *et al*. (2022) highlighted that, indices such as NDVI, NDWI, and several mangrove-specific indices account for a significant proportion of spectral indices utilized in mapping efforts. The use of normalized VIs mitigates issues related to sensor calibration degradation and atmospheric factors, which are prevalent in satellite imagery (Tran *et al*., 2022). As remote sensing technology becomes more accessible, the application of VIs for mangrove mapping is likely to grow, providing a robust framework for enhancing classification accuracy. Each index offers unique strengths and limitations and may be affected by various confounding factors, including sensor calibration effects and local environmental conditions.

` The advances in satellite technology have markedly improved mangrove species classification. These advancements include multispectral data and the application of machine learning algorithms, such as RF and SVM, which have emerged as leading techniques in this field (Deur *et al*., 2020). In this study, the classification accuracy for mangrove species using textural features reached 68.29% (k= 0.62) for RF and 67.07% (k=0.60) for SVM. When utilizing VIs, the accuracy improved to 72.64% (k= 0.67) for RF and 67.78% (k=0.61) for SVM. Notably, the classification for water (W) achieved a perfect user accuracy of 100%, while *Bruguiera gymnorrhiza* had the lowest user accuracy of 65.91% (RF) and 60.00% (SVM). The widespread use of RF and SVM for mangrove mapping emphasizes their effectiveness in leveraging spectral, textural, and contextual characteristics extracted from satellite data (Cha *et al*., 2023). Comparisons indicate that RF often yields better results for low spatial resolution images like those from Landsat 9, while SVM performs better with higher-feature datasets (Zagajewski *et al*., 2021). Despite this, findings suggest SVM could also provide competitive accuracy, highlighting the need for further exploration of various classifiers in future research. Lower overall classification accuracies in this study compared to others may stem from data imbalances, as certain mangrove species had significantly more samples than others, leading to biases in prediction. Difficulties in accessing certain areas for training point collection also posed challenges, compounded by the persistent cloud cover characteristic of Zanzibar's tropical climate.

Mapping mangrove species using satellite imagery is crucial for ecological, forestry, and remote sensing applications, particularly in the context of climate change. Accurate species classification is fundamental for managing, monitoring, and inventorying mangrove forests. Multi-temporal imagery provides insights into temporal variations in mangrove ecosystems, facilitating the identification of different species and monitoring their health and growth. This study identified *Rhizophora mucronate, Ceriops tagal, Sonneratia alba*, *Avicennia marina*, and *Bruguiera gymnorrhiza* as the predominant species, noting that their distribution is influenced by both physical and anthropogenic factors. The incorporation of multi-temporal satellite imagery enhances species classification by providing high spatial and temporal resolution data that capture variations in the mangrove ecosystem (Kwenda *et al*., 2024). Additionally, multispectral data offer insights into the spectral behavior of mangroves across various wavelengths, further aiding in species differentiation and health assessment (Cha *et al*., 2023). Satellite imagery provides an objective data collection method, reducing biases associated with traditional ground-based methods and offering a cost-effective means to monitor long-term changes in mangrove ecosystems (Lemankova, 2024). Ultimately, satellite imagery is indispensable for accurately mapping mangrove species, contributing to effective inventory, monitoring, and management efforts (Yu *et al*., 2023).

Despite progress in satellite-based mangrove species classification, challenges and limitations persist. A significant barrier is the lack of adequate ground-truth data for training and validating machine-learning algorithms (Kwon *et al*., 2021). Future research should prioritize acquiring high-quality ground truth data and developing methodologies for incorporating this data into machine-learning frameworks. Variability in satellite imagery due to capture parameters, sensor noise, and atmospheric conditions presents another challenge (Belgiu *et al*., 2016). Classification accuracy is affected by various factors, including spectral variability due to differences in canopy structure and pigment content, environmental influences, and confusion with other plant species exhibiting similar spectral characteristics (Kwon *et al*., 2021). To enhance mangrove species classification accuracy, several strategies could be employed. Incorporating additional data sources, such as hyperspectral images or LiDAR, can provide more detailed insights into the spectral properties and three-dimensional structure of mangrove forests (Kwon *et al*., 2021). Machine-learning methods, including neural networks that consider multiple factors and their interactions, could also improve classification outcomes (Yu *et al*., 2023). Furthermore, exploring the integration of data from various satellite sensors, such as radar and optical data, may enhance species classification accuracy. Lastly, investigating advanced image processing techniques like deep learning and object-based image analysis holds promise for achieving more reliable and precise results in mangrove species classification.

5.5 Conclusions

This work aimed to map mangrove species found in Menai Bay, Zanzibar, using two machine learning algorithms (MLAs), i.e., support vector machine (SVM) and random forest (RF). To increase accuracy, this study made use of vegetation indices and grey-level co-occurrence matrices (GLCMs) extracted from Landsat 9 OLI-2 imagery. This hybrid method of combining GLCM and VIs in the RF and SVM models increases the accuracy of mangrove species classification. The VIs used in this study were based on the widely used VIs to map mangrove species with improved accuracies. Further research endeavors may explore the potential applications of sophisticated technologies for remote sensing and machine learning algorithms to enhance the accuracy and adaptability of mangrove classifications of species and forest monitoring in various ecosystems and geographical areas. Additionally, more studies are required to apply new machine learning classifiers in mapping mangrove species (Guo *et al*., 2022; Pu *et al*., 2020) Further testing and trials are also required to expand the study area and confirm the viability of this approach. To classify mangrove species accurately and thoroughly, future research should also concentrate on the creation of cutting-edge machine learning algorithms that can successfully combine spectral, contextual information, and textural from satellite imagery data. Using satellite images to classify mangrove species could help with mangrove inventory, conservation, and management.

CHAPTER SIX

Remote sensing-based assessment of mangrove forest change in Zanzibar Island, Tanzania: A synthesis

6.1 Introduction

This synthesis chapter consolidates the research findings, offering an integrated understanding of the study's contributions to mangrove management and mapping. The research connects mangrove ecosystems' historical, spatial, and socio-ecological aspects in Zanzibar's protected bays, emphasizing the interaction between policy frameworks, remote sensing technologies, and community involvement.

Mangrove forests are vital ecosystems recognized for their unique ecological functions and significant socioeconomic benefits to coastal communities. As keystone coastal ecosystems, they serve as a substantial energy base for marine biotopes, exhibiting high ecological productivity (Wang *et al*., 2024). The connectivity of maritime habitats means that a considerable portion of the organic matter produced by mangroves supports the productivity of adjacent marine ecosystems (Fan *et al*., 2023). Despite their many benefits, mangroves are subjected to various forms of environmental and human-induced degradation globally. Natural disturbances, including lightning strikes, insect infestations, diseases, frost, tropical cyclones, sea-level rise, and climate change, pose threats to these ecosystems across multiple spatial and temporal scales (Wang *et al*., 2021). However, human activities, such as oil spills, conversion of land for aquaculture, and urban or industrial development, often have more severe and lasting impacts than natural disturbances (Ellison *et al*., 2020). According to Jia *et al*. (2021), factors like population growth, political and economic changes, technological progress, and shifting consumer behaviors significantly affect mangrove ecosystems, leading to increased demand for their services, including waste decomposition and the provision of food and building materials.

Mangrove forests are often found in remote, hard-to-reach locations, where tides, muddy conditions, and deep root systems make surveying difficult (Maung *et al*., 2024). Regularly monitoring their structure, species composition, and biomass is crucial for effective resource management, conservation, and sustainable utilization. Remote sensing offers a viable solution for monitoring these changes, especially in challenging environments, providing a time- and cost-efficient way to obtain accurate information about the health of these forests (Anneboina *et al.,* 2017). Geographic Information Systems (GIS) and remote sensing techniques are increasingly being used to track changes in mangrove ecosystems (Wang *et al*., 2021).

Remote sensing is a comprehensive, multitemporal, and multispectral technology that spans a wide range of wavelengths from visible light to microwaves, allowing for the timely and accurate collection of data on the extent and condition of mangroves (Ou *et al*., 2023). The reflectance patterns in the visible and near-infrared spectra offer valuable insights into vegetation cover (Ou *et al*., 2023). Satellite-derived indices, such as the Normalized Difference Vegetation Index (NDVI) and the ratio of near-infrared to red wavelengths, serve as effective tools for monitoring the health of mangrove ecosystems (Zhang *et al*., 2021). The NDVI is particularly useful for evaluating vegetation density and overall forest health by capitalizing on differences in chlorophyll absorption and the reflectance of leaf cellular structures (Zhang *et al*., 2021).

This study aims to analyze the patterns, dynamics, policies, regulatory frameworks, and ecosystem services of Zanzibar's mangrove forests in two protected bays by employing a hybrid methodology that includes remote sensing, literature review, and field-based approaches complemented by statistical analysis.

The following objectives guide this thesis:

1. To review policy and regulatory challenges and strategies for sustainable mangrove management in Zanzibar.
2. To assess the perception and contribution of mangrove ecosystem services to the well-being of coastal communities in Chwaka and Menai Bays, Zanzibar.
3. To map the spatial and temporal distribution of mangrove forest cover from 1973 to 2020 in Chwaka Bay and Menai Bay, Zanzibar.
4. To map mangrove species in Menai Bay, Zanzibar, using Landsat 9 OLI-2 and machine learning algorithms.

6.2 Policy and regulatory challenges and strategies for sustainable mangrove management in Zanzibar

The study begins by situating Zanzibar's mangrove management within a historical policy framework, from colonial times to the present. Examining the evolution of policies and regulations from 1890 to the post-independence period illustrates how legal structures have influenced conservation practices and community involvement. This historical context offers a valuable perspective for interpreting the spatial patterns identified in subsequent analyses. The persistent trends of degradation recorded during the colonial and early independence eras correspond with the decline in mangrove cover observed from 1973 to 2020. This integration of historical and spatial data emphasizes that effective conservation strategies must be grounded in strong legal and policy foundations, taking into account both past management failures and successes. The study identified a complex interplay of policy, regulatory, and socio-economic factors affecting the sustainable management of Zanzibar's mangrove forests. Historical and current legislative measures, such as the colonial-era Wood Cutting Decree (1945) and the post-independence Forest Reserve Order (1965), were found to shape mangrove conservation strategies. These policies aimed to regulate forest use, restrict harmful activities, and encourage reforestation efforts. However, enforcement challenges and a lack of coordination among key sectors, such as tourism, land, water, and fisheries, have undermined their effectiveness.

The rapid urbanization, agricultural expansion, and overexploitation of mangroves for timber have persisted as primary threats, compounded by the increasing demand for land and resources driven by population growth and poverty. While historical policies laid a foundation for conservation, gaps in contemporary governance frameworks have limited the sustainable management of mangrove ecosystems. This has led to conflicts between community needs and conservation priorities, highlighting the need for more inclusive, participatory management strategies that integrate local knowledge and practices.

The findings emphasize the importance of developing adaptive management strategies that align with both environmental sustainability and socio-economic development goals. Strengthening local institutions, enhancing intersectoral collaboration, and revising existing policies to reflect current ecological and social realities are crucial steps for ensuring long-term mangrove sustainability.

6.3 Perception and contribution of mangrove ecosystem services in Chwaka and Menai bays, Zanzibar

The research utilized a mixed-methods approach, integrating both qualitative and quantitative elements to capture a range of perspectives. Fieldwork took place from February to May 2022 and involved focus group discussions, key informant interviews, and household surveys to collect data on local perceptions and the socio-economic benefits provided by mangrove services. The study implemented a systematic data collection approach that began with household surveys aimed at assessing residents' general awareness and perceptions of mangrove services. This was followed by focus group discussions and key informant interviews to obtain deeper insights into the importance of these services. Participants for the focus groups were chosen through purposive sampling, focusing on specific groups such as local administrators (Shehas), villagers, herbalists, active and retired fishermen, past and present mangrove harvesters, and fish product sellers. Representatives from the Jozani-Chwaka Bay Community Organization and ward-level forest officers also took part. These discussions occurred in four wards: Chwaka, Uzi Ukongoroni, Unguja Ukuu, and Charawe.

Key informant interviews were conducted with experts and government officials, including academics specializing in mangrove ecosystems from Zanzibar's universities and officials from the district and regional offices, as well as representatives from the Ministry of Agriculture and Natural Resources. A snowball sampling technique was used to identify participants with relevant knowledge of mangrove ecosystem services in the study area. In total, 31 key informants were interviewed. The household survey used a standardized questionnaire that was revised based on feedback from the key informant interviews and focus group discussions. The survey targeted heads of households or adult family members, with a sample size of 10% of households in each ward. This ensured the collection of detailed information on the perceived importance of various ecosystem services. A pilot study was conducted to validate the research instruments.

Data analysis was performed using IBM SPSS Version 23. A chi-squared test was used to evaluate respondents' awareness of the services provided by mangrove ecosystems. One-way ANOVA was applied to analyze differences in respondents' perceptions of the relative significance of mangrove services across different wards. Post-hoc tests (Tukey's test) were used to assess the relationship between perceived ecosystem services and participants' occupations. Variables considered included age, gender, marital status, level of education, household income, household size, occupation, accessibility to mangrove forests, and household duration in the area. Responses were scored on a Likert scale to facilitate comparison.

The study identified 16 mangrove ecosystem services, which were categorized into four major classes: provisioning, regulating, supporting, and cultural services. Provisioning services, which include poles, firewood, medicinal products, honey, fruits, picnic sites, and fodder, were the most recognized by local communities, with 83.9% of respondents indicating them as crucial. Supporting services (46.2%), regulating services (45.4%), and cultural services (21.0%) followed in terms of awareness. There were significant differences in household awareness between the Chwaka, Charawe, Ukongoroni, Unguja Ukuu, and Uzi wards for regulating services ($\chi2 = 6.061$, $p = 0.014$) and supporting services ($\chi2 = 6.006$, $p = 0.014$). However, there were no significant differences in awareness of provisioning ($\chi2 = 1.510$, $p = 0.919$) and cultural services ($\chi2 = 1.601$, $p = 0.901$) across the wards.

The perception of the importance of ecosystem services also varied significantly among wards. For instance, Chwaka ward residents placed higher value on provisioning services, while respondents from Unguja Ukuu and Uzi wards prioritized supporting and regulating services. This variation could be attributed to differences in livelihoods and direct interactions with mangrove resources. For example, small-scale farmers, civil servants, and artisans rated poles as highly important provisioning services. Similarly, wild habitats were more valued by fishermen and educators, highlighting the relationship between occupational background and the perception of specific ecosystem services. Despite the high recognition of mangrove ecosystem services, respondents highlighted several challenges affecting their sustainable use. Approximately 76% of key informants indicated that mangroves were being degraded during the extraction of resources, while 24% reported severe degradation in some areas. Illegal harvesting was identified as a significant problem, with 74.5% of respondents in Unguja Ukuu ward having witnessed such activities more than once.

The most significant drivers affecting the availability of mangrove ecosystem services included a lack of alternative livelihoods and weak institutional frameworks. These factors had mean scores of 3.5 in the household survey, indicating a critical need for improved management and policy interventions. Insufficient resources to support forestry institutions and the absence of qualified personnel to oversee sustainable management were also highlighted as major barriers, particularly in Chwaka, Ukongoroni, and Unguja Ukuu wards.

The study concluded that while mangrove ecosystem services are widely recognized and valued by local communities in Chwaka and Menai Bays, the lack of alternative livelihoods and inadequate institutional support pose serious threats to their sustainability. Addressing these challenges requires targeted interventions that incorporate local perceptions and prioritize the sustainable management of mangrove resources. The study also suggests that awareness campaigns and community-based management strategies could enhance the long-term conservation of mangrove ecosystems in Zanzibar.

6.4 Mapping spatial and temporal distribution of mangroves using change detection techniques in remote sensing

The examination of mangrove ecosystems in Chwaka and Menai Bays through remote sensing methodologies underscores the critical role that advanced technology plays in monitoring these vital coastal resources. Given the challenges associated with traditional ground-based assessments, including accessibility and costs, remote sensing emerges as an invaluable tool for providing comprehensive spatial and temporal insights into mangrove health and dynamics. This synthesis encapsulates the findings of the study while drawing connections between the various aspects of the research.

This research utilized Landsat satellite data from 1973 to 2020 to conduct a comprehensive analysis of changes in mangrove cover, benefiting from the historical and global reach of the Landsat missions. By employing various versions of Landsat imagery, the study maximized the use of available historical records while enhancing the robustness of its data across different temporal scales. The integration of supplementary data sources—such as Google Earth images, topographical maps, and drone photographs—further improved the accuracy of the classification outputs. This approach underscores the critical role of ground-truthing in remote sensing studies, ensuring that the analyses reflect the true state of mangrove ecosystems.

The rigorous methodology employed in the image processing phase, including radiometric corrections and the conversion of digital number (DN) values to surface reflectance, ensured reliable comparisons over the decades. The hybrid classification approach used in TerrSet software combined pixel-based and segment-based methodologies to enhance land use and land cover mapping accuracy. The Maximum Likelihood Classification (MLC) algorithm's effectiveness was evident in its ability to navigate the complexities of the dataset, resulting in high overall classification accuracies ranging from 82.5% to 94.5%. Such precision is crucial in identifying subtle changes in mangrove ecosystems that may otherwise go unnoticed.

The analysis of temporal changes revealed alarming trends in mangrove degradation, with both Chwaka Bay and Menai Bay experiencing significant losses. In Chwaka Bay, a staggering 57.2% decline in mangrove cover was observed, translating to an annual loss of 1.2%. This loss was largely attributed to external pressures such as sea level rise, land conversion, and competition from other vegetation types. Similarly, Menai Bay faced a 51.7% reduction in mangrove cover, with the highest rates of loss occurring in the earlier years of the study. Such findings highlight the urgent need to understand the multifaceted drivers of mangrove decline to implement effective conservation measures.

The study's use of the CROSSTAB module to analyze temporal changes allowed for a detailed understanding of land cover transitions. This approach not only measured the extent of mangrove loss but also placed these changes within the context of broader landscape dynamics, offering a more holistic view of environmental changes over nearly five decades. Although the findings are alarming, they underscore the critical importance of mangrove ecosystems in coastal regions. Their roles in carbon sequestration, supporting biodiversity, and protecting against coastal erosion are essential. Thus, combining remote sensing with effective policy frameworks and community involvement is crucial for tackling the ongoing threats to these vital ecosystems.

Future research should focus on utilizing high-resolution imagery and advanced classification methods to detect small-scale changes that could have substantial ecological consequences. These techniques will improve the accuracy of mangrove mapping and provide more effective guidance for conservation strategies. Ultimately, integrating remote sensing data with local ecological knowledge and participatory methods will be essential for promoting sustainable mangrove management practices and enhancing the resilience of these critical ecosystems in the face of climate change and human pressures.

6.5 Remote sensing and machine learning in mangrove species classification

The study explored the application of machine learning techniques—specifically, Random Forest (RF) and Support Vector Machine (SVM)—to map mangrove species in Menai Bay, Zanzibar, using texture features and vegetation indices derived from Landsat 9 OLI-2 imagery. The research demonstrated the potential of combining texture metrics and spectral indices to enhance species-level discrimination, but several limitations were highlighted. The uneven distribution of mangrove species and data imbalance were primary challenges that affected classification accuracy, underscoring the complexity of mapping heterogeneous mangrove ecosystems.

The textural features, derived using the Gray-Level Co-occurrence Matrix (GLCM) with a 10×10 window size, were found to be effective in characterizing local structural variations of mangroves. However, the results revealed that the accuracy achieved using textural features alone was relatively low (68.29% for RF and 67.07% for SVM), indicating that textural data might not be sufficient for distinguishing certain mangrove species. This issue was particularly evident for less dominant species such as *Avicennia marina* and *Bruguiera gymnorhiza*, which had significantly lower user accuracies compared to more abundant species like *Rhizophora mucronata, Ceriops tagal,* and *Sonneratia alba*. The study suggests that a more nuanced approach may be necessary to address class imbalances, such as the use of data augmentation or targeted sampling strategies.

The integration of vegetation indices (VIs) showed a slight improvement in classification performance, with RF achieving 72.64% accuracy compared to 67.78% for SVM. The inclusion of VIs captured additional information about species-specific canopy properties and health, which was beneficial for species discrimination. However, the overall improvement was not substantial enough to mitigate the impact of skewed sample data, resulting in high classification errors for certain species. Despite these limitations, the research identified that certain spectral bands, notably bands 3, 5, and 6 of Landsat 9, were particularly effective for mangrove classification. This finding suggests that optimizing the selection of spectral features is crucial for improving the robustness of species-level classification models.

The study's findings emphasize the need for more advanced classification algorithms and additional spectral inputs, such as hyperspectral data, to enhance species differentiation. Moreover, future research should consider incorporating spatial contextual information and multi-temporal datasets to capture seasonal variations in mangrove phenology, which may provide better insights into species distribution patterns. By refining methodological approaches and addressing existing data challenges, remote sensing combined with machine learning can be a valuable tool for sustainable mangrove management and conservation.

Overall, the research provides valuable insights into the potential and limitations of using RF and SVM for mangrove species classification. The study advocates for continued exploration of hybrid methods to tackle the inherent complexities in mangrove ecosystem mapping, ultimately supporting more effective conservation strategies.

6.6 Conclusions

The thorough assessment of mangrove ecosystem services in Chwaka and Menai Bays, Zanzibar, reveals the complex relationship between local communities and their natural surroundings. This study utilized a mixed-methods approach that combined both qualitative and quantitative research techniques, enabling a nuanced understanding of how mangrove ecosystems support the well-being of coastal populations. By engaging with a variety of stakeholders through focus groups, key informant interviews, and household surveys, the research illuminated the diverse perceptions, attitudes, and experiences of community members regarding the benefits provided by mangroves.

The study's findings indicate that local residents have a strong awareness of the provisioning services offered by mangroves, with vital resources such as poles, firewood, and medicinal plants recognized as essential to daily life. Approximately 83.9% of households identified provisioning services as the most critical, highlighting their dependence on these resources for sustenance and economic activities. Conversely, there was less awareness of regulating, supporting, and cultural services, signaling a need for increased emphasis on these aspects in community education and outreach initiatives. Variations in awareness and perception of mangrove services across different wards also provide insight into the localized valuation of ecosystem services. For example, residents in Chwaka ward demonstrated a greater awareness of provisioning services, while those in Unguja Ukuu and Uzi wards prioritized regulating and supporting services. These differences suggest that local ecological conditions, economic activities, and cultural practices significantly influence community interactions with mangrove ecosystems, making it essential to understand these localized perceptions for effective conservation strategy development.

Despite the acknowledgment of the importance of mangrove ecosystem services, significant challenges threaten the sustainability of these crucial resources. Participants highlighted concerns about habitat degradation due to the extraction of ecosystem services, with 76% of key informants reporting negative impacts on mangrove health. Additionally, illegal harvesting of mangrove products was frequently observed, especially in Unguja Ukuu ward, where 74.5% of respondents noted such activities. These findings emphasize the urgent need for improved governance and regulatory frameworks to combat the overexploitation of mangrove resources. The study also identified several drivers affecting the supply of mangrove ecosystem services, with a lack of alternative livelihoods being a significant issue that forces community members to rely heavily on mangrove resources for their economic survival. Inadequate institutional structures and funding for forestry management further exacerbate these challenges, highlighting a strong perception of the necessity for better institutional responses to promote sustainable resource management.

To ensure the sustainable management of mangrove ecosystems, it is crucial to incorporate local knowledge and perspectives into conservation efforts. Engaging communities in decision-making processes can enhance the effectiveness of management strategies and foster a sense of ownership over local resources. Additionally, developing alternative livelihood programs that lessen dependency on mangrove resources could reduce pressure on these ecosystems while providing economic opportunities for community members. In conclusion, the study's findings underscore the multifaceted value of mangrove ecosystems and the urgent need for their sustainable management. By recognizing and addressing the challenges faced by local communities, policymakers and conservation practitioners can develop strategies that balance ecological health with socio-economic needs. The insights gained from this research contribute to the broader discourse on ecosystem services and coastal management, providing a valuable foundation for future initiatives aimed at preserving the ecological integrity of mangroves while enhancing the livelihoods of coastal populations in Zanzibar and similar regions worldwide. Ongoing collaboration between stakeholders, informed by local perspectives, is essential for fostering resilient ecosystems and thriving communities.

6.7 Synthesis and Implications for Conservation

This thesis synthesizes historical, spatial, and community-level insights to provide a comprehensive perspective on mangrove management in Zanzibar. It underscores the vital role of remote sensing in monitoring species composition and long-term ecosystem changes, offering data-driven insights to inform policymakers. By combining historical policy analysis, spatial mapping, and socio-ecological assessments, the study demonstrates that sustainable mangrove management requires a multi-dimensional approach, incorporating strong legal frameworks, advanced geospatial tools, and active community involvement.

The findings highlight that effective mangrove conservation cannot rely solely on remote sensing or policy reforms; it must also address the social dynamics that influence resource use and governance. This integrated approach reveals the importance of understanding the social, economic, and cultural factors that shape how communities interact with mangrove ecosystems.

Community engagement emerges as a crucial component of conservation strategies, as local perspectives and knowledge can enhance the effectiveness of legal and technological interventions.

Overall, this research advances the field by showcasing the complementary roles of policy analysis, remote sensing, and community participation in managing complex coastal ecosystems. Future conservation strategies should build on these findings to create integrated management plans that combine technological innovations with local insights, ensuring sustainable mangrove conservation in Zanzibar and other coastal regions globally.

6.8 The future

Using Landsat satellite data, this study offered alternate techniques for identifying and mapping the distribution of species and the dynamics of mangroves in Zanzibar. The study found that monitoring mangrove forest changes requires using a range of techniques and sensors. While there has been a noticeable upsurge in the number of studies mapping mangroves, several issues still need to be addressed.

Some suggestions for sustainable mangrove management include the following:

6.8.1 Principles and recommendations for mangrove protection

Mangrove ecosystems are vital for coastal protection, carbon sequestration, and biodiversity. Effective management and conservation of these forests require a multifaceted approach grounded in both ecological principles and technological innovations. This section outlines broad principles for mangrove protection and provides recommendations for employing new technologies to monitor and expand mangrove forests, enhancing their role in environmental conservation and carbon sequestration.

Broad principles for mangrove protection

1. **Ecosystem-based management (EBM):**

   Mangrove conservation should be framed within an ecosystem-based management approach that considers the entire coastal zone, integrating land, water, and biodiversity management. EBM emphasizes the importance of protecting ecosystem functions and services, balancing ecological health with human activities (McLeod and Leslie, 2009).

2. **Community involvement and co-management:**
   Local communities play a crucial role in the sustainable management of mangrove forests. Co-management practices that actively engage local populations in conservation efforts enhance the effectiveness of mangrove protection (FAO, 2014). These practices foster a sense of ownership and provide economic benefits through sustainable harvesting, tourism, and other activities.
3. **Integrated coastal zone management (ICZM):**
   A comprehensive ICZM strategy is essential to harmonize mangrove conservation efforts with broader coastal development objectives. This approach addresses the multiple pressures on coastal ecosystems, such as urbanization, agriculture, and aquaculture, promoting sustainable use and mitigating degradation (Cicin-Sain and Belfiore, 2005).
4. **Adaptive management:**
   Mangrove ecosystems are dynamic and sensitive to environmental changes. An adaptive management framework allows for flexible and responsive strategies that can be adjusted as conditions change, ensuring the long-term sustainability of conservation measures (Walters, 1986).
5. **Climate change mitigation and resilience:**
   Protecting mangroves is critical to building climate resilience in coastal regions. Mangroves act as buffers against storm surges and sea-level rise while providing significant carbon storage. Conservation policies must prioritize the protection of existing mangroves and facilitate the natural regeneration and expansion of these ecosystems to enhance their role in climate change mitigation (Alongi, 2012).

6.8.2 Employing new technologies for mangrove monitoring and expansion

Technological advances offer powerful tools for monitoring mangrove ecosystems and identifying potential areas for mangrove restoration and expansion. The integration of remote sensing, geospatial analysis, and field-based techniques can significantly enhance the management and protection of these ecosystems.

1. **Remote sensing and Geographic Information Systems (GIS):**
   High-resolution satellite imagery and GIS platforms such as Google Earth Engine (GEE) provide valuable tools for continuous monitoring of mangrove forests. These technologies enable the detection of changes in mangrove cover, biomass, and health over time, supporting conservation planning and early intervention (Giri, 2011). For example, Sentinel-2 and Landsat data are highly effective in mapping mangrove extent and detecting deforestation or degradation.
2. **Unmanned Aerial Vehicles (UAVs):**
   Drones equipped with multispectral or hyperspectral sensors allow for detailed mapping and monitoring of mangroves at a finer spatial scale. UAVs can capture high-resolution imagery of hard-to-reach areas, providing insights into species composition, canopy structure, and biomass, which are crucial for effective management and restoration efforts (Duffy *et al*., 2018).
3. **Lidar technology:**
   Light Detection and Ranging (Lidar) can be used to assess the vertical structure of mangrove forests, allowing for precise estimation of biomass and carbon stocks. This technology helps identify suitable areas for reforestation or afforestation efforts, contributing to enhanced carbon sequestration strategies (Simard *et al*., 2019).
4. **Artificial Intelligence (AI) and Machine Learning:**
   Machine learning algorithms can be employed to analyze large datasets from satellite and drone imagery, automating the classification of mangrove species and detecting areas of degradation. AI-driven models can also predict suitable locations for mangrove expansion based on environmental variables such as soil salinity, elevation, and proximity to water sources (Joshi *et al*., 2021).
5. **Blue carbon mapping and monitoring:**
   New technologies enable the mapping of blue carbon—the carbon stored in coastal ecosystems like mangroves. Using satellite imagery and in-situ carbon data, managers can track changes in carbon stocks over time, informing policies aimed at maximizing carbon sequestration through conservation and restoration (Howard *et al.,* 2017).

6.8.3 Recommendations for mangrove expansion

1. **Prioritize degraded coastal areas:**
   Identification and restoration of degraded coastal areas that were once suitable for mangroves can significantly contribute to ecosystem recovery. Remote sensing technologies can help identify areas where mangrove restoration can thrive, supporting broader coastal resilience efforts.
2. **Promote natural regeneration:**
   In areas where natural seed dispersal mechanisms are still active, efforts should focus on promoting the conditions necessary for mangrove natural regeneration. Monitoring of soil salinity, hydrology, and tidal flow can guide these efforts, ensuring the long-term success of natural restoration.
3. **Incorporate mangroves into national climate policies:**
   Mangroves should be integrated into national climate action plans, including Nationally Determined Contributions (NDCs) under the Paris Agreement. Restoration and expansion projects should align with broader climate change mitigation goals, leveraging the carbon sequestration potential of these ecosystems.
4. **Use species-specific planting strategies:**
   Different mangrove species have distinct ecological preferences and restoration needs. Data from new technologies can inform species-specific planting strategies, ensuring that the right species are planted in suitable locations for optimal survival and growth (Ellison, 2000).

These recommendations provide a roadmap for enhancing mangrove conservation and expansion through both broad ecological principles and cutting-edge technologies, supporting global efforts to mitigate climate change and safeguard coastal ecosystems.

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Appendix 1: Questions for government officials and the FGD guide

An interview schedule for government officials and FGD guide

1. Why are mangrove forests important?
2. Describe mangrove species and abundance in Zanzibar.
3. Outline the history of the conservation of mangroves in Zanzibar.
4. What are the main factors contributing to mangrove deforestation?
5. Where does most deforestation occur in Zanzibar?
6. What are some of the devastating effects that can be attributed to the loss of mangroves?
7. What is your opinion on the destruction of mangrove forests and loss of biodiversity?
8. How can mangrove forests in Zanzibar be saved?
9. Do you think appropriate policies have been effected for the protection of mangroves?
10. Do you think integrating the concept of community participation is a key move in championing forest conservation and management practices at the local level?
11. Which measures have been introduced to enhance participation by the local community in the conservation and management of forests?
12. Do local communities benefit from the maintenance of mangrove forests?
13. How is Zanzibar doing in the conservation of mangrove forests, compared to other countries?
14. What is the outlook for the Zanzibar's mangrove forests in the future?
15. Do you advocate more governmental regulation?
16. Does technology play any role in the conservation, protection, and awareness of mangroves?

Appendix 2: Structured questionnaire for household survey

My name is __________________________. I am conducting an academic survey to collect information about the awareness among the communities of Chwaka and Menai Bays of the benefits of mangrove forests. Therefore, your assistance filling out this questionnaire will go a long way in my academic pursuit and conservation of mangrove forests. Your responses may be used to influence the policy direction of mangroves. Your participation is voluntary and confidential. Do not indicate your name or any other form of identification.

Record Number: _________________

Demographic and socio-economic information of respondent

Date:	*Time:*
District:	*Ward:*

1. Household composition

Marital status: (1) Married (2) Divorced (3) Widowed (4) Not married

Religion: (1) Muslim (2) Christian

Education: (1) No formal education (2) Primary (3) Secondary (4) Tertiary

Gender: (1) Male (2) Female

Age: (1) Under 20 (2) 20-30 (3) 40-49 (4) 50-59 (5) 60-69 (6) 70+

Main occupation: (1) Crafts (2) Small business (3) Transporters (4) Farming
(5) Fishing (6) Bee keeping (7)Salaried employee (8) Wage labour
(9) Other ______________________

2. For how long have you in this ward: (1) <5 year (2) 5–10 years (3) 10–15 years
(4) 15–20 years (5) >20 years
3. Household income per month: (1) <100,000 (2) 100,000–200,000 (3) >200,000
4. Source of cooking energy: (1) Electricity/gas (2) Firewood/charcoal
(3) Other (specify) ____________
5. Distance from the village to the forest: _________km

Mangrove ecosystem services

6. How much do you agree that mangroves give benefits to the community?

(1) Strongly disagree (2) Disagree (3) Neither agree or disagree (4) Agree (5) Strongly agree

7. On a scale of 1–5, indicate your level of awareness of mangrove benefits in your area: not aware (1), slightly aware (2), somewhat aware (3), moderately aware (4), extremely aware (5).

Benefits	**1**	**2**	**3**	**4**	**5**
Poles					
Firewood					
Medicine					
Honey					
Fruits					
Picnic sites					
Fodder					
Control of soil erosion					
Regulation of climate					
Attenuation of waves					
Wild habitat					
Soil formation					
Ecotourism					
Spiritual activities					
Educational purposes					
Scenic viewing					

8. On a scale of 1–5, indicate the level of importance of each mangrove benefit to the community: not important (1), least important (2), moderately important (3), most important (4), not sure (5).

Benefits	**1**	**2**	**3**	**4**	**5**
Poles					
Firewood					
Medicine					
Honey					
Fruits					
Picnic sites					
Fodder					
Control of soil erosion					
Regulation of climate					
Attenuation of waves					
Wild habitat					
Soil formation					
Ecotourism					
Spiritual activities					
Educational purposes					
Scenic viewing					

9. Which mangrove ecosystem services listed in 8 above have you benefited from (list them in order of preference)?

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.
16.

10. Do you agree or disagree that the following factors have contributed to how people perceive mangrove ecosystem services? (1) Strongly disagree, (2) Disagree, (3) Neither agree/disagree, (4) Agree, (5) Strongly agree

Factors	**1**	**2**	**3**	**4**	**5**
Engagement in mangrove conservation activities					
Age of respondents					
Education level					
Socio-economic status of the local community					
Government policies related to the conservation of ecosystem services					
Intensity and frequency of utilizing mangrove products					
Institutions responsible for managing mangroves					

11. Do you agree that the following factors have affected the benefits from mangrove forests in the ward? (1) Strongly disagree, (2) Disagree, (3) Neither agree or disagree, (4) Agree, (5) Strongly agree

Factors	**1**	**2**	**3**	**4**	**5**
Insufficient resources to fund institutions & hiring of adequate personnel to manage forestry resources					
Unresponsive/faulty institutional structure in forestry management					
Population growth					
Climate change					

Unresponsive/faulty government forestry policy	
Agricultural development	
Expanded aquaculture	
Unchecked/uncontrolled coastal development	
Underfunded judicial system	
Weak government institutions	
Flawed/Unclear/opaque/poorly formulated forestry policy and legal framework	
Lack of policy/laws specifically for mangroves	
Local communities feel they are entitled to ownership and access to mangrove ecosystem services	
Lack of expertise and adequate staff in management of mangroves at local level	
Poor public participation in design & decision-making involving mangrove ecosystem services	
Unclear/faulty/discriminatory land tenure system	
Corruption	

12. Rate change in mangrove ecosystem services in the ward compared to 10 years ago.

(1) Substantial decrease (2) decreased (3) Same (4) Increased (5) Substantial increase (6) Not sure

13. Explain why change has or has not occurred.

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14. What do you think will be the main reasons for changes in the benefits accrued from mangrove forests over the next 10 years?

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15. Do you agree or disagree that it is important to protect mangrove forests for posterity?

(1) Strongly disagree (2) Disagree (3) Neither agree/disagree (4) Agree (5) Strongly agree

16. To what extent do you agree or disagree that if mangrove forests are conserved, there will be more mangrove ecosystem services?

(1) Strongly disagree (2) Disagree (3) Neither agree/disagree (4) Agree (5) Strongly agree

Please provide any additional comments here below:

Thanks for your time and participation.