ANTIDIUS RAPHAEL KASIMBAZI

THE IMPACT OF MANGROVE RESTORATION ON MANGROVE DIVERSITY, SEDIMENTATION AND SEDIMENT CHARACTERISTICS IN THE RUFIJI DELTA, TANZANIA

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Erasmus Mundus Mestrado em Ecohidrologia Aplicada, 2023

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Trabalho efetuado sob a orientação de:
Prof. Luis Manuel Zambujal Chicharo

Faculdade de Ciências e Tecnologia
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Declaration of Authorship

I declare I am the author of this work, which is original and unpublished. The sources consulted have been duly cited in the text and included in the list of references.

(Antidius Raphael Kasimbazi)

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Above all, I praise my God the Almighty to whom I pray and seek blessing as I look forward to contributing further to the shared quest for knowledge and understanding.

DEDICATION

I dedicate this thesis to my parents Mr. and Mrs. Raphael Emmanuel Kasimbazi, they are the reason for who I am. May God bless you abundantly to continuously pray for and see the success of your beloved son, Antidius Raphael Kasimbazi.

ABSTRACT

Mangroves are vital for coastal ecosystems but are continuously degraded, requiring restoration. This study examined the effects of mangrove restoration at 4 years on mangrove diversity, sediment characteristics and quality, in the Rufiji Delta, Tanzania from February to April 2023. Plants were sampled using a passive quadrat sampling technique and analyzed for diversity by the Shannon-Wiener Diversity Index. Sediment quality parameters were determined using a HANNA (HI98194) multiparameter probe. Sedimentation rates were examined using aluminium sediment traps. Organic matter, grain size distribution and statistical significance were determined by LOI, sieve granulometry, and ANOVA and Tukey's HSD test respectively. Mangrove diversity decreased from Natural (1.47), restored (1.22) to degraded (1.08) with 6, 4 and 3 species respectively. Organic matter doubled from degraded to restored sites and tripled to the natural site. Sediments from the natural and restored mangrove had high Dissolved oxygen, low temperature and pH close to neutral (7) while those from degraded mangrove had low Dissolved Oxygen, high temperature and slightly acidic pH of less than 7. Thus, 4 years of restoration demonstrated partial recovery in mangrove diversity and sediment quality. The study recommends the government and conservation stakeholders continue restoration initiatives for mangrove recovery against degradation and harness alternative activities in the local population to reduce mangrove unsustainable harvesting and clearance for agriculture as the drivers for degradation.

Keywords: Mangrove Restoration, Sediment Quality, Sieve Granulometry, Organic Matter, Rufiji Delta.

Resumo

Os manguezais desempenham um papel vital nos ecossistemas costeiros, mas estão continuamente degradados, necessitando de restauração. Este estudo examinou os efeitos da restauração de manguezais após 4 anos na diversidade dos manguezais, características e qualidade do sedimento, no Delta de Rufiji, Tanzânia, de fevereiro a abril de 2023. As plantas foram amostradas usando uma técnica de amostragem de quadrat passivo e analisadas quanto à diversidade pelo Índice de Diversidade de Shannon-Wiener. Os parâmetros de qualidade do sedimento foram determinados usando uma sonda multiparâmetro HANNA (HI98194). As taxas de sedimentação foram examinadas usando armadilhas de sedimento de alumínio. O teor de matéria orgânica, a distribuição do tamanho dos grãos e a significância estatística foram determinados pelo LOI, granulometria por peneiramento e ANOVA e teste HSD de Tukey, respectivamente. A diversidade dos manguezais diminuiu de Natural (1,47), restaurado (1,22) para degradado (1,08), com 6, 4 e 3 espécies, respectivamente. A matéria orgânica duplicou nos locais degradados em comparação com os restaurados e triplicou em relação ao local natural. Os sedimentos dos manguezais naturais e restaurados tinham alto teor de oxigênio dissolvido, baixa temperatura e pH próximo ao neutro (7), enquanto os dos manguezais degradados tinham baixo teor de oxigênio dissolvido, alta temperatura e pH ligeiramente ácido, inferior a 7. Assim, 4 anos de restauração demonstraram uma recuperação parcial na diversidade dos manguezais e na qualidade do sedimento. O estudo recomenda que o governo e os stakeholders de conservação continuem com iniciativas de restauração para a recuperação dos manguezais contra a degradação e promovam atividades alternativas para a população local, a fim de reduzir a colheita insustentável de manguezais e o desmatamento para a agricultura, que são os principais impulsionadores da degradação.

Palavras-chave: Restauração de Manguezais, Qualidade de Sedimentos, Granulometria de Peneira, Matéria Orgânica, Delta de Rufiji.

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List of Abbreviations

ANOVA	Analysis of Variance
CU	Uniformity Coefficient
DO	Dissolved Oxygen
EC	Electroconductivity
GSD	Grain Size Distribution
LOI	Loss on Ignition
MAEH	Masters in Applied Ecohydrology
OM	Organic Matter
SdR	Sedimentation Rate
SOM	Sediment Organic matter
SWI (H)	Shannon-Wiener Diversity Index
TDS	Total Dissolved Solids

1. INTRODUCTION

1.1. Background Information

Mangroves are salt-tolerant trees mostly at the land-sea interface, in the intertidal zone (Shilla and Shilla, 2020) with global distribution of around 30˚N–30˚S latitude (Giri *et al.*, 2011) (Fig. 1), in about 123 countries (Spalding *et al.*, 2010). Mangroves are found in the sub-tropic and tropic coasts, with temperatures of around 20°C and above (Alongi 2002; Duncan, 2017 Matiz, 2020). The most known extensive mangrove forests follow the order of Asia, Africa and America (North and Central) (FAO, 2007). They form typical intertidal forest ecosystems with about 70 tree species, covering approximately 152,400 km^2 of land space (Spalding *et al.*, 2010). Mangrove forms the most globally productive ecosystems (Alongi, 2014; Donato *et al.*, 2011; Duncan, 2017) with high biomass (Komiyama *et al.*, 2008).

Figure 1: Global Mangrove (in green) distribution

Source: Giri *et al*. (2011).

Mangroves have exceptional features and reproductive morphology and physiology that make them cope with and tolerate salt and unstable tidal action (Matiz, 2020; Alongi 2002). The low floral diversity and lack of diversified understory (apart from their seedlings) distinguish mangroves from other tropical forests (Duncan, 2017; Semesi and

Mtolera, 2019). These features make them occupy stressed niches with greater functional and ecological diversity as one of the world's most productive ecosystems (Donato *et al*., 2011; Lee *et al*., 2014). However, their structure, diversity, and composition vary on both spatial and temporal basis (Duncan, 2017). The most acknowledged diverse mangrove forest ecosystems are found in the Indo-West Pacific region (Mangora *et al.*, 2016; Monga *et al*., 2018; Duncan, 2017) with up to 30-40 mangrove species (Fig. 2).

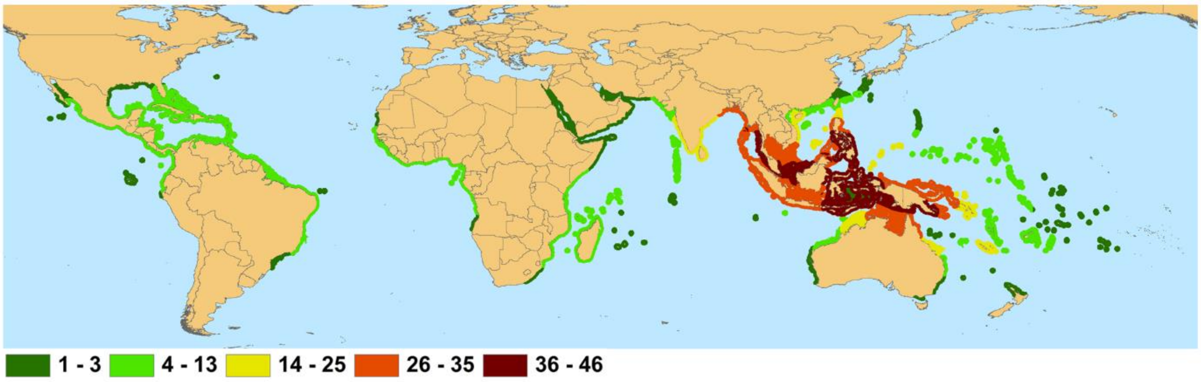


Figure 2: Global mangrove species richness

Source: Polidoro *et al*. (2010).

Being at the terrestrial-aquatic interface, mangrove forests play a significant hydrological role in the coastal ecosystem. By trapping sediment load from the inland freshwater rivers, they stabilize tropical coasts and shorelines from severe erosion. The protection role of mangroves against the waves, shields the coast against tropical storms and tsunamis, thus preventing wave-induced coastal erosion and flooding (Lovelock *et al*. 2015; Duncan, 2017).

According to Polidoro *et al*. (2010), mangroves are considered a foundational species that regulate food webs and biodiversity. They offer a variety of ecosystem services such as coastal protection, habitat, sediment regulation and carbon sequestration (Daniel *et al*., 2011; Donato *et al*., 2011; Alongi, 2014; Duncan, 2017; Matiz, 2020). Despite their economic and socio-ecological roles, the globally growing coastal population has significantly increased massive disappearance by up to 8% (Polidoro *et al*., 2010). This is because, they are used by coastal communities as the waste sink (Alongi *et al*., 2004; Bouchez *et al*., 2013) due to their ability to accumulate organic matter (Duke *et al*., 2007; Barbier *et al*., 2011; Shilla and Shilla, 2020).

In Tanzania, mangroves cover about 115,500 ha along the Indian Ocean coast (Taylor *et al*., 2003; Lupembe, 2013). The Rufiji Delta ecosystem contains the country's largest mangrove area (Giri *et al*., 2011) constituting about 46% of the country's mangrove (Lupembe, 2013; Duncan, 2017). It is also the largest mangrove forest in East Africa (UNEP-WCMC, 2003; Whitney *et al*., 2003; Spalding et al., 2010). Various species inhabit this ecosystem, including *Heritiera littoralis, Rhizophora mucronata, Avicennia marina, Bruguiera gymnorrhiza, Ceriops tagal*, *Sonneratia alba*, *Lumnitzera racemosa, Xylocarpus granatum,* and *Xylocarpus molucensis* (Taylor *et al*., 2003; Mangora *et al*., 2016; Japhet, 2018). The delta has high productivity, which is attributed to the influence of freshwater inputs and organic sediment loads from the Rufiji River (Spalding *et al*., 2010; Lupembe, 2013; Pundwong *et al*., 2013).

Despite being designated as a forest reserve under the greater Rufiji-Mafia-Kilwa Biosphere Reserve, it still faces anthropogenic degradations. Land conversion for rice farms and timber extraction contribute to the loss of mangrove cover (Pundwong *et al*., 2013; Monga *et al*., 2018). They provide important sources of terrestrial resources, timber, and medicinal products for coastal communities and beyond.

This ecosystem provides a range of ecological, economic, and cultural values and benefits (Monga *et al*., 2018). It plays a crucial role in climate change mitigation through carbon sequestration. Additionally, it supports the feeding and breeding of rare species such as the African fish eagle and the red colobus monkey (Japhet, 2018). The mangroves also serve as a source of fuelwood, charcoal, and other resources used for both domestic and commercial purposes. It attracts ecotourism, contributing to the country's economy by drawing local and international visitors (Gathitu *et al*., 2014). However, they still face numerous threats (Japhet, 2018; Shilla and Shilla, 2020). Despite the efforts to address these issues, the effects persist, indicating the need for further attention to the local hydrology and its impact on the ecosystem (Monga *et al*., 2018).

1.2. Problem Statement and Justification

The Rufiji Delta mangroves protect the Tanzanian part of the west-Indian Ocean coastal ecosystem from tidal and wave actions (Monga *et al*., 2018; Japhet, 2018). However, they are progressively degraded (Semesi and Mtolera, 2019) and over-exploited due to human interference (Alongi, 2014), and their impacts are evident (Mangora *et al.*, 2016). Since then, management strategies, including restoration have been put in place even though timely assessment to inform managerial decisions has been inadequate. In some cases, however, assessments have been focusing on the mangrove cover change (Brown *et al*., 2016; Mwansasu, 2016; Monga *et al*., 2018) to estimate the extent of mangrove cover gain due to restorative actions in the area. Yet, studies on the impact on local ecology are still lacking and unknown. This study assessed the impact of mangrove restoration by comparing the sedimentation rates, sediment grain size characteristics and organic matter, and physicochemical parameters of the water in the natural, degraded and restored mangroves. It provides insight into the impact of mangrove restoration and a foundation for understanding the ecological impact of varied mangrove statuses in the Rufiji Delta ecosystem.

1.3. Research Objective

This aimed to investigate the effect of mangrove restoration at 4 years on mangrove diversity, sediment characteristics and quality parameters.

1.4. Research Questions

- Is there any differences in sediment quality parameters across sites with different mangrove statuses?
- How does the sedimentation rate vary across natural, degraded and restored mangroves?
- What is the difference in the sediment grain size distribution across mangroves of different statuses?
- How do mangrove diversity and organic matter content differ across mangroves of different statuses?

2. LITERATURE REVIEW

This section presents a review of the roles of mangroves, focusing on sediment characteristics and quality parameters.

2.1. Sediment quality regulation

The role of mangroves in regulating sediment quality cannot be overstated, and efforts to restore degraded mangrove ecosystems are among the major priorities. This is achieved by directly measuring the physicochemical parameters that reflect the sediment quality status in restored, natural and degraded mangroves, comparatively (Alshawafi *et al*., 2016; Febriansyah *et al*., 2022). These parameters include pH, DO (dissolved oxygen), electrical conductivity, temperature, and turbidity (Singh *et al*., 2017). Mangroves preserve sediment quality by enhancing sediments settling and absorbing pollutants from the water column (Verge, 2017). Reportedly, heavy metals, nutrients, and suspended particles are usually removed by active filtration by mangroves (Wells *et al*., 2005).

The presence of anaerobic conditions in the intertidal zone where mangroves thrive results in high soil redoxomorphic potential which facilitates nitrate removal by denitrification (Verge, 2017; Tam and Wong, 1999). Mangroves also help in removing pollutants such as heavy metals, pesticides, and hydrocarbons. They absorb them through their roots and store them in their tissues or break them down through chemical processes. Rhizophoric processes like adsorption, ion exchange, organic matter binding, precipitation (conversion into insoluble compounds), and incorporation into lattice structures help to immobilize pollutants (Tam and Wong, 1999) and thus improve sediment quality.

Mangroves are also known for buffering pH and conductivity. Areas with well-conserved mangroves have pH values close to neutral, compared to those in the degraded sites

(Jitthaisong *et al*., 2012). In Jakarta Bay, Indonesia, Sari *et al*. (2019) found a considerable variation in pH between areas in and out of mangrove forests. The pH within the mangrove area was close to neutral (7–8) while those outside the mangrove forest were acidic with a pH of 3–4. Same wise, Febriansyah *et al*. (2022) reported a regular pH value of 7-8.5 in restored areas as compared to 7-7.8 in natural areas and degraded areas where the values were too low.

Mangroves also play a significant role in regulating electroconductivity levels. This is because, some mangrove species like *Sonneratia alba*, *Avicennia marina* and *Rhizophora mucronata* are recognized for regulating salt concentration in estuaries (Martuti *et al*., 2018; Rahmania *et al*., 2018). These species usually uptake inorganic ions and accumulate them in leaves through translocation from roots and stems (Martuti *et al*., 2018; Sari *et al*., 2019). There is evidence to suggest that degraded mangrove forests generally have higher salinity and electrical conductivity (EC) levels compared to non-degraded mangrove forests. This is because degraded mangroves are often subject to increased seawater intrusion, which in turn leads to elevated levels of dissolved ions in the sediments (Alshawafi *et al*., 2016). A study by Febriansyah *et al*. (2022) for instance, found conductivity values in a range of 0.18-2.14 S/m. The highest conductivity values of up to 2.14 S/m were recorded in degraded mangroves and the lowest values (0.18 S/m) in non-degraded mangroves.

Degraded mangrove forests, which may have experienced deforestation, pollution, or other forms of disturbance, may have higher temperatures compared to non-degraded forests. This is because deforestation results in the loss of the shade provided by mangrove trees, which can lead to increased solar radiation and higher temperatures in the deposited sediments (Alshawafi *et al*., 2016). A study to compare temperature between areas with and without mangroves in Thailand reported a significantly lower temperature (26.99°C) in mangrove sites as opposed to 27.41°C and 27.69°C in exposed land and seawater (Jitthaisong *et al*., 2012).

In terms of Dissolved Oxygen (DO), degraded mangroves exhibit lower levels compared to non-degraded forests. Febriansyah *et al*. (2022) reported the highest levels of DO (5.21 mg/L) in undisturbed mangroves and low values (2.47 mg/L) in degraded mangroves. This is because degradation leads to the accumulation of organic matter in the sediment, which consumes oxygen during decomposition. Additionally, the loss of mangrove trees can result in a reduction in the number of roots that provide oxygen to the sediment through aeration. DO is being used in the reduction and oxidation of organic and inorganic materials (Jitthaisong *et al*., 2012; Pour *et al*., 2014).

2.2. Sedimentation rates and grain size distribution

Mangrove ecosystems are often called "makers of land" due to their ability to promote deposition, trap, and augment sediments (Kimeli *et al*., 2022). They facilitate both sediment accumulation and agglomeration. Sediment agglomeration refers to the process by which individual sediment particles, such as sand or silt, are bound together into larger, cohesive units. This process influences sediment stability and nutrient cycling (Cinco-Castro *et al*., 2022). By regulating sediment trapping, accumulation, and consolidation through their dense and complex root structures, mangroves are also considered to be coastal ecosystem engineers (Gutiérrez *et al*., 2012; Kimeli *et al*., 2022). They play a key role in promoting sediment agglomeration by providing physical structure and organic matter inputs that facilitate particle binding and consolidation. Understanding the dynamics of sediment agglomeration in mangrove ecosystems is thus important.

Regulation of sedimentation and sediment capture is one of the critical supporting ecosystem services provided by mangrove forests (Cinco-Castro *et al*., 2022). Mangroves do that by regulating tidal flow speed (Kobashi and Mazda, 2005) and the concentrations of suspended and organic matter in the water flowing through them (Kobashi and Mazda, 2005; Adame *et al*., 2015; Kimeli *et al*., 2022). Hypothetically, mangroves regulate the rate of sediment deposition through their modified root systems. There is a direct relationship between features such as tree density and dead trunks and water flow, thus determining sedimentation patterns in mangroves (Mazda *et al*., 1997; Montgomery *et al*., 2019). With respect to mesoscale hydrodynamics and sediment supply, mangroves develop different structures which enable them to provide specific ecosystem services (Cinco-Castro *et al*., 2022) including enhancing sedimentation. MacKenzie *et al*. (2021) defined mangroves' capacity to capture sediments in terms of their relatively high carbon accumulation of up to 1,722 g cm^{-2} $year^{-1}$. This contributes to greenhouse gas regulation by assimilating atmospheric CO_2, and further coastal zone protection against sea storms, and sea-level rise through the land-building process (Alongi, 2008; McKee, 2011).

However, the source and nature of the sediments deposited in a particular zonation dictate the rate at which sediments accumulate in different local mangrove ecotypes. According to the geomorphological features and the age of mangroves, the rate of sediment accumulation might differ from place to place, in the same ecosystem (Mazda *et al*., 1997). The rate is furthermore dependent on the mineral composition and the size of the individual particles of the materials to be sedimented (Cinco-Castro *et al*., 2022). Tiny particles are faster transported at greater distances and settle when the energy decreases; they do not easily settle compared to large-sized ones (Van de Broek *et al*., 2018). On the other hand, the individual sediment particle size defines the ability of sediments to absorb organic materials and so, to the carbon content and extent of binding at the site.

2.3. Regulation of organic matter

Mangroves produce carbon-rich peat soil with high organic matter content (Verge, 2017; Imra *et al*., 2021). Peat production is associated with methane (greenhouse gas) emissions. In mangrove peat, the saline soils dampen produced methane (Spalding, 2013; Ezcurra *et al*., 2016) thus reducing its risk. The carbon fixing and storing capabilities of mangrove forests make them play a distinctive role in the fate of the global climate (Alongi, 2008). Mangroves store both below-ground and above-ground carbon, the former as organic matter. Compared to other ecosystems (rain forests, salt marshes, swamps and seagrasses), mangroves store a vast amount of organic matter as organic carbon, approximately 140–1023 mgC ha^{-1} (Donato *et al*., 2011; Alongi, 2014; Adame *et al*., 2015). A more recent estimation by Atwood *et al*. (2017) reports about 2.6 billion mgC stored in mangrove sediments down to a 1m depth.

This storage capacity of mangroves is to a large extent attributed to the accumulation of organic matter in their sediments (Imra *et al*., 2021; Suello *et al*., 2022). The sediment organic matter (SOM) originates from autochthonous inputs (local biomass production) and allochthonous inputs (particulate sediment deposition during tidal inundation) in mangroves (Kristensen *et al*., 2008). Above- and below-ground organic matter accumulates in sediments through litterfall, root exudation and growth, vegetation die-off and peat formation (Ezcurra *et al*., 2016). Allochthonous inputs are contributed by regular tidal flooding events whereby mangroves trap organic matter from tidal waters containing fine particles from estuarine, marine, freshwater rivers and terrestrial environments (Alongi, 2014). These materials are all buried and stored in the mangrove sediments via sedimentation (Kristensen *et al*., 2008; Adame *et al*., 2015).

Recent studies (Atwood *et al*., 2017; Van de Broek *et al*., 2018; Mueller *et al*., 2019) indicate that autochthonous SOM is abundant in the top 5–20 cm of sediment profiles and it keeps on decreasing with increasing depth. This change in sediment profile is further related to mineralization and leaching (Suello *et al*., 2022). SOM is also added through the assimilation of atmospheric CO_2 by the mangroves themselves (Van de Broek *et al*., 2018; Mueller *et al*., 2019; Suello *et al*., 2022). This becomes part of the biomass in the litter. This is evident in Suello *et al*. (2022) who reported high SOM contents (7.8%) in the old mangrove sites compared to that (1.1%) in the young counterparts.

3. METHODOLOGY

3.1. Study area

3.1.1. Location and Climate

This study was conducted in the mangrove forests in the Rufiji Delta (Fig. 3) in Tanzania. The Delta forms part of the Rufiji River basin (the largest river basin in Tanzania) which covers an area of 177,000 km^2 (Mwalyosi, 2002; Taylor *et al.*, 2003) and drains about 20% of the country (Duvail and Hamerlynck, 2007). The Delta is specifically located between the Rufiji and Kibiti Districts and is about 200 km south of Dar es Salaam between latitudes 8˚ 20′ 00″, 7˚35′ 00″S and longitudes 39˚10′ 00″, 39˚20′ 00″E (Monga *et al.*, 2018).

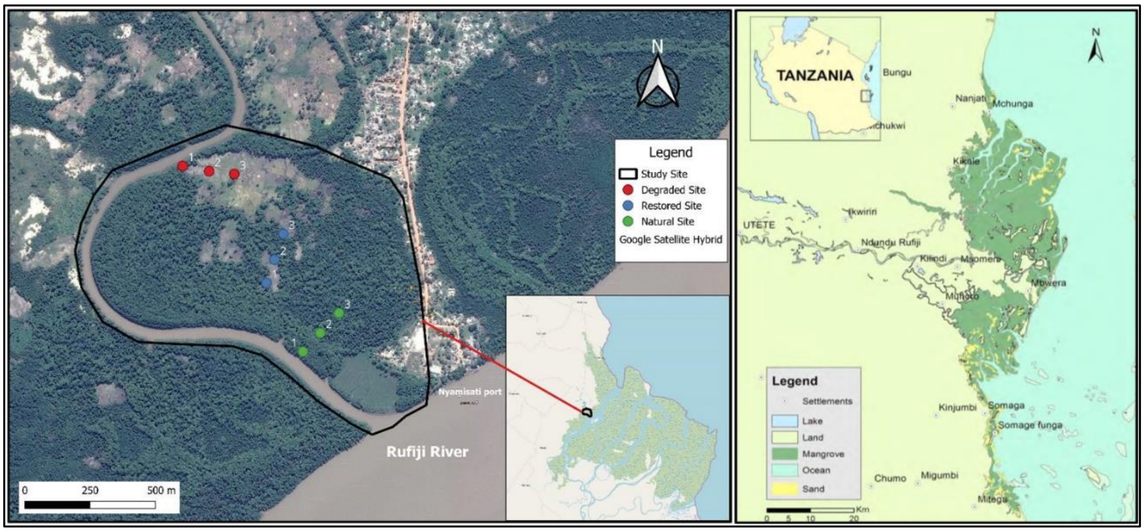


Figure 3: Location of the study area (left) in the Rufiji Delta (right) in Tanzania showing the natural (green), restored (blue) and degraded (red) mangrove sites.

The local climate in the Rufiji Delta is characterized by temperatures ranging from 24 to 41°C temperature and rainfall of 750 to 1250 mm throughout the year (Mwansasu, 2016). However, the Delta experiences variations in temperature throughout the year (Duvail and Hamerlynck, 2007; Dai *et al.*, 2022). Along the coast, mean monthly minimum temperatures range from 21 °C in July to 24.9 °C in February. Mean maximum temperatures range from 28 °C in July to 41.7 °C in February. The rainfall is bi-modal, with two seasons, short rains season starts from October to December whereas the long rains season continues from February to May (Mwalyosi, 2002; Lupembe, 2014). The mean annual precipitation ranges from 1,000 mm at the most upstream regions of the delta to more than 1,400 mm along the coast, with considerable inter-annual variation (Dai *et al*., 2022). The vulnerability of the Rufiji Delta to tropical storm activity has been documented. Cyclones in the region result in heavy rainfall, often occurring during inter-monsoonal periods in November-December and March-May. These cyclones regularly lead to extensive local flooding (Duvail and Hamerlynck, 2007).

3.1.2. Ecology and Hydrogeology

The Delta ecosystem like the rest of others in the Rufiji-Kibiti Districts is mainly characterized by tropical forest and grassland vegetation. The inner, landward zone is dominated by *Avicennia marina* and occasionally by *Ceriops tagal* or *Lumnitzera racemosa*, and the seaward zone by *Sonneratia alba* or *Avicennia marina* (Semesi, 1992; Mwalyosi, 2002; Taylor *et al*., 2003; Mangora *et al*., 2016). Geologically, the delta is underlain by shales and limestones Cretaceous and Jurassic (Wang *et al*., 2003; Mwansasu, 2016). The alluvial silt, sand and clay deposits from the tertiary period overlay the limestone foundation. Sediment deposition from the Rufiji River has produced a deltaic region characterized by dynamic shifting river channels (Mwalyosi, 1990).

3.1.3. Socio-economic profile

The population of the Rufiji and Kibiti districts where the delta lies are 159,906 and 195,638 with 48,704 and 37,977 households respectively (URT, 2022). The level of education is relatively low with reportedly less than 60% having received formal education (Mbiha and Senkondo, 2001). The main socio-economic activity is agriculture which accounts for about 93% of the available household (Lupembe, 2014) in the Rufiji floodplain and Delta. Cultivation occurs mostly at the fringe zones of the mangrove that are continuously fed by freshwater flux from the upstream and flooding during the rainy season. The residents grow mostly (76%) rice for staple production. The estimated area for the major food crops in the district is Cassava 16,845.5 hectares, Paddy 16,213.4 hectares and Maize 15,526 hectares. The main cash crops are cashew nuts (4150 hectares), sesame (3088.5 hectares), fruit (14,295.4 hectares) and vegetables (4367.5 hectares) (Rufiji District Council, 2023). Alongside cultivation, other livelihood activities in the delta include fishing, livestock keeping and extraction of forest products (Mbiha and Senkondo, 2001; Mwansasu, 2016). These activities have been contributing to the degradation of the mangrove ecosystem in different aspects. With time, soil in the paddy fields becomes too saline leading to clearance of new areas for agriculture while abandoning the old fields (Mwansasu, 2016).

3.2. Research design

This study used a case study research design due to its ability to retain the characteristics of real-life events while a specific situation at hand is being investigated (Schell, 1992). The study area was categorized into three sites: natural, degraded and restored, indicated by green, red and blue color (Fig. 3) respectively. The natural site was characterized by the mangroves with minimal interference (no agriculture fields within and where clearance was not evident compared to the other sites). The degraded site was the one whose mangroves have been cleared and converted to other uses, mainly agricultural fields. The restored site on the other hand is the one that was previously degraded but has been planted with mangroves for 3 to 4 years. The natural site was used as the reference site (positive control), degraded as the negative control, and restored as the site under investigation that was compared to the positive and negative controls.

3.3. Data Collection and Processing

The data were collected directly from the field for the period of three months from February to April 2023. It involved collecting data from three different sites each with different mangrove conservation status: natural, restored, and degraded. Three sampling locations were systematically established at each site at 25 meter intervals from the inundation area, and triplicate samples were taken per site during sampling time. A total of 27 samples were thus collected per site per month. Sampling for organic matter and sedimentation was done during the low tide and environmental parameters at receding and flooding tides. The tides were monitored using a tidal calendar and the mobile Tides Application. Sampling was done for sedimentation, organic matter and sediment grain size analysis. Data collection and processing were divided into field and laboratory work as follows.

3.3.1. Filed measurement

Water quality data in the sediments were measured directly from the sampling sites at about 20 cm deep by using the HANNA (HI98194) pH/EC/DO multiparameter probe. These were physicochemical parameters which included temperature, dissolved oxygen (DO), total dissolved solids (TDS), pH and electroconductivity during the receding tide.

Data for sedimentation rate were collected by using specially constructed aluminium sediment traps which were installed in the field for a 24-hour (1-day, allowing for the capturing of cumulative effect of the 2 high tides per day) period during the low tide, This procedure was done for three days consecutively at each site in each month. Each device was equipped with three PVC containers with a 5 cm diameter and 19.63 cm^2 surface area (in which sediment materials were collected) fixed in 8.2 cm diameter aluminium stand, held firmly by the wire fasteners. This allowed for triplicate samples at each site in the natural, degraded and restored areas. The distribution of these devices was made equal in all three sites: natural, restored, and degraded. Three sediment traps were installed at the soil surface level at about 2 m from the trees in each sampling plot (at a higher elevation than the normal inundation area to the landward where water cannot reach without high tides) to measure the daily (24 hours) sedimentation rate for 3 days consecutively. The stand was then fixed in soil with a pointed metal shaft to hold it more firmly against the incoming tides. The sediment traps were installed and exposed in the field for 3 days at each sampling site. After 24 hours, the traps were monitored, and, retained materials (sediments) were collected, packed, and labelled for further laboratory analysis.

Sediment samples for organic matter and granulometry (grain size distribution) were sampled using an open-faced auger. This allowed for the collection of uncompressed sediments to a maximum of 200 cm depth from the surface which is referred to as the appropriate depth for sediment sampling (Howard *et al.*, 2014; 2018). Samples from the natural and degraded mangrove sites were used as positive and negative controls, respectively.

For vegetation sampling, the study employed a passive quadrat sampling technique to assess mangrove species within the study area, following a sampling protocol from the Bureau of Land Management (1999). A 30-meter transect was established using a measuring tape. At three-meter intervals along this transect, 1x1 meter quadrat frames were systematically placed on alternating sides. Within each quadrat, all mangrove seedlings were meticulously recorded by their common names and quantities. This procedure was executed across all sampling sites: natural, degraded, and restored areas. Field identification of mangroves was done by local names and subsequently verified using the mangrove identification kit developed by the Kenya Marine and Fisheries Research Institute (Okello, 2020) and, the PlantNet mobile application for respective botanical nomenclatures.

3.3.2. Laboratory Procedures

3.3.2.1. Estimation of the sedimentation rate

Sediment samples were oven-dried at 100°C for 24 h to obtain the dry weight. The dry weight was then used to estimate the sedimentation rates taking into account the container's surface area, and exposure time (Cinco-Castro *et al.*, 2022) based on the following guiding equation (eqn. 1).

$$SdR = \frac{w_e - w_s}{A_c * t} \text{ .... eqn. 1}$$

Whereas:

SdR = Sedimentation rate (g.cm^{-2}.day^{-1})

W_e = Weight of empty crucible (g)

W_s = Weight of crucible with dry sediments (g)

A_c = Surface area of the container (cm^2)

t = Time (days)

3.3.2.2. Determination of organic matter

The Loss on Ignition (LOI) method (Ball, 1964) was used for sediments' organic matter determination. LOI estimates the organic matter content by thermal oxidation at 500–550 °C (Dean, 1974; Leelamanie *et al.*, 2015). It is a fast and inexpensive method of determining the organic matter with accuracy and precision as other, more sophisticated geochemical methods (Dean, 1974; Heiri *et al.*, 2001; Leelamanie *et al.*, 2015). This temperature allowed all organic matter to be burnt, leaving behind the inorganic content. The weight loss during the reactions was measured and correlated to the organic matter (Heiri *et al.*, 2001; Imra *et al.*, 2021).

The following procedures summarizes the whole process.

i. Weighing of the empty crucible (C_e)

ii. Weighing of the wet sample (S_w) in a crucible (C_{ws})

$$S_w = (C_{ws} - C_e) \text{ ………………………………………… eqn. 2}$$

iii. Drying the wet sample in the oven at 100 °C for 24 hours.

iv. Weighing of the dried sample (W_{dm}) in a crucible (C_{ds}) and computation of the actual weight of the dry matter.

$$W_{dm} = (C_{ds} - C_e) \text{ ……………………………………… eqn. 3}$$

v. Calculating the sediments' water content (W_c)

$$W_c = \left(\frac{S_w - W_{dm}}{S_w}\right) * 100\% \text{ ………………………………… eqn. 4}$$

vi. Heating the dry sample at 500 °C for up to 3 hours in the muffle furnace to ashes.

vii. Weighing of the ashes (W_{as}) and computation of the OM (W_{OM}) content

$$W_{OM} = (W_{dm} - W_{as}) \text{ ………………………………… eqn. 5}$$

viii. Computation of the OM proportion in the sediments.

$$\%W_{OM} = \left(\frac{W_{OM}}{W_{dm}}\right) * 100\% \text{ ……………………………… eqn. 6}$$

3.3.2.3. Determination of sediment grain size

Sieve granulometry was used for grain size determination due to its ability to determine the particles' size from 0.075 mm to 100 mm which is the main characteristic of the retained sediments (ASTM International, 2017). A stacked sieve tower (Fig. 4) was used, and the sediments were placed and allowed to pass through to enable separation by size while electrically shaking the tower for about 10 minutes. The sediment grains whose diameter was larger than the size of the mesh openings were retained by the sieve, while those with smaller diameters were allowed to pass through to the next sieve.

Mesh size
2 mm
1mm
500 µm
250 µm
152 µm
63 µm
20 µm
< 20 µm
Shaker

Figure 4: Stacked mesh tower for sieve granulometry

Adopted from ASTM International (2017), the following procedures were followed.

i. Weighing of the empty container (C_e)

ii. Weighing of the wet sample (S_w) in a container (C_{ws})

$$S_w = (C_{ws} - C_e) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eqn. 7}$$

iii. Drying the wet sample in the oven at 100 ^{o}C for 24 hours.

iv. Weighing of the dried sample (S_d) in a container (C_{ds}) and computation of the actual weight of the dried sample.

$$S_d = (C_{ds} - C_e) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eqn. 8}$$

v. Sieving of the dry sample for Grain Size Distribution (GSD) analysis.

vi. Drying the mesh separated re-wetted sample in the oven at 100 ^{o}C for 24 hours.

vii. Air cooling and weighing of the re-dried samples in the containers whose empty weight (C_e) has been pre-determined. This gave a weight of the size-separated sediment grains in the container (Cg_{ds}).

viii. Computing weight of individual mesh retained sediment (Wg_{ds}).

$$Wg_{ds} = (Cg_{ds} - C_e) \text{ ……………………………………… eqn. 9}$$

ix. Computation of the individual grain sizes proportion in the sediments

$$\%Wg_{ds} = \left(\frac{Wg_{ds}}{S_d}\right) * 100\% \text{ ……………………………..… eqn. 10}$$

The GSD result was plotted and further used to deduce the sediments' Uniformity Coefficient (CU) (eqn 11).

$$C_u = \frac{D_{60}}{D_{10}} \text{ …………………………………………… eqn. 11}$$

Whereas;

D_{60} = Grain diameter at which 60% of soil particles are finer and 40% are coarser, and

D_{10} = Grain diameter at which 10% of particles are finer and 90% are coarser.

The D_{60} and D_{10} parameter values were determined after plotting the GSD.

3.3.3. Vegetation analysis

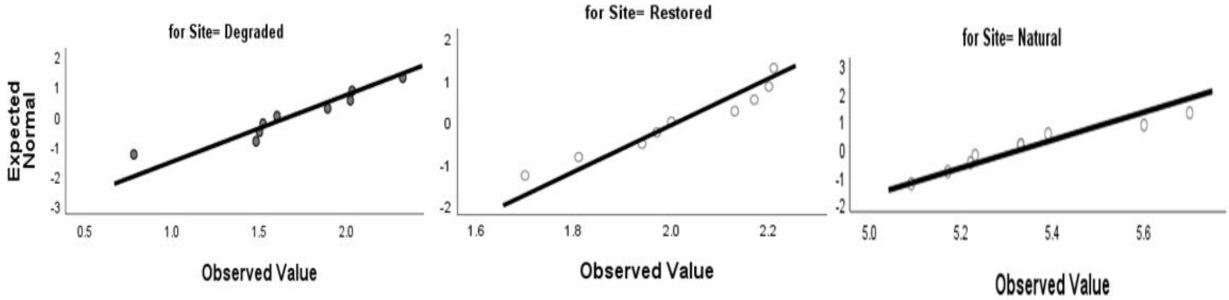
Shannon-Wiener Diversity Index (H) was used to analyze the diversity of mangrove species. This index is a robust metric that takes into account both species richness and evenness, offering a more holistic understanding of ecological diversity (Magurran, 2004; Girma and Maryo, 2018). The index (H) was calculated as,

$$H = \sum \mathrm{pi}(ln.pi)$$

where "pi" is the proportion of individuals of species "i" in the community.

3.3.4. Statistical analysis

Shapiro-Wilk and Levene's tests were performed to determine the normality and homogeneity in the dataset to inform further types of tests (whether parametric or non-parametric) to be considered. These tests confirmed that the dataset was homogeneous and normally distributed (below), meeting assumptions for the parametric tests below.



A One-way (also called One Factor) Analysis of Variance (ANOVA) test was then done to compare the mean organic matter content across the groups (mangrove status) at a 95% confidence interval. This test aimed to check whether the mean difference between the groups (Natural, restored and degraded) was statistically significant. A significant ANOVA result necessitated a post hoc test to be done. Tukey’s HSD test was then performed to determine which group pairs were statistically significant different.

4. RESULTS

This chapter presents the major findings emanating from the study, based on the specific objectives, each comparing the natural, degraded, and restored mangrove site statuses.

4.1. Variation of sediment quality

The study compared the water quality parameters in the study area across the natural, restored and degraded sites. From the results (Fig. 5), it can be observed that the parameters varied across the sites, with the worst condition in degraded sites.

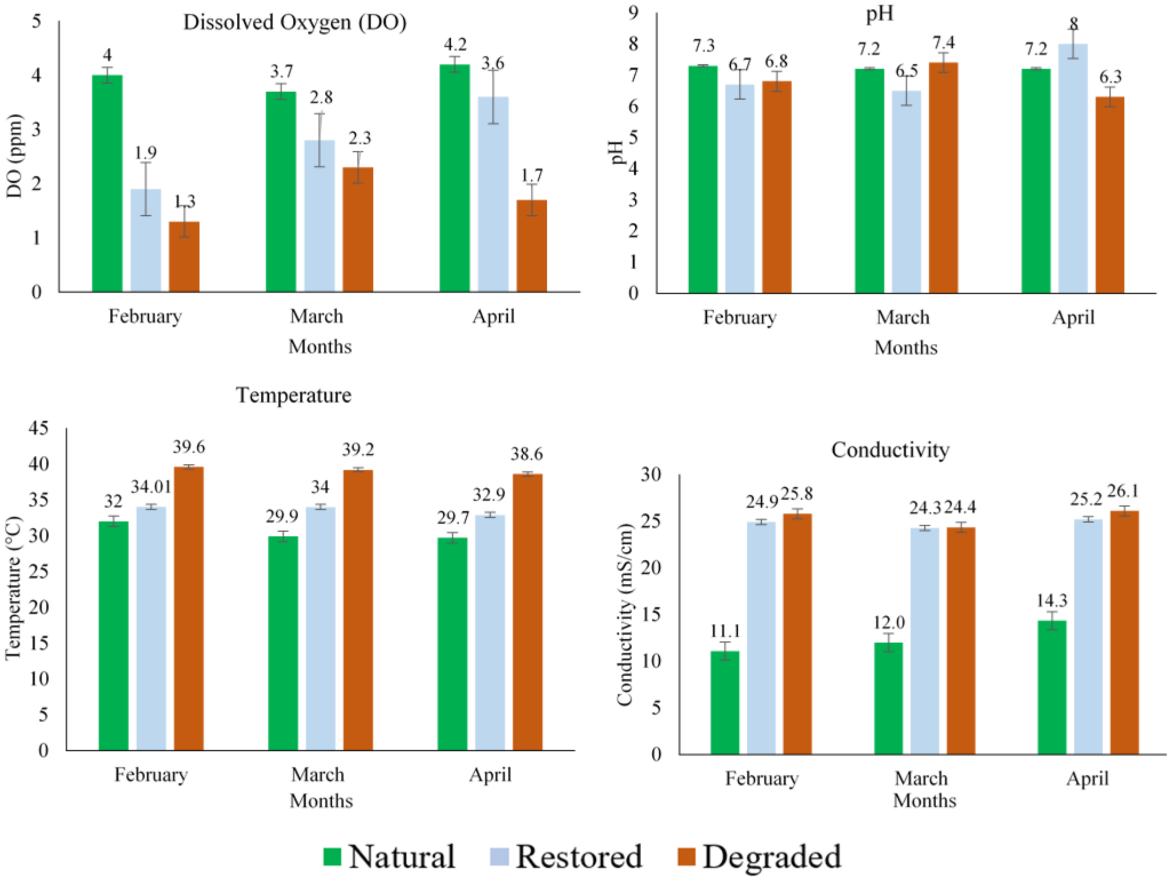


Figure 5: Comparison of sediment quality parameters in natural, restored and degraded mangroves

The level of DO in the restored site was higher than in degraded but lower than in natural conditions. Conductivity values were higher in the restored and degraded sites compared to the natural sites. The water temperature was also highest (39.6° C) in the degraded, intermediate in the restored, and lowest (28° C) in the natural site. The average values (Table 1) were then used to provide a general highlight of the parameter values across the different mangrove statuses.

Table 1: Average sediment quality parameter values across the three sites

Site	**Temp (°C)**	**Conductivity (mS/cm)**	**pH**	**DO %**	**DO ppm**
Natural	29.90	20.67	7.38	62.58	4.10
Restored	35.02	26.50	7.11	44.48	2.91
Degraded	39.10	25.25	6.75	29.38	1.73

Temperature was high in the degraded site and lowest in the natural site while DO had the opposite trend, high in natural and low in the degraded site. Moreover, sediments in the natural and restored mangroves had pH values (7.38 and 7.11) close to neutral while in the degraded site, sediments had a slightly acidic pH (6.75).

4.2. Sedimentation across the sites

The actual sediment weight was estimated after oven-drying the sample, taking into account the effect of the blank weight of the crucible. The container used for sediment collection had a diameter of 5 cm, equivalent to a surface area of 19.63 cm^2. This area was used against the respective actual weight of sediment to estimate the sedimentation rates (SdR) per day. The results are presented in Table 2.

The degraded mangrove site exhibited the highest average sedimentation rate of 4.169 $kg/m^2/d$ (over four times higher than the restored). In contrast, the natural mangrove site had the lowest average sedimentation rate of 0.076 kg/m²/d. The restored mangrove site showed an intermediate average sedimentation rate of 1.010 kg/m²/d.

Table 2: Distribution of sediment grain sizes across the Natural, restored and degraded mangrove

	Sedimentation rates (SdR) in kg/m²/d		
Replicates	**Degraded**	**Natural**	**Restored**
1	4.432	0.051	0.051
2	4.126	0.102	1.732
3	3.923	0.153	3.362
4	3.872	0.051	0.102
5	3.923	0.051	0.560
6	4.738	0.051	0.255
7	4.642	0.063	0.421
8	3.890	0.120	2.101
9	3.980	0.042	0.502
Average	**4.169**	**0.076**	**1.010**

Where replicate 1,2,3 are for February, 4,5,6 for March, and 7,8,9 for April

4.3. Sediment grain size distribution

The sieve granulometry of the collected sediment samples collected by open-faced auger (refer to methodology) from all sampling sites was performed. Table 3 below presents the average distribution of sediment grain sizes across the natural, degraded and restored sites.

Table 3: Distribution of sediment grain sizes across the restored, natural and degraded mangrove conditions

Particle Diameter (mm)	% Proportion		
	Restored	Natural	Degraded
2	23.2	26.2	0.73
1	17.6	27.5	3.49
0.5	17.2	21.5	1.79
0.25	8.7	8.1	11.81
0.152	12.4	7.0	30.94
0.063	2.7	3.6	13.65
0.02	9.7	4.8	10.21
<0.02	8.5	1.4	27.4

The results indicate variation in sediment grain size distribution among the three sites. In the natural mangrove, the highest proportions were observed in the particle diameter categories of 2 mm (26.2%), 1 mm (27.5%), and 0.5 mm (21.5%). In contrast, the degraded mangrove sites showed a higher proportion of smaller particle sizes, particularly in the categories of 0.152 mm (30.94%), 0.063 mm (13.65%), and a large proportion (27.4%) of the finer materials (<0.02 mm).

The distribution of grain sizes of the sediments from the natural, restored and degraded mangroves is presented by the GSD plot in Figure 7 below.

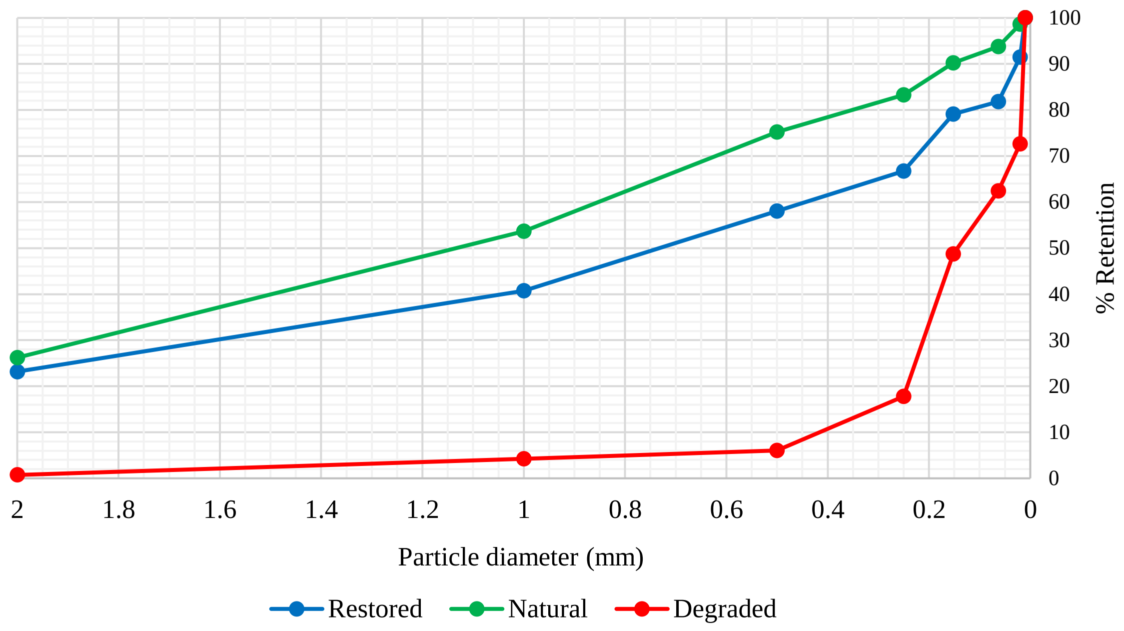


Figure 6: Distribution of sediment grains comparing sediment sorting in the natural, restored and degraded mangrove

The GSD plot in Fig. 7 allowed for the derivation of the CU values for the respective mangrove statuses as shown in Table 4.

Table 4: Sediments' Uniformity Coefficient values in the natural, degraded and restored mangrove sites

Parameter	**Restored**	**Natural**	**Degraded**
D60	1.05	1.5	0.0156
D10	0.013	0.15	0.0125
Cu	80.8	10	1.25

The comparison of UC values among the degraded, restored, and natural mangrove sites provides insights into the particle size distribution and drainage ability. The natural and restored mangrove sites had higher CU values (10 and 80.8 respectively).

4.4. Sediment composition

The comparison of the sediment content's average weight across the three mangrove statuses is presented in Table 5. The main focus is drawn on the organic matter content in relation to the rest of the sediment mass across the sites.

Table 5: Average sediment composition by weight across the mangrove sites

Site	Average Weight (g)		
	Water Content	**Organic Matter**	**Inorganic Matter**
Restored	15.82	2.47	17.69
Natural	17.27	3.25	15.01
Degraded	14.64	1.10	19.61

The sediment samples from different mangrove sites: natural, degraded, and restored, were further analyzed for percentage composition (in terms of water content, organic and inorganic matter). The results (Fig. 6) provide valuable insights into the sediment composition of these sites as the fraction of the whole.

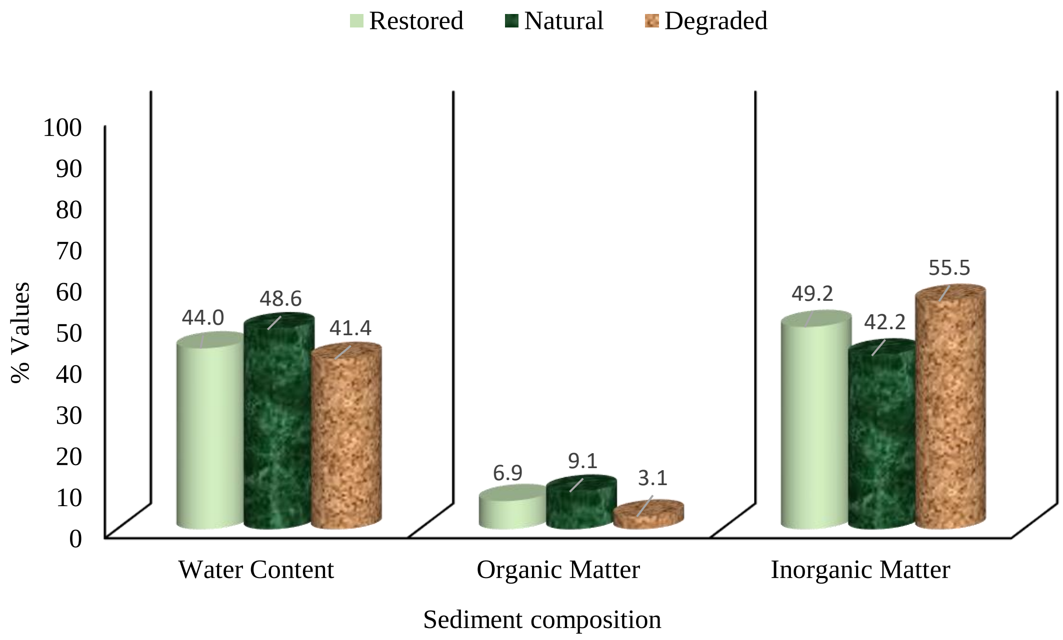


Figure 7: Percentage composition of sediments across mangrove statuses

The results show that the natural mangrove sites exhibited the highest organic matter content, with a value of 3.25 g (9.1%). The restored sites had a slightly lower average organic matter content of 2.47 g (6.9%), while the degraded sites showed the lowest organic matter content of 1.10 g (3.1%). The OM doubled in the restored site and tripled in the natural site, in comparison to the degraded. On the contrary, the amount of inorganic matter followed the opposite pattern, with the highest value of 19.61 g (55.5%) in the degraded site and the lowest of 15.01 g (42.2%) in the natural site. The water content varied among the different mangrove site statuses. The natural mangrove had the highest water content of 17.27 g (48.6%), followed by the restored site with 15.82 g (44.0%), and the degraded site with 14.64 g (41.4%).

Results from confirmatory statistical analyses

The ANOVA results presented in Table 6 indicate evidence of significant differences across the statuses based on the p-value and calculated F-value in comparison with the critical F-value.

Table 6: ANOVA results on the statistical test between mangroves with different statuses

Variation	SS	df.	MS	F	P-value	F crit
Between Groups	73.64709	2	36.82354	404.918	3.23E-19	3.402826
Within Groups	2.182578	24	0.090941			
Total	75.82967	26				

(α=0.05)

The F-value across the mangrove status (the "Between Groups") variation was 404.918, which is quite above the critical F-value of 3.402826. To determine statistical significance, the obtained p-value was compared to a predefined significance level (α=0.05). In this case, the p-value (3.23E-19) was significantly smaller than the critical value. The remarkably small p-value provided strong evidence against the null hypothesis, suggesting that the observed group differences are unlikely to be random and are instead statistically significant. Thus, it was concluded that there are significant differences between the studied groups.

The ANOVA results provided strong statistically significant differences among the groups under investigation. The considerable F-value, extremely small p-value, and comparison with the critical F-value all concurred in rejecting the null hypothesis and confirming the presence of statistically significant group variations.

The significant ANOVA results necessitated further analysis, the post hoc test. Table 7 presents the results of a Tukey's HSD test to compare the means of the natural, restored and degraded conditions in the Rufiji Delta.

Table 7: Tukey HSD results for significance test of organic matter content variation in Natural and Restored and Degraded mangrove conditions

Mangrove status	**Subset**	
	1	**2**
Degraded	1.6822	
Restored at 4 years	2.0144	
Natural		5.34
Significance (α=0.05)	0.070	1.000

The mean score was calculated to be 5.34 for the mangroves in natural condition, 2.0144 for the restored mangroves and 1.6822 for the degraded mangroves. Thus, the mean organic matter content in the mangroves in natural conditions was the highest of all.

The post hoc Tukey's HSD test at a 0.05 significance level (95% confidence interval) indicated that the difference in the organic matter content in the degraded and restored mangroves (subset 1) is not statistically significant. However, the organic matter in the natural mangroves (subset 2) was statistically significantly different from that of the degraded and restored mangroves. Therefore, Tukey's HSD test demonstrated a statistically significant difference in the organic matter content in natural mangroves in contrast to the restored and degraded mangroves.

4.5. Mangrove diversity

The species profile and diversity in different conditions in the study area are presented in the table below.

Table 8: Mangrove diversity in the natural, restored and degraded sites

Species' Botanical name	**Natural**				**Restored**				**Degraded**			
	#	**Pi**	**ln(Pi)**	**Pi.lnPi**	**#**	**Pi**	**ln.Pi**	**Pi.ln(Pi)**	**#**	**Pi**	**ln(Pi)**	**Pi.ln(Pi)**
Rhizophora mucronata	8	0.12	-2.14	-0.25	0	0	0	0	0	0	0	0
Ceriops tagal	2	0.03	-3.53	-0.10	11	0.28	-1.27	-0.36	3	0.43	-0.85	-0.36
Bruguiera gymnorrhiza	3	0.04	-3.12	-0.14	18	0.46	-0.77	-0.36	2	0.29	-1.25	-0.36
Avicennia marina	20	0.29	-1.22	-0.36	3	0.08	-2.56	-0.20	0	0.00	0.00	0.00
Xylocarpus granatum	8	0.12	-2.14	-0.25	7	0.18	-1.72	-0.31	0	0.00	0.00	0.00
Sonneratia alba	27	0.40	-0.92	-0.37	0	0	0	0	2	0.29	-1.25	-0.36
	68	**SWI (H)**		**1.47**	**39**	**SWI (H)**		**1.22**	**7**	**SWI (H)**		**1.08**
	Richness			**6**	**Richness**			**4**	**Richness**			**3**

The data illustrates variations in mangrove diversity across three sites: Natural, Restored, and Degraded, assessed through the Shannon-Wiener Diversity Index (H) and species richness. The Natural site exhibits the highest diversity (H = 1.47) with 6 species, the degraded site had the lowest diversity (H = 1.08) with 3 species whilst the restored exhibited intermediate diversity (H = 1.22) with 4 species.

4. DISCUSSION

4.1. Sediment quality variation with mangrove status

Mangrove restoration is known to improve sediment quality in degraded mangrove ecosystems (Alshawafi *et al*., 2016; Febriansyah *et al*., 2022). The results of this study revealed variations in sediment quality parameters across the different mangrove sites and are consistent with previous studies (Wells *et al*., 2005; Verge, 2017; Febriansyah *et al*., 2022) that highlighted the importance of mangroves in regulating sediment quality. Sediments from the natural mangrove sites exhibited a better quality characterized by moderate temperature, conductivity, pH levels, and high levels of DO in contrast to other sites (Table 1). The restored sites showed improvement in some parameters compared to the degraded sites but not in the natural state.

These findings were consistent with those of Jitthaisong *et al*. (2012), Sari *et al*. (2019) and Febriansyah *et al*. (2022) among others that reported the ability of well-conserved mangroves to maintain a pH close to neutral and control temperature levels compared to degraded mangrove sites. The loss of mangroves in the Rufiji Delta is thus correlated to the observed higher temperatures in degraded areas as opposed to intermediate values in the restored mangrove areas. This is because areas whose mangrove was cleared were fully exposed to solar radiation without protective canopy and shades. Furthermore, Alshawafi *et al*. (2016) and Febriansyah *et al*. (2022) insisted on the fact that the degradation of mangroves often increases inorganic ions content leading to elevated EC (Martuti *et al*., 2018) as found out by this study.

DO levels were also highest in the natural sites and lowest in the degraded site, indicating the impact of degradation of oxygenation and potentially unfavourable conditions for aquatic organisms, as reported by Febriansyah *et al*. (2022). The restoration efforts showed improvements in DO levels compared to the degraded site, but the values were still lower than those observed in the natural site. However, this study found that 4 years of mangrove restoration had some improvements in terms of DO but not yet comparable to that of natural mangroves. This suggests that restoration efforts can improve DO status but may require more than four years (that was the case in this study) and measures to fully recover to natural conditions as previously reported (Jitthaisong *et al*., 2012; Pour *et al*., 2014; Alshawafi *et al*., 2016; Febriansyah *et al*., 2022).

4.2. Regulation of sedimentation and sediments' grain size

Sedimentation is a fundamental process in mangrove ecosystems, and understanding its dynamics is crucial for assessing the ecological functions and the impacts of anthropogenic activities on these systems (Gutiérrez *et al*., 2012; Kimeli *et al*., 2022). Sedimentation was highest (4.169 kg/m²/d) in the degraded mangrove area, implying poor ecosystem function. These findings are in line with previous studies (Cinco-Castro *et al*., 2022; Kimeli *et al*., 2022) that highlighted the increased sediment deposition in degraded mangrove areas due to reduced vegetation cover and increased erosion. The reported reduced vegetation cover is in line with the low mangrove diversity and richness (Table 9) as this study found. The higher sedimentation rate in the degraded site suggests the potential for sediment accumulation and associated changes in coastal morphology and habitats (Mazda *et al*., 1997; Montgomery *et al*., 2019). The lower sedimentation rate in natural mangroves reported in other studies has been attributed to their mature and stable vegetation, which effectively traps and retains sediment, resulting in reduced deposition rates (Gutiérrez *et al*., 2012; Kimeli *et al*., 2022). The intermediate sedimentation rate in restored mangrove sites highlights the potential of mangrove restoration in regulating sedimentation and reducing deposition rates (Cinco-Castro *et al*., 2022). However, the restored sites do not compare to the same level as natural mangroves. These are all further supported by high species diversity in natural mangrove sites and low diversity and richness in degraded mangrove sites. This collectively affects the capacity of mangroves in the Rufiji Delta to absorb and retain sediments.

The grain size distribution analysis provided further insights into the sediment dynamics of the Rufiji Delta. Sediments from the natural mangrove sites exhibited higher proportions of larger particle sizes (2 mm, 1 mm, and 0.5 mm) compared to those from the degraded mangroves (Table 7) where most of them were finer. This indicates a reduced accumulation of fine sediments in the mangrove area, thus, many of them were collected in the traps. This situation is related to the observed mangrove clearance for agricultural fields and poles extraction, leading to erosion and thus reduced sediment trapping capacity as previously reported (Cinco-Castro *et al*., 2022). The restored mangrove sites, on the other hand, displayed intermediate values for most particle diameter categories, indicating a partial recovery of sediment grain size distribution after four years of planting. While the proportions of larger particle sizes were still lower than those in the natural sites, there was a reduction in the proportion of finer sediments compared to the degraded site. This observation suggests the need for further restoration measures and time for the restored mangroves to fully restore sediment sorting (Cinco-Castro *et al*., 2022).

The uniformity coefficient (CU) further supported the variation of sediment sorting by grain size distribution with the mangrove status. While the natural and restored mangrove sites had higher CU values (10 and 80.8 respectively), the degraded mangrove site had the lowest CU value (1.25). Having values greater than 4 suggests that natural and restored mangroves are associated with well-graded sediments with a wide range of particle sizes within the soil. This further translates to a high likeliness of being well-drained and aggregated (ASTM International, 2017; Van de Broek *et al*., 2018). Based on these results, the natural mangrove sites have a high potential for water movement and drainage, favouring infiltration, followed by the restored one. A low CU value in the degraded mangrove sediments was an indication of poor grading and a narrow range of particle sizes within the sediments. Sediments from the degraded mangroves were mostly fine-textured, justifying the observed low CU value. This property results in low water infiltration capacity and poor drainage as earlier reported by other studies (Van de Broek *et al*., 2018). With the reduced infiltration and poor drainage, the degraded mangrove sites will also have a low ability to sustain excess water during the flood event, unlike the natural mangrove site.

Analysis of sedimentation rates revealed an increased sediment deposition in the degraded mangroves of Rufiji Delta, potentially due to reduced vegetation cover that could otherwise been evenly distributing materials to be deposited. Natural mangroves appear to have lower sedimentation rates, which may be attributed to their mature and stable state that effectively traps sediment in a wider area before they are available to settle at a single point. The restored mangrove site had a moderate increase in sedimentation rates, indicating the contribution of restoration efforts on improving sediment trapping capacity compared to degraded mangroves, albeit not to the level of natural mangrove systems. These findings were similar to those of Kimeli *et al*. (2022) and Gutiérrez *et al*. (2012) which demonstrated increased and moderately low sedimentation in degraded and undisturbed mangrove areas respectively. The partial recovery of sediment trapping capacity in the restored mangrove further aligns with Cinco-Castro *et al*. (2022) findings.

4.3. Sediment Organic Matter

Mangrove sediments store carbon in organic matter (Alongi, 2008; Donato *et al.*, 2011; Atwood *et al.*, 2017; Suello *et al.*, 2022). This study is in line with previous studies, reporting that undisturbed mangroves have a higher input of organic material, resulting in increased organic matter content in their sediments (Kristensen *et al.*, 2008; Alongi, 2014; Suello *et al.*, 2022). The restoration efforts like mangrove replanting and regeneration have some positive influence on sediment organic matter, however, the restored sites still did not compare to the natural conditions (Suello *et al.*, 2022).

The significantly high OM content in the natural (undisturbed) mangroves indicated a higher input of organic material such as decomposing plant matter as compared to the restored mangroves. On the other hand, the slight increase in the 4 years of restored mangroves suggests a positive response to restoration and partial recovery from the previous degraded status. These findings further highlight the necessity to continuously restore mangroves in the Rufiji Delta and are in line with other studies (Suello *et al.*, 2022; Mueller *et al.*, 2019; Van de Broek *et al.*, 2018) that also reported the increase in organic matter content with the mangrove age.

However, the same findings suggest that the Rufiji Delta mangrove restoration process at 4 years still did not have a significant impact on the retention and accumulation of organic matter that could be comparable to the natural mangroves. However, further investigation may be required to explore other factors that could influence the observed differences. This corresponds to the findings of Chen *et al*. (2018) and Mashoreng *et al*. (2022) that the age of the mangrove greatly influences the organic matter due to an increased ability to retain materials within their roots and increased litter fall. The lower content of organic matter in the degraded mangrove suggests that mangrove degradation in the delta leads to accumulation of inorganic matter from inputs like agriculture, and potentially due to increased sediment disturbance. Mineralization without build-up due to mangrove clearance commonly for agriculture fields in Rufiji Delta vegetation causes an increased inorganic matter. Some previous studies (Alongi, 2008; Atwood *et al*., 2017) have linked similar mangrove degradation to the alteration of the carbon sequestration capacity of mangrove ecosystems. The degradation of Rufiji Delta mangroves puts this role at risk, because of mangrove clearance thus reducing the extent of organic carbon that can be captured and stored in the area.

5. CONCLUSION AND RECOMMENDATIONS

This study provided an overview of the effect of mangrove restoration on their diversity and sediment dynamics at four years of planting in Rufiji Delta. The restoration partially reduced sedimentation rates and restored mangrove diversity and sediment characteristics (sediment quality, organic matter and grain size distribution). These findings contribute to the potential of mangrove restoration in enhancing sediment dynamics and mangrove ecosystem functioning against degradation. However, the study disclosed that, at 4 years of restoration, there is only partial recovery in some sediment quality parameters while others are still comparable to degraded status and some aspects were not captured due to time limitations.

The study recommends a need for continued restoration of mangroves in the Rufiji Delta beyond four years which the degraded mangroves are yet to recover in terms of their richness, diversity, and sediment characteristics. Further, the government should work collaboratively with the conservation partners, institutions and local communities to increase awareness and harness alternative livelihood activities to reduce pressure on the mangroves that are currently degraded due to local unsustainable harvesting and clearance for agriculture.

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