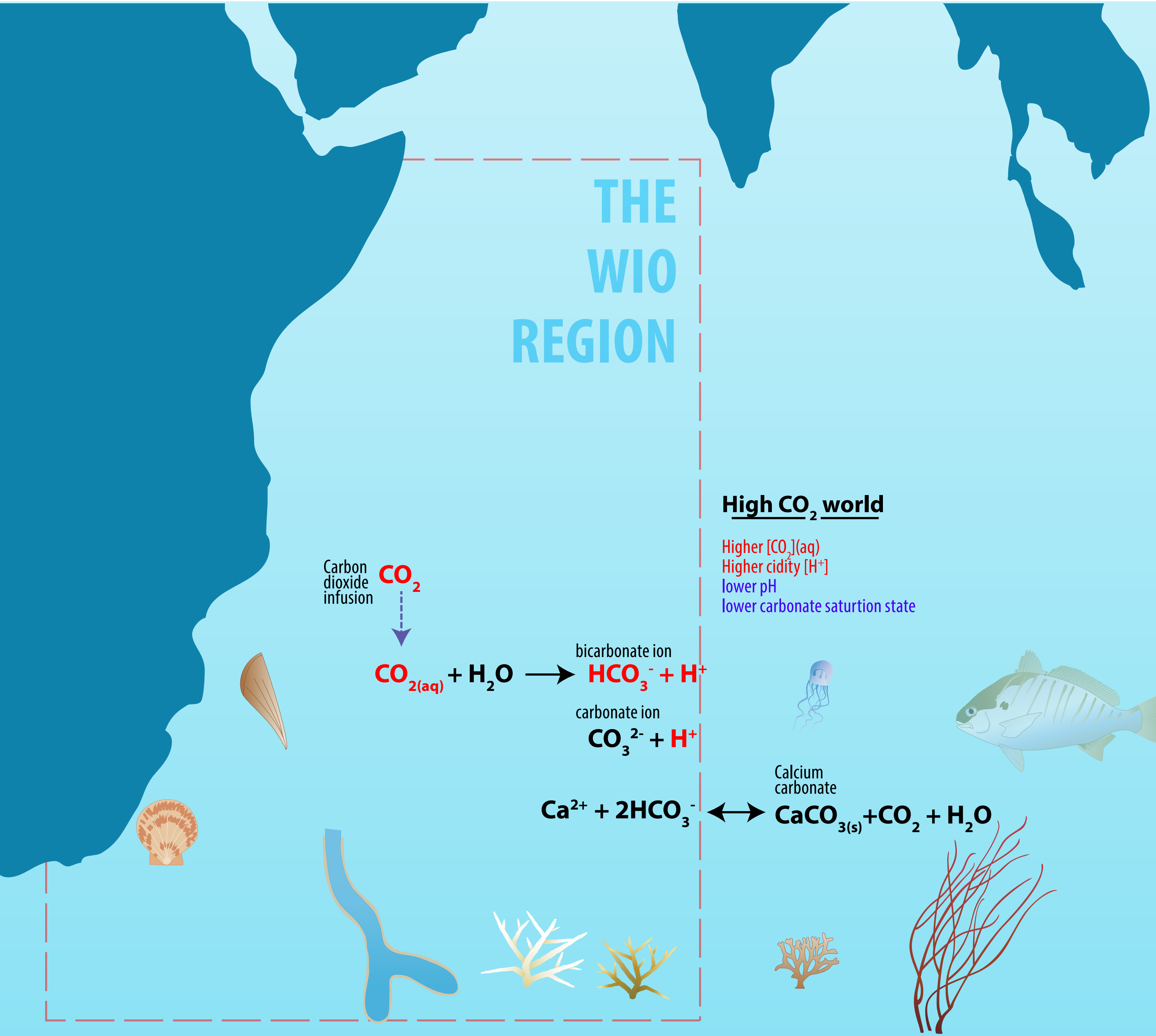
An Action Plan

OCEAN ACIDIFICATION IN THE WESTERN INDIAN OCEAN REGION

2024



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An Action Plan

OCEAN ACIDIFICATION IN THE WESTERN INDIAN OCEAN

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FOREWORD

The marine and coastal ecosystems of the Western Indian Ocean region are invaluable in terms of their natural, built, human and social capital. The region's unique geology contributes to remarkable biodiversity and high endemism in the countries of Kenya, Mozambique, Somalia, South Africa and the United Republic of Tanzania, and the island States of Comoros, Madagascar, Mauritius, Reunion (France) and Seychelles. More than 2,200 species of fish, 300 species of hard coral, 10 species of mangrove, 12 species of seagrass and 1,000 species of seaweed, as well as hundreds of species of sponges, molluscs and crabs, are found in the region. Over 65 million people along the region's coastline depend on the goods and services of the marine ecosystem to sustain their livelihoods.

Oceanographic assessments indicate that climate change in the WIO region is increasing environmental variability, with ramifications for weather, fisheries and biodiversity. Climate impacts due to increasing air and sea surface temperature, precipitation changes, increasing frequency and severity of extreme weather events, and sea level rise are compounded by emerging ocean acidification due to elevated levels of atmospheric carbon dioxide. The details are captured in the 2016 Climate Change Strategy for the Western Indian Ocean region.

The continued acidification of oceans is likely to have a dramatic effect on shelled organisms. Some calcifying species, such as sea urchins, shallow water corals, oysters, clams and calcareous plankton, are at risk and, consequently, the entire food web may also be at risk. Shifts in marine food webs threaten not only marine biodiversity but also the socio-economic stability of the region's coastal communities. Recognizing the gravity and the consequences of ocean acidification, the ninth Conference of Parties to the Nairobi Convention called for a comprehensive regional response to the challenge.

The Ocean Acidification Action Plan employed a collaborative partnership process reflecting the shared commitments by the Contracting Parties to the Nairobi Convention for an environmentally healthy Western Indian Ocean providing ecosystems goods and services and supporting a vibrant blue economy. A separate situational analysis provides further detailed information on the status and trends of ocean acidification in the Western Indian Ocean and its potential impacts on the marine environment and food security. The analysis provides recommendations to improve our understanding of ocean acidification, enhance capacity to address impacts, and approaches to sustainable development in the context of climate change.

The Action Plan provides an overview of the causes, relevance and vulnerabilities of marine organisms to the impacts of ocean acidification. A ten-year 'call for action' on six strategic priorities has been included in the Action Plan, accompanied by specific actions, indicators and timeframes to mitigate ocean acidification and enhance resilience across the region.

Implementation of the Ocean Acidification Action Plan is proposed through Contracting Parties for alignment of policies and governance mechanisms, regional cooperation, through the provision of human and other resources, including active engagement of partners.

EXECUTIVE SUMMARY

Ocean acidification (OA) is the decrease in ocean pH resulting from the uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere.OA is an environmental threat that jeopardizes the health of ocean ecosystems and marine organisms. It also interacts with other ocean–climate threats, including ocean warming, deoxygenation, and changes in coastal water quality – coastal pollution mainly contributed by sewage discharges and land-based pollutants. Consequently, these interconnected issues are expected to have increasingly detrimental effects on coastal communities, impacting food security and economic stability. Recognized by the United Nations (UN) as a major global threat, OA is addressed under Sustainable Development Goal (SDG) 14, with Target 14.3 specifically focused on its mitigation and minimization of its impacts. Additionally, the World Meteorological Organization (WMO) has identified OA as a Global Climate Indicator, highlighting its importance for global climate monitoring. Within the Western Indian Ocean (WIO) region, the Regional State of the Coast Report and the Climate Change Strategy for the Nairobi Convention have identified OA as a major threat.

In response, the **Ninth Conference of Parties to the Nairobi Convention**[1] called for the implementation of concrete actions to address OA impacts in the WIO Region. However, initiatives to address OA in the region have been limited due to limited data and information, which is exacerbated by inadequate infrastructure, instrumentation, and financial support. The lack of coordination among existing initiatives, driven by the absence of a clear framework, has also hindered these initiatives to address these challenges, and therefore the development of a WIO Regional OA Action Plan, aligned with national climate change priorities, is essential. This plan provide a cohesive framework for trans-national collaborative efforts in OA monitoring, impact assessment, and mitigation across the region. The WIO Regional OA Action Plan was developed through a comprehensive process involving literature review, expert consultation, data analysis, policy review, expert review, and a validation workshop.

The WIO Regional OA Action Plan is organized into three chapters. **Chapter One** provides an overview of OA from both global and regional perspectives, highlighting the scope of the issue in the WIO region. It also explains the rationale for developing a WIO Regional OA Action Plan and describes the methods employed in its development. **Chapter Two** provides a comprehensive overview of the current state and trends of OA in the WIO region. Key OA indicators are analyzed to assess the current state of OA in the WIO, while different carbon emission pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) are evaluated to understand projected OA trends in the region. The chapter explores the local drivers of OA, its impacts on marine organisms, ecosystems, food security, and the economy in the WIO Region.

Additionally, it reviews the current knowledge of OA in the WIO Region, identifies a suitable

[1] https://nairobiconvention.org/clearinghouse/node/199

pathway to mitigate OA and minimize its impacts under future climate scenarios, and highlights potential barriers to mitigation.These barriers guided selection of key priority areas that require strategic intervention in the WIO Regional OA Action Plan. **Chapter Three** describe the WIO Regional OA Action Plan. This chapter defines the vision, mission, and goals of the WIO Regional OA Action Plan. Six strategic priorities are outlined, each accompanied by specific actions, Key Performance Indicators (KPI) and timeframes to address current and future OA and its impacts in the WIO region.

The plan covers a period of ten years (2025-2035) and includes strategic priorities for both mitigating and adapting the current and future impacts of OA on marine organisms and ecosystems as well as livelihood and food security in the WIO region. By implementing the WIO Regional OA Action Plan, the countries can effectively address the challenges posed by OA and safeguard the health of marine organisms, ecosystems and dependent communities.

ACKNOWLEDGEMENT

We would like to express our heartfelt gratitude to the Nairobi Convention for placing its trust in us and for providing invaluable support, which enabled the development of the WIO Regional OA Action Plan. The timely provision of funding and effective communication were crucial for the smooth execution of this assignment. Without such support, the development of the WIO Regional OA Action Plan would not have been feasible within the WIO region. We also extend our sincere appreciation to the OA regional working group, initiated by the Western Indian Ocean Marine Science Association (WIOMSA). Experts from this network reviewed the draft of the WIO Regional OA Action Plan and provided valuable input that enhanced the plan.

Additionally, we are particularly grateful for logistical support from the Tanzania Fisheries Research Institute (TAFIRI), the University of Dar es Salaam (UDSM), and the Nelson Mandela African Institution of Science and Technology (NM-AIST). The provision of accessible office space allowed scientists from these esteemed institutions to carry out their activities smoothly, and we deeply appreciate their contributions to this initiative. We would like to express our gratitude to Dr. Jérôme Harlay, Dr. Leonard Chauka, Dr. Babatunde Adeleke, and Prof. Roshan Ramessur for their valuable review of the WIO OA Regional Action Plan. Their constructive feedback and insights have greatly enhanced the quality of the plan.

The Nairobi Convention is committed to fully achieving the goals outlined in the WIO OA Regional Action Plan, in close collaboration with all members of the Conference of Parties.

ABBREVIATION

CO_2 — Carbon dioxide

DIC — Dissolved Inorganic Carbon

EIA — Environmental Impact Assessment

IMTA — Integrated Multi-Trophic Aquaculture

IPCC — Intergovernmental Panel on Climate Change

IMTA — Integrated Multi-Trophic Aquaculture

MPA — Marine Protected Areas

OA — Ocean Acidification

OAE — Ocean Alkalinity Enhancement

pCO_2 — Partial pressure of CO_2

SDG — Sustainable Development Goal

SSPs — Shared Socioeconomic Pathways

UN — United Nations

UNFCCC — United Nations Framework Convention on Climate Change

USA — United States of America

WIO — Western Indian Ocean

WMO — World Meteorological Organization

1 INTRODUCTION

1.1 Background

Ocean acidification (OA) is a direct impact of the increasing uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere by the oceans (Feely et al., 2009). This process leads to a decrease in pH and changes in seawater carbonate chemistry, including dissolved inorganic carbon (DIC), partial pressure of CO_2 ($_pCO_2$), and carbonate ions (CO_3^{2-}), with significant implications for marine organisms and ecosystems (Doney et al., 2020). Since the Industrial Revolution, the pH of the oceans has decreased by approximately 0.1 units, equivalent to a 30% increase in acidity (Bindoff et al., 2019). This decline has reduced the availability of carbonate minerals essential for the growth and development of calcifying organisms, such as corals, plankton, crustaceans, and shellfish.As a result, OA is widely recognized for its negative impacts on marine organisms, ecosystems, and reliant human communities.

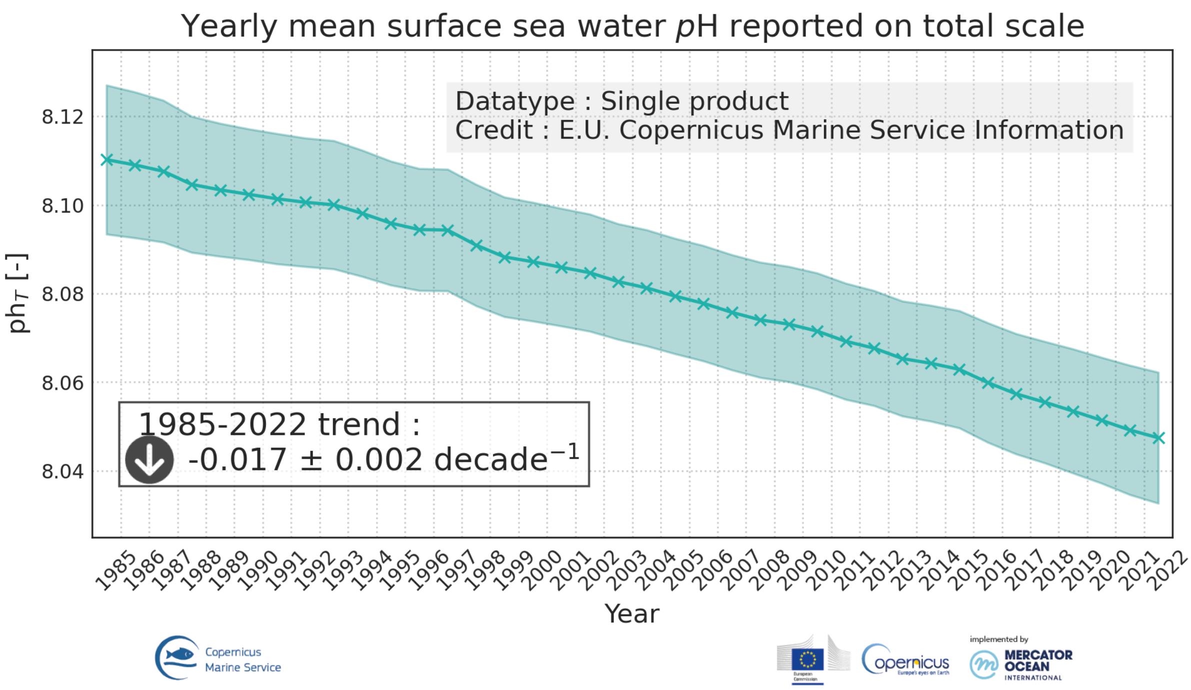

Figure 1: Concstructed global decline in pH under *Business-as-Usual*. Source: Copernicus Marine Servicel.

The impacts of OA can be further exacerbated by other climate change-related stressors, including increasing sea surface temperature and decreasing oxygen levels (Kroeker et al., 2023). Under a "business-as-usual" scenario, with continued CO_2 emissions, projections indicate a further pH decrease of 0.4 units from pre-industrial levels by 2100. The average global surface ocean pH has been decreasing at a rate of 0.017 units per decade since the 1980s (Figure 1) [2]. However, in the Equatorial Indian Ocean, a decreasing rate of 0.015 per decade was reported (Chakraborty et al., 2024). This will significantly intensify the impacts of OA on marine organisms and ecosystems as well as human communities depending on these resources.

OA is a pressing global concern, recognized by the United Nations (UN) as a significant threat to marine organisms, ecosystems and human communities reliant on them.The UN's 2030 Agenda for Sustainable Development has recognized OA as a critical issue under Sustainable Development Goal (SDG) 14, with Target 14.3 specifically calling for its mitigation and minimization of its impacts through enhanced scientific cooperation. Additionally, the World Meteorological Organisation (WMO) has also designated OA as a Global Climate Indicator, ensuring its inclusion in reports to the United Nations Framework Convention on Climate Change (UNFCCC) to inform governments, agencies, and the public about global climate trends.

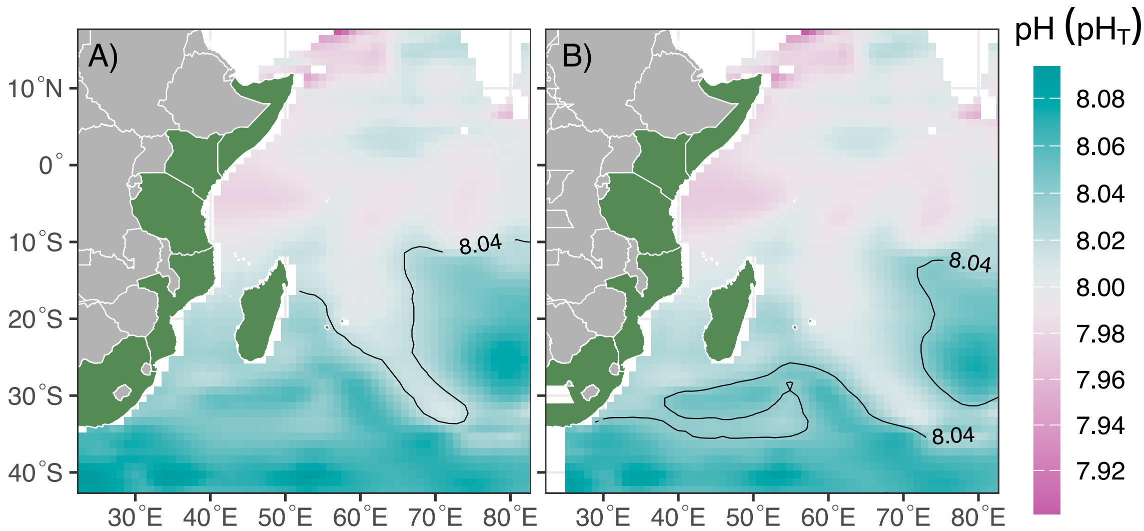

Figure 2: The spatial distribution of pH across the WIO region for a) 2020 and b) 2030. Data source: Global Surface Ocean Acidification Indicators.

Within the Western Indian Ocean (WIO) region, the Regional State of the Coast Report (WIOMSA & UNEP, 2015), the Climate Change Strategy for the Nairobi Convention (Convention, 2016) and publications (George et al., 2024; Ramessur et al., 2022) have identified OA as a major threat. Projected global model indicates that WIO region also experiences pH changes (Figure 2). In response, the Ninth Conference of Parties to the Nairobi Convention prioritized OA (Decision CP.9/1) and called for dedicated actions to mitigate and minimize its impacts including capacity development, scientific cooperation, and regional monitoring and adaptation programs (Decision CP.9/9) in the WIO region. The widespread global impacts of

[2] Found at: https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/global-ocean-acidification-mean-sea-water-ph-time-series

OA on the environment and food security necessitate a coordinated regional and global response to mitigate OA and minimize its impacts in the WIO region. To achieve this, a comprehensive regional OA action plan is essential. This plan will serve as a framework for coordinated joint initiatives, promoting collaboration in monitoring, assessing, and mitigating OA impacts across the WIO region.

1.2 Rationale

Marine organisms and ecosystems in the WIO are increasingly threatened by OA, putting at risk the essential ecosystem services such as fisheries and mariculture, which are crucial for the livelihoods of local communities and food security in the region. The impacts of OA in the coastal waters of the WIO are intensified by other climate change-related factors such as increasing temperature and decreasing oxygen levels, alongside local factors like sea surface temperature, land-based pollution, localized upwelling, habitat loss, and sewage discharge. The severity of these impacts across countries in the WIO region vary depending on the level of coastal communities' dependence on marine resources. OA in the WIO is increasing at constant rate due to increasing atmospheric CO_2 levels, creating an urgent need for immediate and coordinated actions to prevent further ecological and socio-economic impacts in the near future. However, efforts to mitigate OA and minimize its impacts in the WIO region have been limited and uncoordinated, primarily due to the lack of a clear framework (Nairobi Convention, 2021, 2023). Therefore, developing a WIO Regional OA Action Plan, aligned with national climate change priorities, is crucial. This plan would establish a clear framework for collaborative initiatives among WIO countries, focusing on OA monitoring, impact assessment, and mitigation and adaptation measures. It would also enhance coordination and enable more effective measures to address OA and minimize its impacts across the region.

1.3 The Regional Action Plan Formulation Process

Various approaches, methods, and techniques were employed to generate the information and data used in the development of the WIO Regional OA Action Plan.

- **Comprehensive Literature Review**: A thorough review of existing data and information on key indicators of OA and its impacts within the WIO region was conducted, drawing from both published and gray literature. These indicators included pH, carbonate ion concentration, aragonite and calcite saturation states, fugacity of carbon dioxide (fCO_2), Revelle factor (RF), dissolved inorganic carbon (DIC), total alkalinity (TA), total and free hydrogen ion (H^+) concentration, temperature, and salinity.
- **Expert Consultation**: Consultation with scientists, institutions, and regional bodies

working on OA in the WIO region was conducted to gather valuable insights and expertise.

- **Country and Global Dataset Analysis**: Country datasets were analyzed to assess the status of OA in those countries with available monitoring data. In addition, global datasets of selected OA indicators were analyzed to assess OA trends, threats, and opportunities in the WIO Region under various future climate scenarios including optimistic (SSP1-2.6), middle-of-the-road (SSP2-4.5), moderate (SSP3-7.0), and pessimistic (SSP5-8.5). The analysis placed special emphasis on the trends of OA indicators for the years between 2030 and 2100.
- **Policy Review**: A thorough review of existing climate change policies, regulations, and strategies in WIO countries was carried out to identify opportunities for incorporating OA mitigation measures. This ensures that the WIO Region OA Action Plan aligns with relevant policy and regulatory frameworks on climate change mitigation and adaptation measures.
- **Expert Review**: The WIO Regional OA Action Plan was reviewed by relevant OA experts to obtain valuable feedback and ensure its quality. Inputs from experts were incorporated to produce the near final WIO Regional OA Action Plan, which was then presented in a validation workshop.
- **Validation Workshop**: A validation workshop was held to gather input from stakeholders and ensure the WIO Regional OA Action Plan's relevance and effectiveness. Inputs from workshop participants were incorporated to produce the final WIO Regional OA Action Plan, which was then submitted to the Conference of Parties for adoption.

2 SITUATIONAL ANALYSIS

2.1 Causes and Drivers of OA

2.1.1 Anthropogenic CO_2 Emissions

OA is primarily caused by the ocean's absorption of anthropogenic CO_2 emissions, largely attributed to activities such as cement production, deforestation, and fossil fuel combustion (Feely et al., 2009; Orr, 2011). As CO_2 is absorbed in sea water, it leads to a decline in pH and alters the equilibrium of carbonate species, causing an increase in aqueous CO_2 and HCO_3^- concentrations and a decline in CO_3^{2-} concentration (Figure 3). The decrease in pH along with shift in carbonate species poses a serious threat to marine organisms, ecosystems and livelihoods of local communities in the WIO Region.

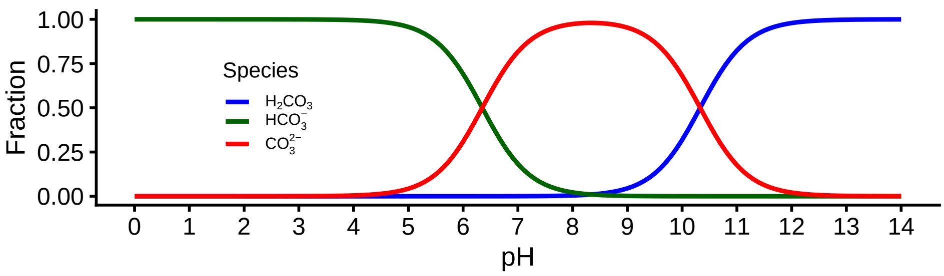

Figure 3: Conceptual diagram showing the distribution of carbonate species in seawater as a function of pH.

2.1.2 Local Drivers of OA

In addition to anthropogenic CO_2 emissions described in Section 2.1.1, local factors can exacerbate OA and its impacts in coastal waters of the WIO (Boodhoo et al., 2022; Imrit et al., 2023; Samson, 2022). The primary drivers of pH in coastal habitats (mangroves, seagrass meadows, and coral reefs) are biogeochemical processes such as calcification, respiration, and photosynthesis (George & Lugendo, 2022). Photosynthetic activity in plants consumes CO_2, which subsequently increases the pH of a system during the daytime (Semesi et al., 2009a). On the other hand, community respiration produces CO_2, which increases the partial pressure of CO_2 (pCO_2) and subsequently lowers the pH of the system (Semesi, Beer, et al., 2009). As a result, pH and dissolved oxygen (DO) in coastal waters fluctuate with diurnal and tidal cycles (George & Lugendo, 2022). The calcification process, for example, in coral reefs and other calcifying organisms, consumes bicarbonate ions (HCO_3^-) and produces CO_2, which raises the pCO_2 and lowers both pH and total alkalinity (TA) in the system (Semesi, Kangwe, et al., 2009). In seagrass meadow, pH is relatively high during the day due to plant photosynthesis and low at night due to community respiration (George et al., 2024; George & Lugendo, 2022).

Another local factor exacerbating OA in WIO coastal waters is the occurrence of upwelling (Kyewalyanga et al., 2020; Painter et al., 2021). As shown by George et al. (2024), upwelling events significantly reduce pH, DO, and temperatures in the Tanga-Pemba Seascape, increasing the risk of OA and deoxygenation impacts in the seascape. However, seagras meadows may help mitigate the adverse effects of reduced pH and DO during upwelling events. Seagrass meadows increase pH and DO levels during the day in upwelling-affected areas and were found to have higher pH levels compared to the open ocean in the Tanga-Pemba Seascape (George et al., 2024). Another significant local driver of OA in WIO coastal waters is freshwater input from rivers and underground discharge (George et al., 2024; George & Lugendo, 2022). Freshwater is typically characterized by low pH levels and high levels of CO_2 aq, and increased freshwater discharge during heavy rains and flooding can dilute seawater carbonate species (Figure 1), potentially lowering pH in coastal habitats. This has been a primary reason for lower pH levels in mangrove habitats influenced by freshwater input (WIOMSA, 2022b).

The morphology and mouth condition of an estuary also affect its pH (Omarjee et al., 2020). In non-perched systems, strong tidal fluctuations and physical mixing significantly impact pH when the estuary is open to the open ocean (Omarjee et al., 2020). However, freshwater from upstream sources has high total alkalinity (TA), which can help to increase the buffering capacity of nearby seawater (Figure 4). Nordstrom (2011) and Omarjee et al. (2020) demonstrated an exponential relationship between pH, conductivity, and TA, suggesting that geological factors can influence pH levels, causing them to deviate from the ambient equilibrium established by freshwater input.

Land-based pollution and sewage discharge also significantly contribute to the overall OA threat in WIO coastal areas. The use of fertilizers and sewage discharge lead to eutrophication in coastal ecosystems (Machiwa, 2010). Phosphate- and nitrate-rich fertilizers used in upland agriculture are often transported to the ocean via runoff, leading to eutrophication in coastal ecosystems. Eutrophication can create oxygen-depleted coastal areas known as "**dead zones**" due to increased respiration rates, resulting in lower pH conditions and exacerbating OA in coastal ecosystems (Alam, 2023). Upwelling can also induce eutrophication by enhancing primary productivity, which subsequently increases respiration during the decomposition of organic matter (George et al., 2024). It is important to note that pH changes in seawater are dependent on the seawaters buffering capacity (Middelburg et al., 2020). This ability refers to seawater's capability to withstand pH changes when acids like CO_2.aq are introduced, relying on the concentration of bases such as HCO_3^-, CO_3^{2-}, and $B(OH)_4^-$, which neutralize H^+ to keep the ocean's pH relatively stable.

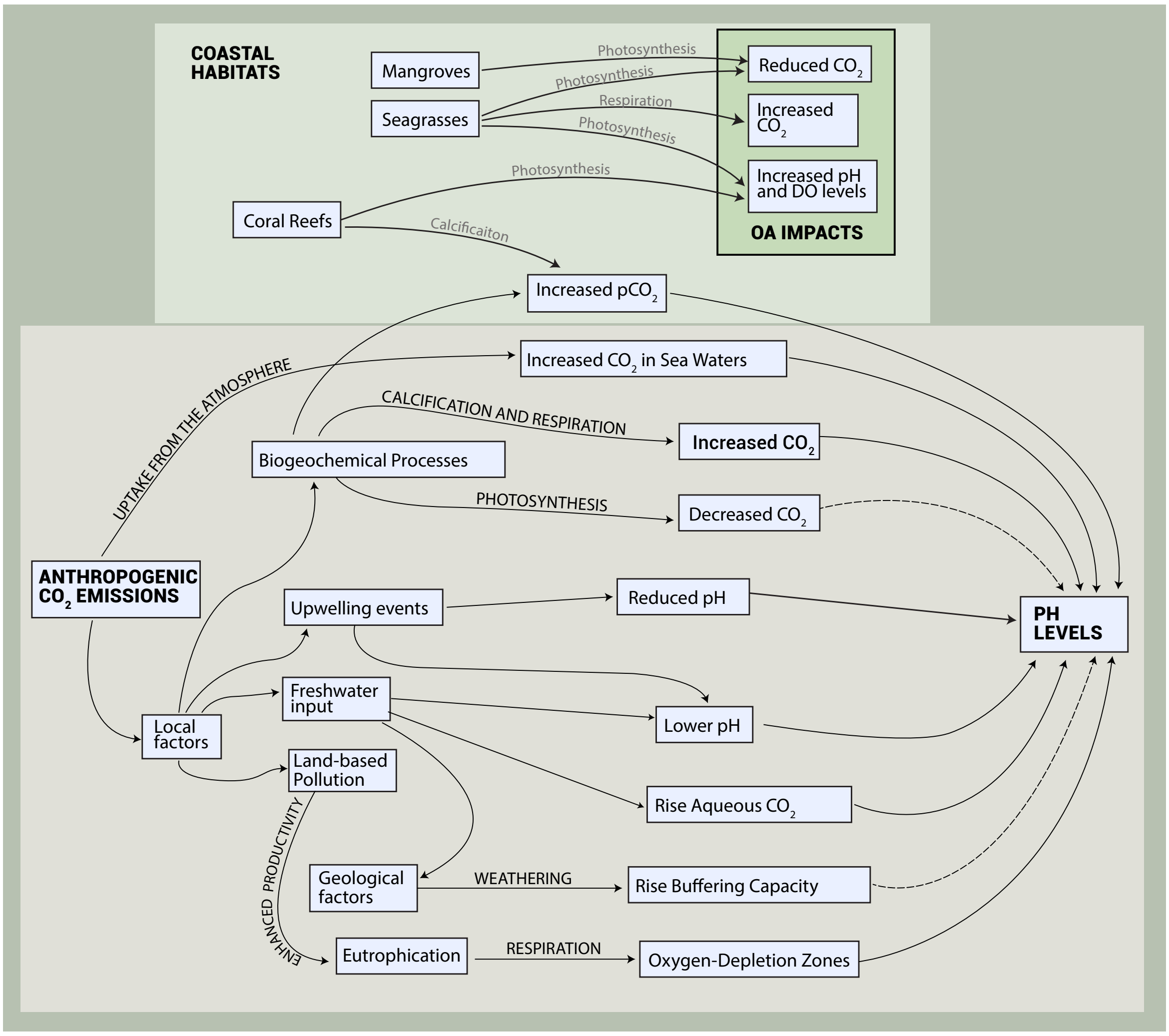

Figure 4: A conceptual diagram of oA drivers in Coastal waters.Each **node** represents a process like anthropogenic CO_2 emissions, local factors (biogeochemical processes, upwelling, freshwater input, and land-based pollution), and their impacts on pH levels. **Arrows** indicate the flow of influence between different elements such as anthropogenic CO_2 emissions lead to increased CO_2 in coastal waters, which lowers pH levels. The **Feedback Mechanisms** are also highlighted, such as the role of seagrass meadows in rising pH during day time and geological factors that influence buffering capacity seawater. **Coastal Habitats** — mangroves, seagrass meadows and coral reefs play a key role in carbon cycle, regulating CO_2 levels in seawater.

2.2 The State of OA Knowledge in the WIO

Knowledge of OA is limited within the WIO region. Out of thirty available documents related to OA in the WIO region, 25 are peer reviewed journal articles, which account for 83.3% (Figure 5 a). This is followed by reports, which account for 10% with three documents (WIOMSA, 2022b, 2022a, 2024) and theses accounting for 6.7%. The dominance of journal articles suggests existence of OA initiatives in the WIO Region. However, the number of published documents from the WIO region is significantly lower compared to other regions (Yang et al., 2024), contributing very little to the global database of OA research (Figure 5 b).

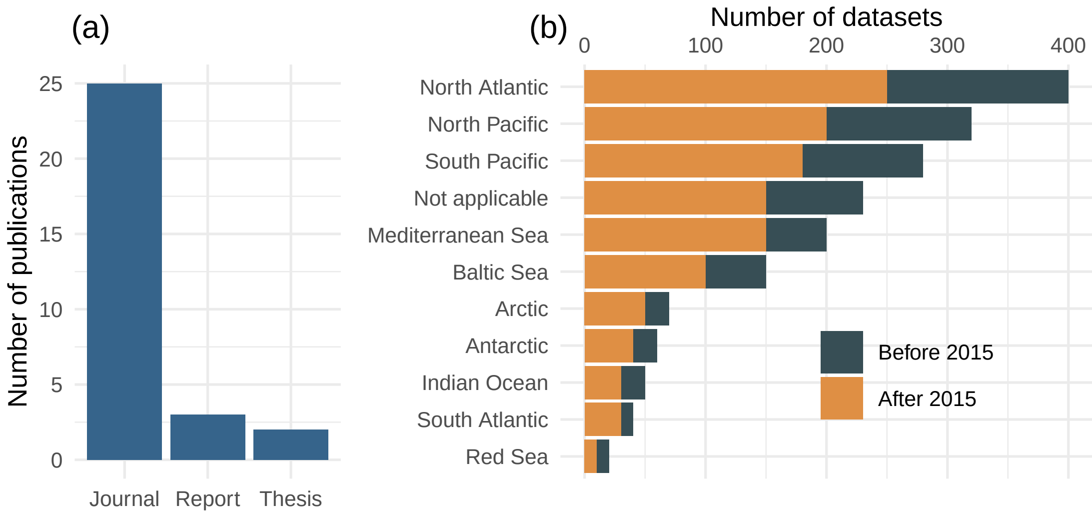

Figure 5: a) The numbers of document types on OA in the WIO region, and b) geographical distribution of datasets included in the Ocean Acidification International Coordination Centre (OAICC) data compilation, compared to those archived before 2015, Redrawn from Yang et al. (2024).

The majority of OA information in the WIO region consists of experimental studies, accounting for 50% of the total (Figure 6). Observational studies follow with 36.7%, while a smaller percentage (6.7%) combine both observation and experimentation. Review reports and modeling studies each contribute 3.3%. This distribution indicates a strong focus on experimental approaches in OA research within the WIO, with South Africa leading, contributing 69.2% of experimental studies. Tanzania accounts for 15.4%, while Kenya and Mauritius each contribute 7.7%. These results reveal a skewed distribution of OA experimental studies relevant to the south in subtropical and temperate regions. This highlights a significant knowledge gap regarding the responses of tropical marine organisms to OA. A similar pattern is evident in observational studies, with South Africa contributing 60%, Tanzania 20%, and Seychelles and Mauritius each accounting for 10%. Notably, the only modeling study was conducted in Mozambique.

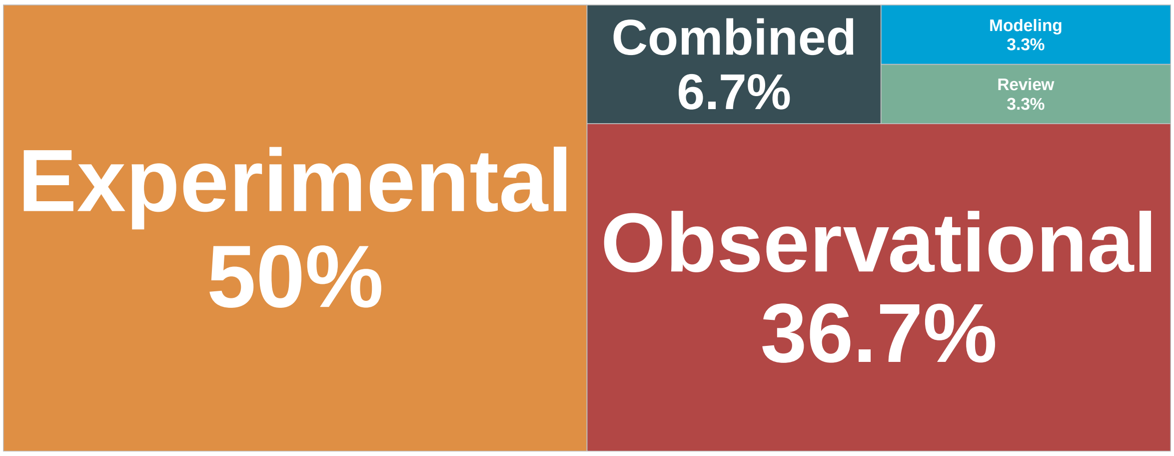

Figure 6: Share of OA in the WIO by study type.

WIOMSA established a regional working group on OA in 2019, involving six WIO countries. This regional initiative contributed to advancing OA knowledge in the region (WIOMSA, 2022a). It also established a baseline of OA indicators for developing an integrated science strategy for OA monitoring and impact assessment in the region. However, the lack of funding has hindered ongoing OA monitoring efforts in most countries. Therefore, there is a need for dedicated actions to improve OA knowledge in the WIO region.

2.3 Status and Trends of OA

2.3.1 State

The average pH levels in the open waters of the WIO countries ranges between 8.0 and 8.1 units. This figure indicates a 0.1 pH unit decrease from pre-industrial level of 8.2. This suggest that WIO region is experiencing OA. Table 1 summarizes the status of OA indicators in the open ocean of the WIO region, based on published and gray literature. However, the reviewed studies assessed only a subset of OA indicators, with many remaining undetermined. Lack of observational studies in many WIO countries prevented documentation of OA indicator status in those countries (Table 1).

Table 1: Status of OA indicators in selected open ocean environments within the WIO region. The values represent mean with plus-minus standard deviation. The reference source(s) for each data point is also included.

	WIO Countries					
Indicator	Tanzania	South Africa	Kenya	Seychelles	Mozambique	Mauritius
pH	8.09±0.03 (George et al., 2024; WIOMSA, 2022b; WIOMSA, 2024)	8.07 (Dziergwa et al., 2019; Emanuel et al., 2020; Garner and Oosthuizen, 2023; WIOMSA, 2022b)	7.90-8.10 (Wanjeri et al., 2023; WIOMSA, 2022b)	8.122±0.01 (Camp et al., 2016)	7.463±0.01 (OA Report 2022)	8.06±0.05 (Boodhoo et al., 2022; Imrit et al., 2023; WIOMSA, 2022b)
Total alkalinity	2181.83±285.76 (Job, 2022)	2284.87±16.58 (WIOMSA, 2022b)	2092-2162 (WIOMSA, 2022b)	2358.5±0.05 (Camp et al., 2016)	2313.27±3.12 (OA Report 2022)	2602±278 (Boodhoo et al., 2022; 2023)
Aragonite	3.22±0.86 (Job, 2022)	3.22±0.50 (WIOMSA, 2022b)	-	4.3±0.01 (Camp et al., 2016)	1.02±0.01 (OA Report 2022)	-
Calcite	4.67±1.24 (Job, 2022)	4.57±0.65 (WIOMSA, 2022b)	-	-	1.56±0.01 (OA Report 2022)	-
pCO_2	395.57±131.4 (Job, 2022)	396–435 (WIOMSA, 2022b)	993±268 (OA Report 2022)	-	1673.48±28.3 (OA Report 2022)	-
Temperature	27.62±0.35 (Job, 2022)	25.6±1.7 (WIOMSA, 2022b)	27.9±0.4 (WIOMSA, 2022b)	29.2±0.02 (Camp et al., 2016)	21.7±0.08 (OA Report 2022)	23-31 (Boodhoo et al., 2022)

2.3.2 Trends

The projected OA indicators in the WIO Region show both decreasing and increasing trends over various socio-economic pathways (Figure 7). The CO_2 trends continue to increase until mid-century and then gradually decrease toward 2100 for SPP1-2.6 while continue to increase even after mid-century for other socio-economic pathways (Figure 7 a). The increase of carbon dioxide fugacity (fCO_2) levels in seawater lead to an increase in temperature (Figure 7 e) and DIC (Figure 7 d), while pH (Figure 7 b) and aragonite saturation (Figure 7 c) state show decreasing trends. Since OA is driven by CO_2 increase in the atmosphere, efforts to mitigate CO_2 emissions are required to mitigate OA and its impacts in the WIO region and beyond.

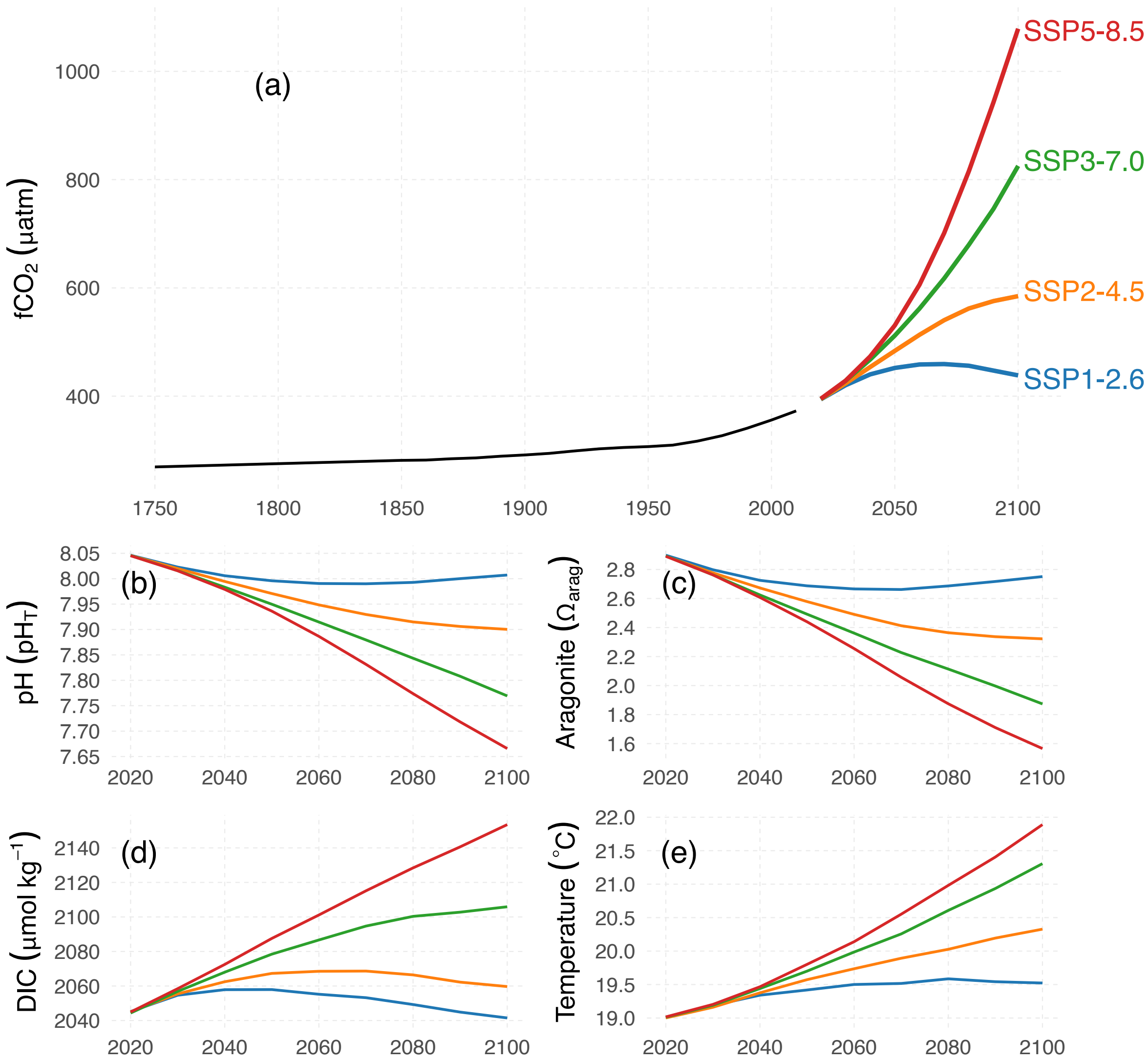

Figure 7: Projected trends in OA indicators for the WIO region under various socio-economic pathways for a) fugacity of carbon dioxide (fCO_2), b) pH, c) aragonite saturation state, d) DIC, and e) temperature. Data source: Global Surface Ocean Acidification Indicators.

2.4 Impacts of OA in the WIO Region

Marine organisms and ecosystems are highly vulnerable to the impacts of OA, particularly under extreme changes in pH and carbonate mineral saturation states (Cornwall et al., 2023). These effects can be intensified by additional climate change stressors such as increasing sea surface temperatures and decreasing oxygen levels (Chakraborty et al., 2024; Kroeker et al., 2013, 2023). However, the response of marine organisms and ecosystems to these stressors depends on their adaptive capacity (Foo & Byrne, 2016). OA presents a significant threat to the marine environment and food security in the WIO region, due to its impact on marine organisms, ecosystems, and the human communities that depend on fisheries and mariculture, as described in Section 2.4.1 and Section 2.4.2.

2.4.1 Marine Organisms and Ecosystems

OA has significant impacts on marine organisms, particularly those dependent on calcification for growth and development (Doney et al., 2020; Kroeker et al., 2013). Calcareous marine organisms like corals, shellfish, crusteans, certain plankton species, and many others non-calcareous marine organisms are affected with OA (Table 2). However, the impacts of OA on tropical marine organisms remain largely undetermined, as most existing studies assessing OA impacts on marine organisms in the WIO region are concentrated in the temperate region of South Africa.

Table 2: Summary of potential impacts of OA on marine organisms in the WIO, based on findings from available experimental studies.

Organism	Impact of OA	Reference
Bivalves	Bivalve (*Anadara antiquate*) survival rate declines significantly with decreased pH and prolonged exposure	Wanjeri et al. (2023)
Mussels	pH reduction causes dissolution in mussels, with intensified effects at lower temperatures during upwelling.	Emanuel et al. (2020)
Oysters	Reduced pH decreases fertilization success in oysters (*Saccostrea cucullata*)	WIOMSA (2022b)
Fouling Communities	Reduced pH during upwelling reduces the diversity of fouling species	Matikinca and Robinson (2024)
Gastropods	Reduced pH impairs metabolism, stress response, and immune function of gastropod species	Carroll and Coyne (2021); Martin et al. (2023), (Martin et al., 2022a); Martin et al. (2022b)
Coralline/Red algae	Increased CO_2 concentration and decreased pH reduce calcification in coralline/red algae	Semesi et al. (2009b)
Crustaceans	Reduced pH affects the survival of crustaceans species	Balloo and Appadoo (2017)
Echinoderms	Reduced pH leads to decreased fertilization success in echinoderms	WIOMSA (2022b)
Crabs	Reduced pH affects physiological process of crabs	Adeleke et al. (2020); (Adeleke et al., 2021)

(continued)

Organism	Impact of OA	Reference
Corals	Reduced aragonite saturation severely impacts coral growth and development, increasing vulnerability to strong waves	Obura et al. (2022), Sumaila et al. (2014)
Sea cucumbers	pH reduction causes extracellular acidosis in sea cucumbers, affecting their growth and development.	Collard et al. (2014)
Fish	Reduced pH levels affect early life stages of many fish species in WIO	Muller et al. (2020), Edworthy (2020)

2.4.2 Food Security

OA threatens the fisheries sector, vital to food security in the WIO Region (Doney et al., 2020; Sumaila et al., 2014). OA directly impacts foundational species like corals, compromising reef health and the socio-ecological-services they provide, such as fisheries and coastal protection (Doney et al., 2020). Coral reef decline severely affects reef fish stocks (Julius et al., 2021; Samoilys et al., 2022), which account for over 70% of capture fisheries in the WIO (Samoilys et al., 2022). The loss of reef species poses a significant impact on food security in the WIO region (Sumaila et al., 2014). Additionally, OA threatens the mariculture sector, which serves as an alternative to declining fish stocks in coastal habitats in the WIO region (Sumaila et al., 2014). Species such as crabs, oysters, bivalves, and sea cucumbers often used in agriculture are highly vulnerable to OA.

2.5 Policy Integration

The WIO countries currently lack a robust integration of OA mitigation and adaptation measures into their existing climate change policies, regulations and strategies. This disjointed approach hinders efforts to effectively address the interconnected challenges posed by climate change and OA. By operating in silos, countries may miss crucial opportunities to enhance the effectiveness of their climate actions. A more comprehensive strategy is urgently needed to create cohesive policies that account for both climate change and OA, ensuring a more resilient and sustainable future for the region.

2.6 Optimal Pathway to Mitigate OA and Minimize its Impacts

Based on projected data, trends of OA indicators for 2030 – 2100 in the WIO region (Section 2.3.2), the Optimistic (SSP1-2.6) scenario is the most effective Socio-Economic Pathway for mitigating OA and minimising its impacts in the WIO region. This pathway aims to achieve significant reductions in carbon emissions, targeting net-zero emissions by the middle of the century (Figure 8), through the implementation of strong policies and investments in cleaner energy sources, improving energy efficiency, reducing carbon footprints, conserving and restoring blue carbon habitats, and promoting sustainable practices.

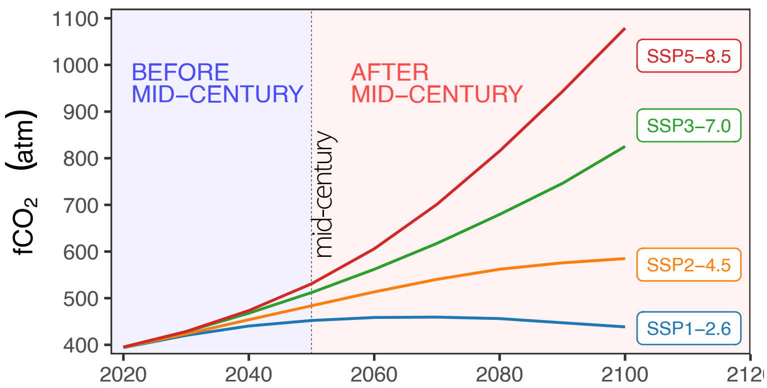

Figure 8: Trends of fCO_2 levels in the WIO Region at different socio-economic pathways before and after the mid-century target of 2050. Data source: Global Surface Ocean Acidification Indicators.

2.7 Barriers to Mitigate OA and Minimize its Impacts

Barriers that could hinder WIO countries from addressing OA are identified based on knowledge gaps (Section 2.2), current state (Section 2.3.1), trends (Section 2.3.2) and impacts of OA on marine organisms, ecosystems (Section 2.4.1) and food security (Section 2.4.2) in the WIO region. Some of these barriers include:

i. **Increasing carbon emissions** – as industrial activities, transportation, deforestation, and energy production continue to expand, carbon emissions will also increase, exacerbating climate change and OA in the WIO region.

ii. **Increasing coastal pollution** – coastal pollution exacerbates OA in WIO coastal waters. Both air and water pollution contribute to this problem, with waterborne pollutants originating from untreated sewage, waste-water, coastal development, and agricultural runoff degrading coastal water quality. This compromised environment creates a synergistic effect, increasing the vulnerability of marine life to the detrimental effects of OA in the WIO.

iii. **Inadequate OA Research and Capacity** – limited research and monitoring programs on OA indicators, which are required to provide data and information on status and trends of OA in the WIO region. The lack of raw data on OA presents a challenge in developing and implementing informed strategies and policies for WIO countries to effectively address the issue. The situation is further aggravated by inadequate infrastructure, skilled personnel, instrumentation, and financial support. A capacity assessment report revealed significant disparities among institutions within and across countries (WIOMSA, 2022b).

iv. **Limited Research on OA Impacts** – knowledge of OA's impacts on marine organisms and ecosystems in the WIO is limited, primarily due to a shortage of experimental studies. This knowledge gap means the specific impacts of OA, along with climate change-related stressors (warming and deoxygenation) on local marine organisms and ecosystems as well as on economic sectors (fisheries and mariculture) are not well understood. As a result, WIO countries end up developing fisheries and mariculture programs without considering the potential impacts of OA.

v. **Low Public Awareness** – There is a general lack of public understanding regarding OA, its impacts and potential mitigation measures in the WIO region. Limited awareness can impede public support for the implementation of necessary actions aimed at addressing OA and its impacts in the WIO.

vi. **Insufficient Integration of OA into Current Climate Change Policies and Strategies in WIO Countries** – Existing national policies, plans, and operational frameworks lack specific measures to address OA impacts. This situation hinders WIO countries from implementing effective interventions to counter the growing threat OA poses to marine ecosystems and the livelihoods they support. This oversight limits the ability of WIO countries to develop comprehensive approaches that address OA alongside other climate-related challenges. Without explicit incorporation of OA into policy frameworks, efforts to combat climate change may overlook critical impacts on marine ecosystems and food security, thereby undermining the overall effectiveness of regional climate initiatives.

vii. **Lack of a Clear Framework for Mitigating OA and Minimizing its Impacts** – the absence of a cohesive framework and coordinated actions among WIO countries to address OA hinders effective mitigation efforts in the region. The lack of a structured approach aligned with climate goals undermines the development and implementation of comprehensive solutions to tackle OA.

3 THE WIO REGIONAL OA ACTION PLAN

The WIO Regional OA Action Plan is developed to address barriers described in Section 2.7 and facilitate implementation of Sustainable Development Goals (SDGs) 14.3 in the WIO region, which specifically addresses OA and its impacts.

3.1 Vison, Mission and Goal

VISION

> *Our vision is safeguard the WIO, ensuring that organisms and ecosystems thrive and continue to deliver essential services for human well-being in the region.*

MISSION

> *Our mission is to empower countries in the WIO region to mitigate OA and minimize its impacts.*

GOAL

> *Our goal is to mitigate OA and minimize its impacts on marine organisms, ecosystems, livelihood and food security in the WIO region by 2035.*

3.2 Scope

The WIO Regional OA Action Plan is a strategic framework designed to guide countries in the WIO region of Somalia, Kenya, Tanzania, Mozambique, South Africa, Seychelles, Mauritius, Madagascar, Comoros, and Reunion (Figure 9). The WIO Regional OA Action Plan describes the actions in implementing Sustainable Development Goal 14.3 to mitigate OA and minimize its impacts in the region. It will also guide countries in the WIO region to align their national climate change strategies and OA mitigation and adaptation measures.

The UNEP Nairobi Convention will serve as the coordinating body for the implementation of the WIO Regional OA Action Plan. This coordinating body will be responsible for overseeing OA activities in the region, specifically, synthesising relevant information about OA, communicating key scientific findings to the Conference of Parties, and providing guidance to support decision-making processes. It is a dynamic document that will be revised as requested by the Conference of Parties. The plan covers a period of ten years (2025-2035) and includes strategic priorities for both mitigating and adapting the current and future impacts of OA on marine organisms and ecosystems as well as food security in the WIO region.

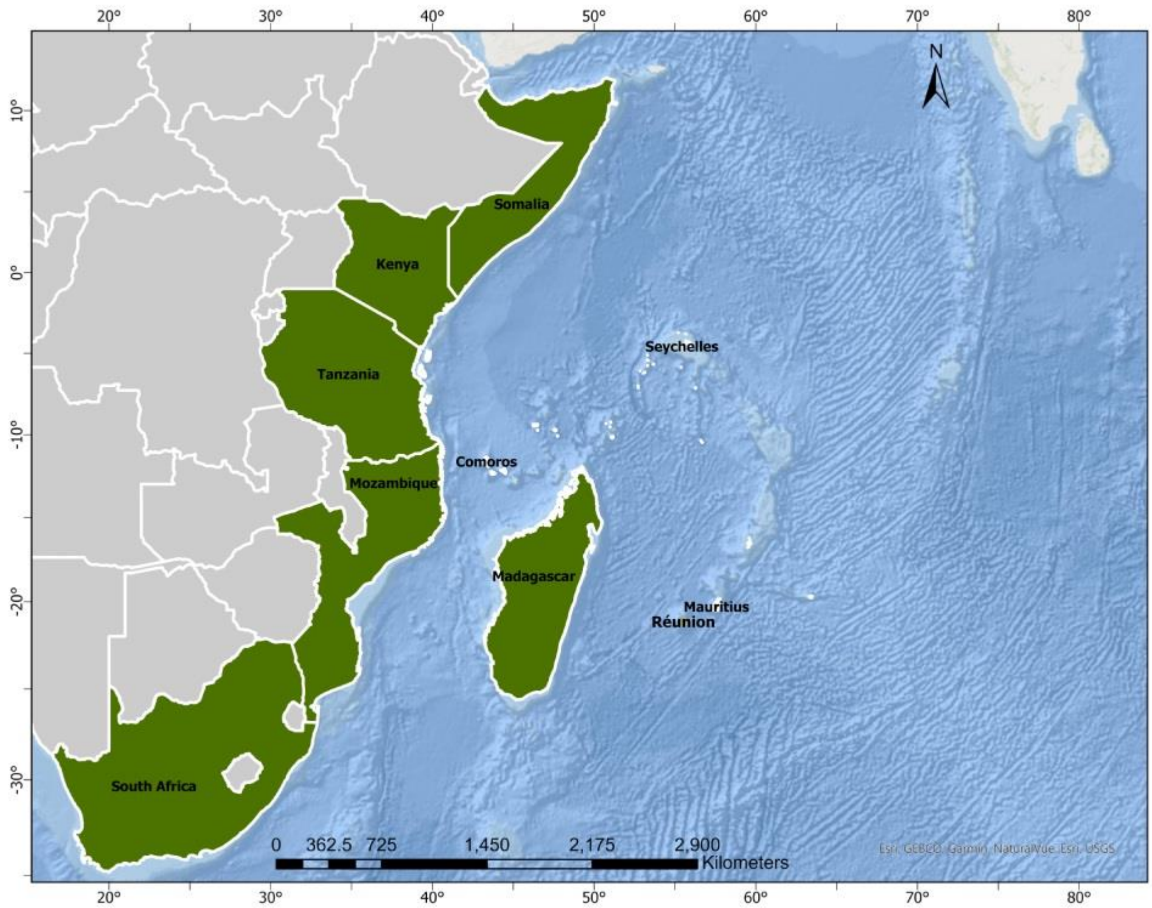

Figure 9: The countries and island states in the WIO region.

3.3 Strategic Priorities for the Action Plan

The WIO Regional OA Action Plan is structured into six strategic priorities, each accompanied by specific actions, key performance indicators (KPIs), and a timeframe (*See* Table 3) aimed at supporting the effective implementation of SDG 14.3 in the region, by addressing barriers described in Section 2.7. The importance of each strategic priority and associated actions may vary considerably among countries in the WIO region. This variance may be influenced by the level of vulnerability to OA impacts and other climate change-related stressors within each country, as well as a country's readiness to implement the WIO Regional OA Action Plan.

Table 3: Strategic priorities for the WIO OA Regional Action Plan along with actions, key performance indicators (KPIs) and the timeframe for implementation. The Short-term time covers 0 to 3 years, medium (4-6 years) and longterm (beyond 6)

Strategy	Actions	KPI	Timeframe
1.Mitigating OA/Climate protection measures	1.1.Promote transitioning to renewable energy sources (solar, gas, wind, geothermal, tidal)	1.1.1.Percentage of energy sourced from renewables	1.1.1.Medium
	1.2.Promote utilisation of gas-fueled vehicles	1.2.2.Number of gas-fueled vehicles in operation	1.2.2.Short
	1.3.Reduce deforestation and promote reforestation	1.3.3.Area of forest restored or conserved	1.3.3.Ongoing
	1.4.Promote conservation and restoration of blue carbon habitats	1.4.4.Extent of blue carbon habitat restored	1.4.4.Ongoing
	1.5.Effectively implement international agreements like the Paris Agreement	1.5.5.Level of adherence to international agreements	1.5.5.Ongoing
	1.6.Implement national and regional policies to reduce emissions	1.6.6.Policies in place to reduce carbon emissions	1.6.6.Ongoing
2.Advancing understanding of OA and its impacts	2.1.Conduct continuous monitoring of OA indicators using advanced technologies	2.1.1.Number of monitoring stations deployed	2.1.1.Ongoing
	2.2.Conduct experimental studies to assess OA impacts	2.2.2.Number of studies on OA impacts published	2.2.2.Medium
	2.3.Conduct OA vulnerability assessments on coastal communities	2.3.3.OA vulnerability assessment reports	2.3.3.Short
	2.4.Conduct modelling studies to forecast OA trends	2.4.4.Forecasting models on OA trends	2.4.4.Medium
	2.5.Build capacity for OA expertise in WIO region	2.5.5.Number of trained scientists and policymakers	2.5.5.Ongoing
	2.6.Build infrastructure capacity for OA research	2.6.6.Upgraded facilities and resources for OA research	2.6.6.Ongoing
	2.7.Build capacity for OA monitoring and data analysis	2.7.7.Capacity development for OA data analysis	2.7.7.Medium
	2.8.Establish community-based monitoring programs to track OA	2.8.8.Community participation in monitoring programs	2.8.8.Medium

(continued)

Strategy	Actions	KPI	Timeframe
3.Reducing local water-borne and airborne pollution	3.1.Upgrade/install new wastewater treatment infrastructure	3.1.1.Number of wastewater systems upgraded	3.1.1.Long
	3.2.Implement policies to reduce plastic production and consumption	3.2.2.Plastic waste reduction metrics	3.2.2.Medium
	3.3.Strengthen waste management systems	3.3.3.Improvement in waste collection coverage	3.3.3.Short to Medium
	3.4.Promote sustainable farming through organic fertilizers	3.4.4.Percentage decrease in chemical fertilizer use	3.4.4.Medium
	3.5.Monitor and regulate industrial waste	3.5.5.Number of industries compliant with waste treatment standards	3.5.5.Ongoing
	3.6.Run public campaigns on pollution impacts and promote sustainable practices	3.6.6.Number of campaigns conducted	3.6.6.Short
	3.7.Protect and restore mangroves and salt marshes	3.7.7.Area of habitats restored	3.7.7.Medium to Long
	3.8.Develop monitoring and reporting systems for industrial emissions	3.8.8.Number of emission reports submitted	3.8.8.Medium
	3.9.Monitor pollution levels in coastal waters	3.9.9.Regularity of pollution monitoring reports	3.9.9.Ongoing
	3.10.Set discharge limits in pollution discharge permits	3.10.10.Number of permits issued with new discharge limits	3.10.10.Short

(continued)

Strategy	Actions	KPI	Timeframe
4.Building resilience and adaptation for affected communities	4.1.Promote mariculture of resilient marine species	4.1.1.Number of mariculture projects established	4.1.1.Short to Medium
	4.2.Raise awareness of OA through education and outreach programs	4.2.2.Number of outreach programs conducted	4.2.2.Short to Medium
	4.3.Promote protection and restoration of seagrass meadows	4.3.3.Area of seagrass meadows restored	4.3.3.Medium to Long
	4.4.Promote adoption of IMTAs incorporating seagrass or seaweeds	4.4.4.Number of IMTAs implemented	4.4.4.Medium
	4.5.Develop financial assistance programs for shellfish farmers	4.5.5.Number of financial programs developed	4.5.5.Short
	4.6.Promote diversification of livelihoods in coastal communities	4.6.6.Increase in non-fishing income sources	4.6.6.Short to Medium
	4.7.Enhance fisheries and aquaculture value chains	4.7.7.Percentage increase in value of fisheries products	4.7.7.Medium
	4.8.Develop micro-credit and loan schemes	4.8.8.Number of schemes implemented	4.8.8.Medium
	4.9.Integrate OA into local development plans	4.9.9.Number of plans integrating OA	4.9.9.Medium
	4.10.Remove excess CO_2 from the water before it enters the mariculture hatchery	4.10.10.Number of hatcheries	4.10.10.NA
	4.11.Adjust total alkalinity of seawater before enters mariculture hatchery	4.11.11.Number of hatcheries	4.11.11.NA
5.Mainstreaming resilience and adaptation measures into policies	5.1.Revise national/regional policies to include OA mitigation	5.1.1.Number of revised policies	5.1.1.Medium
	5.2.Integrate coastal pollution into EIAs for development projects	5.2.2.Number of EIAs incorporating coastal pollution	5.2.2.Ongoing
	5.3.Raise awareness among policymakers through training and workshops	5.3.3.Number of workshops held	5.3.3.Short
	5.4.Enhance access to OA data platforms	5.4.4.Number of active users on OA data platforms	5.4.4.Short to Medium
	5.5.Incorporate OA monitoring into Marine Protected Areas (MPAs) management	5.5.5.Number of MPAs with OA monitoring	5.5.5.Medium
	5.6.Create a multi-stakeholder engagement forum	5.6.6.Number of forums organized	5.6.6.Short
	5.7.Organize annual workshops and meetings on OA resilience	5.7.7.Number of workshops conducted	5.7.7.Ongoing

(continued)

Strategy	Actions	KPI	Timeframe
6.Enhancing collaboration and partnerships	6.1.Support and expand the OA Working Group	6.1.1.Number of working group members	6.1.1.Ongoing
	6.2.Standardize data collection protocols	6.2.2.Number of standardized data protocols established	6.2.2.Short to Medium
	6.3.Organize regional workshops and conferences on OA	6.3.3.Number of regional workshops organized	6.3.3.Ongoing
	6.4.Develop a regional OA data repository	6.4.4.Accessibility of data repository	6.4.4.Medium
	6.5.Promote collaboration between WIO researchers and global counterparts	6.5.5.Number of collaboration projects	6.5.5.Ongoing
	6.6.Develop and implement data sharing mechanisms	6.6.6.Number of data sharing agreements	6.6.6.Medium

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