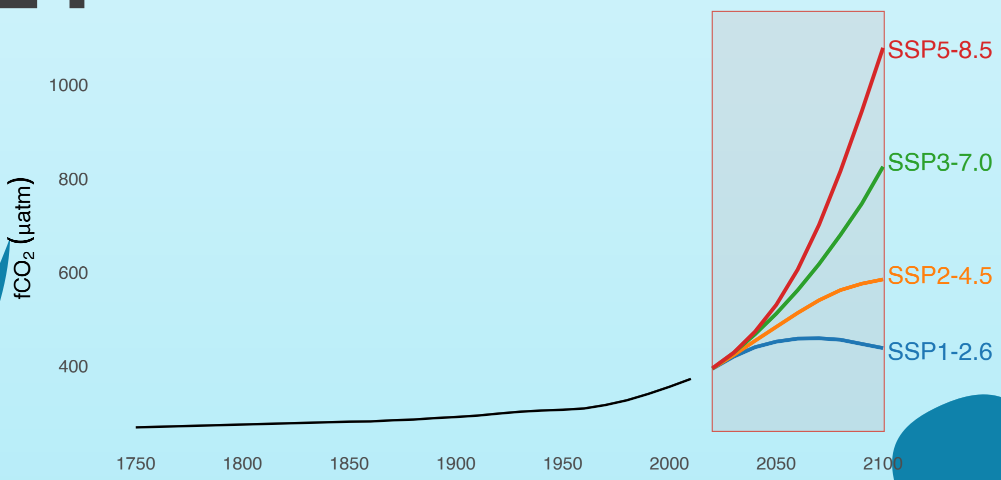
Nairobi Convention

A Review on

OCEAN ACIDIFICATION AND IT'S POTENTIAL IMPACTS ON MARINE ENVIRONMENT AND FOOD SECURITY IN THE WESTERN INDIAN OCEAN REGION

2024



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A Review on

OCEAN ACIDIFICATION AND ITS POTENTIAL IMPACTS ON MARINE ENVIRONMENT AND FOOD SECURITY IN THE WESTERN INDIAN OCEAN

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SUMMARY

The world's oceans serves as a carbon sink, play a crucial role in regulating atmospheric carbon dioxide (CO_2) levels. However, this carbon absorption comes at a cost. Dissolved CO_2 cause ocean acidification (OA) – low seawater pH and changes seawater carbonate chemistry. OA poses a significant threat to marine organisms, ecosystems, and coastal communities. The Western Indian Ocean (WIO) region is particularly vulnerable to OA's impacts because its coastal communities heavily depend on marine and coastal resources for livelihood. In addition, pollution, habitat loss, and over-exploitation further threaten WIO coastal resources, exacerbating OA's impacts on the region.

Despite the threats OA poses in the region, its unfortunate that the current state and trends of OA in the WIO region, along with its potential impacts, remain unknown. The limited information of OA hinders the development and implementation of future plans and strategies for monitoring, assessing impacts, and mitigating OA in the region. Therefore, to address this challenge, this assessment reviewed the available information discern the state and trends of OA in the region. Specifically, the review explored the level of OA knowledge in the WIO region, including its status, trends, driving factors, and potential impacts on marine organisms, ecosystems, and food security. Through a thorough review of latest scientific findings, this report presents summary of key findings, which include:

i. Most countries in the WIO region lack comprehensive OA monitoring programs of key OA indicators;
ii. pH levels in the open ocean of the WIO have decreased from pre-industrial levels of about 8.2 to between 8.0 and 8.1;
iii. Coastal waters are influenced by various OA drivers, including biogeochemical processes (calcification, photosynthesis, respiration), freshwater input and underground discharges, upwelling, land-based pollution, and sewage discharge. These factors can potentially exacerbate OA impacts on marine organisms in key coastal habitats (mangroves, seagrass, coral reefs);
iv. Upwelling regions in the WIO are particularly vulnerable to OA impacts as upwelling events decreases pH and dissolved oxygen (DO) levels to the projected under future climate change scenarios;
v. The pH and carbonate mineral saturation states of the WIO are projected to decline further in the future. However, CO_2, dissolved carbon dioxide (DIC), and temperatures are all projected to increase significantly. However, the magnitude of changes of OA indicators vary depend on Shared Socioeconomic Pathway (SSP) adopted;
vi. OA pose a threat to a wide range of marine organisms in the WIO, including bivalves, mussels, oysters, fouling communities, coralline algae, red algae, crustaceans, echinoderms, corals, sea cucumbers, and fish;

vii. OA pose a risk in food security in the WIO region due to its impacts on fisheries and aquaculture;
viii. Prioritizing intervention strategies to achieve SSP1-2.6 climate goals is the most effective way to mitigate the impacts of OA in the WIO region.

Despite the threats and challenges OA poses in the WIO region, the assessment identified some strategic interventions that once taken mitigate and reduce OA impacts. These strategic interventions include: increase OA research and monitoring, build capacity and awareness, promote mitigation strategies, address food security concerns, and create and implement a WIO regional OA action plan.

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 successful review of the latest scientific findings on Ocean Acidification (OA) and its potential impacts on the marine environment and food security in the Western Indian Ocean (WIO). The timely provision of funding and effective communication were crucial for the smooth execution of this assignment. Without such support, the generation of essential data and information on OA within the WIO region—critical for developing a WIO Regional OA Action Plan—would not have been feasible.

We also extend our sincere appreciation to the OA regional working group, hosted by the Western Indian Ocean Marine Science Association (WIOMSA). Their monitoring data were instrumental in assessing the current state of OA in the WIO region. Their dedication and efforts ensured that the necessary raw data were readily available for this review, significantly enhancing our understanding of OA and contributing to the achievement of the review's objectives.

Additionally, we are particularly grateful for the 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.

ABBREVIATION

AJOL — African Journals Online

Arag — Aragonite saturation state

$B(OH)^{4-}$ — Borate

Calc — Calcite saturation state

Cd — Cadmium

CO_2.aq — Dissolved carbon dioxide

$CO_3{}^{2-}$ — Carbonate ion

DIC — Dissolved carbon dioxide

DO — Dissolved oxygen

$_fCO_2$ — Fugacity of carbon dioxide

H^+ — Hydrogen ion

HCO_3^- — Bicarbonate ion

IOC-UNESCO — Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization

NOAA — National Centers for Environmental Information at National

OA — Ocean acidification

OAICC — Ocean Acidification International Coordination Centre Oceanic and Oceanographic Authority

Pb — Lead

pCO_2 — Partial pressure of carbon dioxide

pH_T — pH on total scale

RF — Revelle Factor

SDGs — Sustainable Development Goals

SIDS — Small Island Developing States

SSPs — Shared Socioeconomic Pathways

TA — Total alkalinity

WIO — Western Indian Ocean

WIOMSA — Western Indian Ocean Marine Science Association

WoS — Web of Science

1 INTRODUCTION

1.1 Background and Rationale

The oceans' play a crucial role in regulating the level of carbon dioxide (CO_2) in the atmosphere, serving as a significant carbon sink (Sabine et al., 2004). Historically, they have absorbed roughly 28% of CO_2 emissions over the past 250 years and continue to take up more than 30% of annual CO_2 emissions (Doney et al., 2014; Gruber et al., 2023). However, this absorption has its drawbacks. CO_2 dissolved in water acts as an acid, lowering its pH and triggering changes in seawater carbonate chemistry, collectively termed ocean acidification (OA). Since the pre-industrial period, the global average pH of surface oceans has decreased by approximately 0.1 units, from around 8.2 to 8.1. This decline has also impacted the availability of saturation states of carbonate minerals like calcite and aragonite, making it more difficult for calcifying marine organisms such as corals, oysters, and pteropods to build their calcium carbonate shells and skeletons (Doney et al., 2020; Figuerola et al., 2021; Kroeker et al., 2013).

Projections indicate a further decrease of 0.2–0.3 units in pH by 2100, along with reduced saturation states of carbonate minerals, even in optimistic emission scenarios (Doney et al., 2014; Feely et al., 2009b). This projected decline in pH and saturation states of carbonate minerals will further impact marine organisms (Kroeker et al., 2013). In response to the threats posed by OA globally, the United Nations' 2030 Agenda for Sustainable Development addresses this issue through Sustainable Development Goal (SDG) 14, Target 14.3, which aims to minimize its impacts. The Western Indian Ocean (WIO) region, encompassing Comoros, Kenya, Madagascar, Mauritius, Reunion (France), Mozambique, the Seychelles, Somalia, South Africa, and Tanzania, is particularly vulnerable to the OA impacts. This vulnerability stems from the heavy reliance of coastal communities and economies, particularly in many countries and Small Island Developing States (SIDS), on coastal and marine resources for sustenance and livelihoods (Moustahfid et al., 2019; Poti et al., 2022; Taylor et al., 2019). The impacts of OA on marine organisms are exacerbated by other climate change-related stressors, including warming and de-oxygenation, and local factors like land-based pollution, upwelling, and sewage discharge, pollution and habitat loss (Kroeker et al., 2013).

A recent study by Taylor et al. (2019) on climate change impacts in the WIO region indicated that Comoros, Mauritius, Mozambique, and Somalia are particularly vulnerable to ocean warming, population pressures, and fluctuations in total fish catch. These nations are projected to experience severe impacts due to changing conditions in the WIO, affecting them at national, community, and individual levels. Despite high vulnerability to OA impacts, the current status and trends of OA, along with its potential impacts for food security and marine environments in the WIO region, remain largely unknown. This lack of understanding of OA in the WIO region hinders the development and implementation of future plans for monitoring, assessing impacts, and mitigating its impacts. Therefore, this review report provides information on the latest scientific findings concerning OA and its potential impacts on food security and marine environments in the WIO region. It summarizes current understanding of OA in the region, including its status, trends, and driving factors. Furthermore, it identifies potential impacts of OA on marine organisms, ecosystems, and food security in the region. This review serves as a foundation for developing a Regional Ocean acidification Action Plan for the WIO.

1.2 Causes and Drivers of OA

1.2.1 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., 2009b; Orr, 2011). As CO_2 is absorbed, it triggers changes in seawater carbonate chemistry, wherein the pH is regulated by weak acids and bases capable of exchanging hydrogen ions (H^+) (Eqn 1-3). These include inorganic carbon species such as dissolved carbon dioxide (CO_2.aq), bicarbonate ions (HCO_3^-), carbonate ions (CO_3^{2}}), and, to a lesser extent, borate ($B(OH)_4^-$). The following are chemical reactions that occur when CO_2 dissolves in seawater:

When CO_2 dissolves in seawater, it behaves as an acid, releasing hydrogen ions (H^+), which then combine with any introduced base to form bicarbonate:

$$CO_2 + H_2O \rightleftharpoons H^+ + HCO_3^- \tag{1}$$

The carbonate ions (CO_3^{2-}}) function as a base, absorbing hydrogen ions (H^+) from any introduced acid to likewise produce bicarbonate:

$$CO_3^{2-} + H^+ \rightleftharpoons HCO_3^- \tag{2}$$

Borate ($B(OH)_4^-$) serves as a base, accepting hydrogen ions (H^+) from any acid to produce boric acid ($B(OH)_3$):

$$H^+ + B(OH)_4^- \rightleftharpoons B(OH)_3 + H_2O \tag{3}$$

In general, elevated levels of dissolved CO_2 lead to a decline in pH and alter the equilibrium of inorganic carbon species in seawater, causing an increase in CO_2.aq and HCO_3^- concentrations and a decline in CO_3^{2-} concentration (Figure 1). As a result, the average pH of the ocean's surface has decreased by approximately 0.1 unit from around 8.2 in the pre-industrial era to

8.1 today, reflecting an unprecedented rate of change not observed in hundreds of thousands of years (Feely et al., 2009a; Feely et al., 2009b). Model forecasts suggest that if CO_2 emissions persist at their current pace (i.e., business-as-usual scenarios), pH could fall by another 0.2-0.3 units, by the end of the 21st century. Even in more optimistic scenarios, the mean ocean surface pH is anticipated to drop below 7.9 (Orr, 2011).

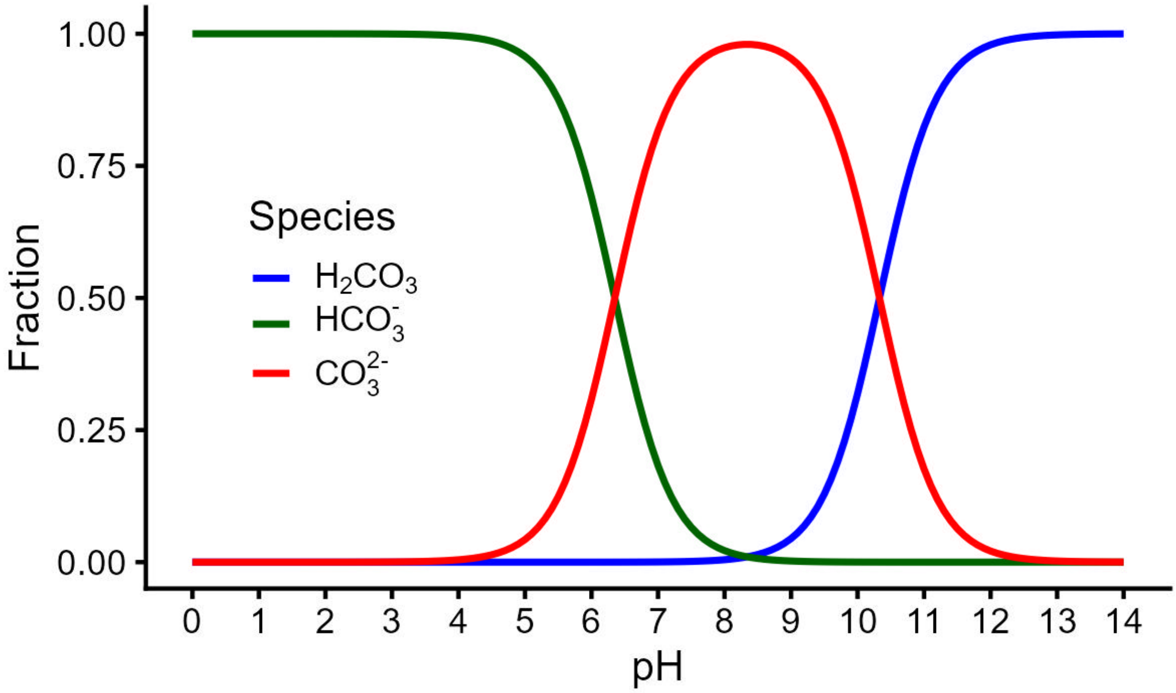

Figure 1: Conceptual diagram showing the distribution of carbonate species in seawater as a function of pH.

1.2.2 Local Drivers of OA

In addition to anthropogenic CO_2 emissions described in Section 1.2.1, local factors can exacerbate OA and its impacts in coastal waters of the WIO (Boodhoo et al., 2022; Job, 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 and 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 et al., 2009a). As a result, pH and DO in coastal waters fluctuate with diurnal and tidal cycles (George and Lugendo, 2022). The calcification process, for example, in coral reefs and other calcifying organisms, consumes carbonate ions (CO_3^{2-}) and produces CO_2, which raises the pCO_2 and lowers both pH and total alkalinity (TA) in the system (Semesi et al., 2009b). In seagrass meadow, pH is high during the day due to plant photosynthesis and low at night due to community respiration (George et al., 2024; George and Lugendo, 2022).

The other 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 discharges (George et al., 2024; George and 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 often contains high levels of TA, which can help to increase the buffering capacity of nearby seawater (Figure 2). Studies by 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 "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; Kyewalyanga et al., 2020). It is important to note that pH changes in seawater are dependent on seawater 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.

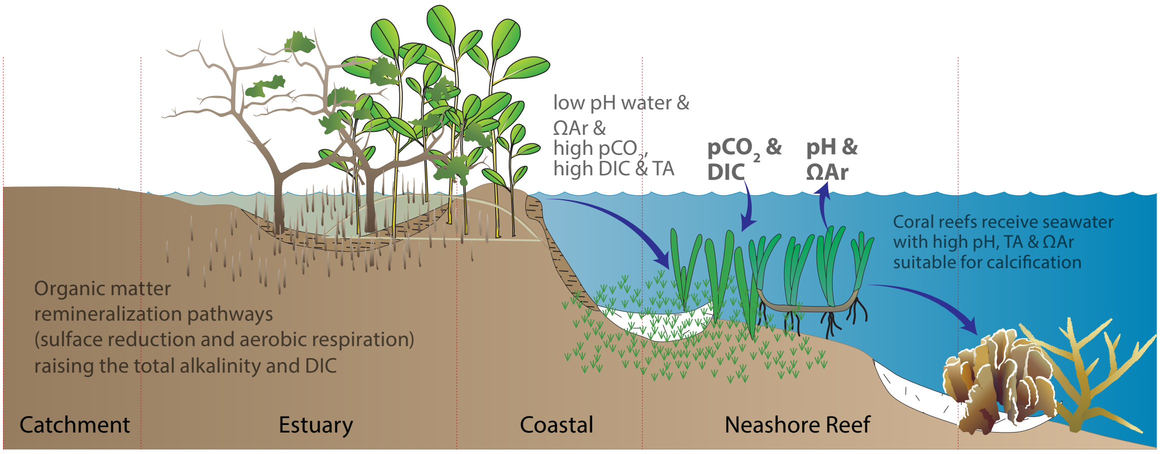

Figure 2: Systematic diagram illustrating the impact of freshwater discharge on seawater carbonate chemistry and total alkalinity (TA) in coastal habitats.

1.3 OA Indicators

OA indicators are key variables that provide insights into changes in seawater chemistry and their effects on marine organisms and ecosystems. The primary indicators used for monitoring and assessing OA impacts globally include:

1. pH on total scale (pH_T): A decrease in the pH of seawater is a direct indicator of OA. pH is measured on a logarithmic scale, with lower values indicating higher acidity;
2. Carbonate ion concentration (CO_3^{2-}): Declines in the concentration of CO_3^{2-} in seawater are indicative of OA. This reduction affects the availability of carbonate minerals, aragonite and calcite, necessary for the formation of shells and skeletons in marine calcareous organisms;
3. Aragonite saturation state (Arag): The saturation state of aragonite, a type of calcium carbonate mineral, offers insights into the potential effects of OA on corals. Declining saturation states under OA affect the survival and growth of corals, and when the Aragonite falls below 1, calcium carbonate dissolution begins;
4. Calcite saturation state (Calc): The saturation state of calcite, a type of calcium carbonate mineral, offers insights into the potential impacts of OA on shellfish. Declining calcite states under OA affect the survival and growth of shelled organisms, and when the calc state falls below 1, dissolution of shells begins;
5. Fugacity of carbon dioxide (fCO_2): the fugacity of CO_2 represents the partial pressure of CO_2 in seawater, providing insight into the concentration of dissolved CO_2. As CO_2 dissolves in seawater, it forms carbonic acid, leading to a decrease in pH and the OA;
6. Revelle Factor (RF): The Revelle Factor is a measure of the sensitivity of seawater pH to changes in atmospheric CO_2 levels. It represents the ratio of the relative change in DIC to the relative change in atmospheric CO_2 concentration. Essentially, it quantifies how

efficiently the ocean can absorb and buffer CO_2 from the atmosphere;

7. Dissolved Inorganic Carbon (DIC): Changes in the concentration of DIC, including CO_2.aq, HCO_3^-, and CO_3^{2-}, can be used to assess the progression of OA;
8. Total alkalinity (TA): TA is a measure of the seawater's capacity to neutralize acids, primarily through the presence of HCO_3^- , CO_3^{2-} and $B(OH)_4^-$. It represents the sum of all the bases in seawater that can accept H^+. As OA progresses, the concentration of carbonate ions decreases, which can lead to a decrease in TA;
9. Total hydrogen ion content often measured as pH, is indeed a crucial indicator of OA. As more CO_2 is absorbed into seawater, it reacts with seawater to form carbonic acid, increasing the concentration of H^+;
10. Free hydrogen ion content often represented by the concentration of H^+, refer to amount of free hydrogen ions in the seawater. As CO_2 dissolves in seawater, it reacts with water to form carbonic acid, which increases the concentration of hydrogen ions. This increase in free hydrogen ions results in a decrease in pH, making the seawater more acidic;
11. Salinity: salinity can indirectly influence OA by affecting the ocean's capacity to absorb and retain CO_2, a major cause of OA. It is also a critical factor in calculating other indicators of OA;
12. Temperature: can indirectly influence OA because warmer waters generally have a lower capacity to absorb CO_2, potentially influencing the rate of OA. It is also a critical factor in calculating other indicators of OA.

Accurate measurement of OA indicators is essential for understanding its status, trends, and impacts on marine organisms and ecosystems. This can be achieved using specialized equipment or calculated using a CO_2-System with measurements of two key variables: DIC, TA, pH, or pCO_2. Integrating these measurements with data on temperature and salinity allows estimation of the other OA indicators. Monitoring DIC, TA, pH, pCO_2, salinity and temperature over time and space helps scientists assess the status, trends, and impacts of OA on marine organisms and ecosystems.

2 METHODS

2.1 Geographical scope

The WIO region is located between the coordinates of approximately 25°E to 80°E longitude and -40°S to 15°N latitude. This region consists of several countries including Somalia, Kenya, Tanzania, Mozambique and South Africa as well as islands states such as Madagascar, Seychelles, Reunion (France), Comoros, and Mauritius (Figure 3).

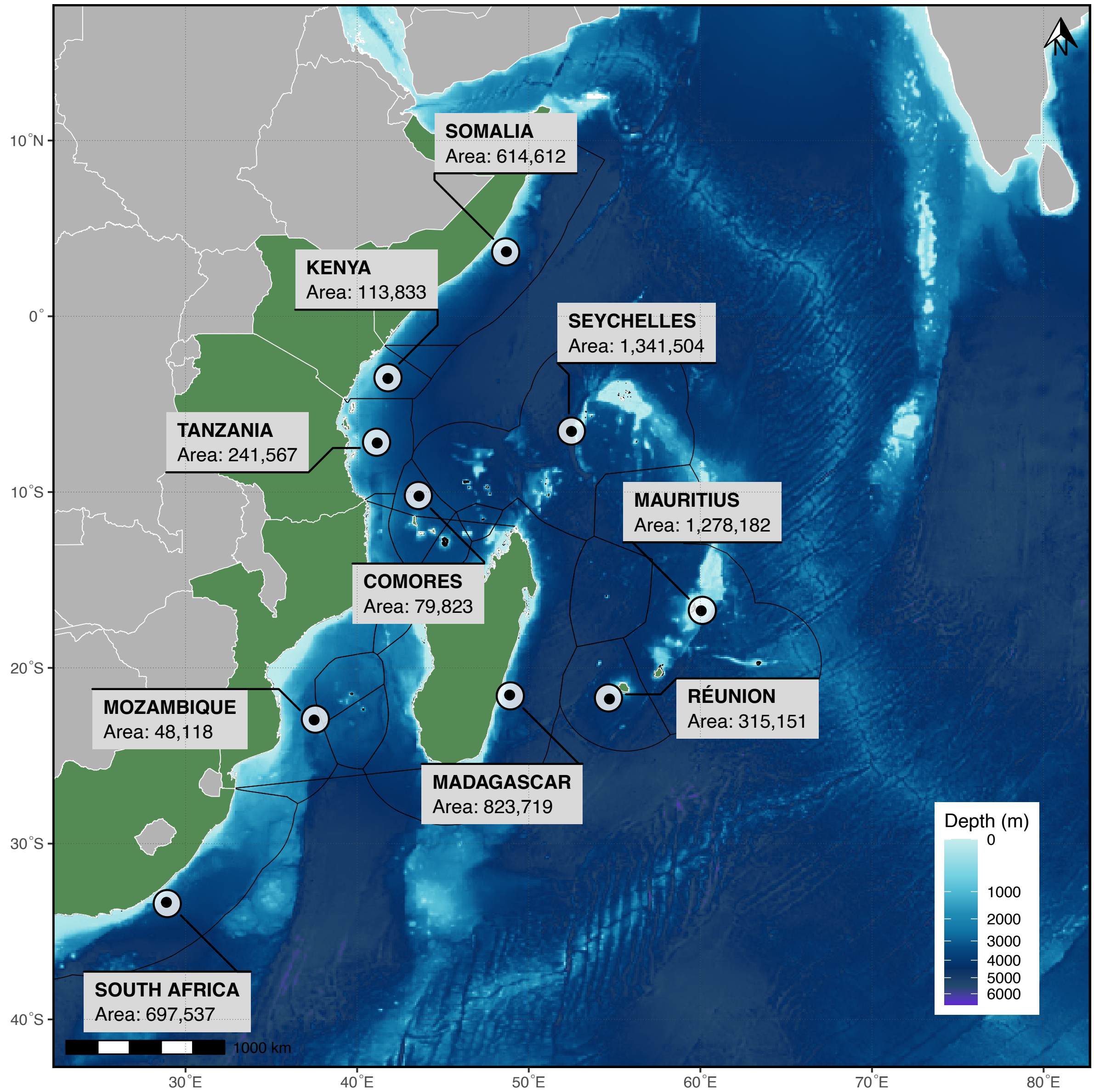

Figure 3: The countries and island states in the WIO region. Blue shades represent bathymetry and black solid lines indicates their Exclusive Economic Zones.

Characterized by productive coral reefs, mangroves, and seagrass beds (Osuka et al., 2021), the WIO region supports high biodiversity and provides crucial ecosystem services. These services include fisheries, a primary source of protein and livelihoods for millions, coastal protection, climate change mitigation, and tourism, among others. However, the WIO faces numerous environmental challenges stemming from both human activities and climate change. Human-induced factors include overfishing, coastal habitat loss and degradation, and pollution, while climate change-related issues encompass OA, ocean warming, and deoxygenation (Obura et al., 2022; Sumaila et al., 2014). These issues put employment, food security in the WIO region at risk, as coastal communities in the region rely heavily on marine and coastal resources for their subsistence and livelihoods.

2.2 Literature Search and Review

The report was developed through a review of both published and unpublished documents of OA in the WIO region. A web search was conducted using two databases: Web of Science (WoS) and African Journals Online (AJOL) with the keyword OA. For WoS, the search was restricted to countries within the WIO region, including Somalia, Tanzania, Kenya, Mozambique, South Africa, Seychelles, Mauritius, Madagascar, Comoros and Somalia. Réunion (France) was excluded from the literature search due to the language barrier, as any publications from the region may be in French. The same keyword was used for AJOL (Figure 4). The search yielded 102 records from WoS and 6 from AJOL (Figure 4). After thoroughly screening the document titles and abstracts, only 25 records that focused specifically on OA within the WIO region were selected.

These studies met the inclusion criteria, ensuring that the research was relevant to the geographic area of interest and directly addressed OA. The selection process prioritized studies with a clear connection to the WIO, filtering out those that were not region-specific or did not focus on OA. Additionally, two theses and three reports from the WIO region, bringing the total number of documents for full-text review to 30 (Figure 4). To assess the current state of OA knowledge in the WIO, key details were extracted from relevant documents, including the document type (journal article, book chapter, thesis), publication year, study location, study type (modeling, experiments, observations, socio-economic research, or reviews), habitat studied (coral reef, mangrove, seagrass meadows, open ocean, estuaries), species studied (fish, shellfish/gastropods, fouling communities, calcareous algae, crustaceans), OA indicators measured, and specific study site locations.

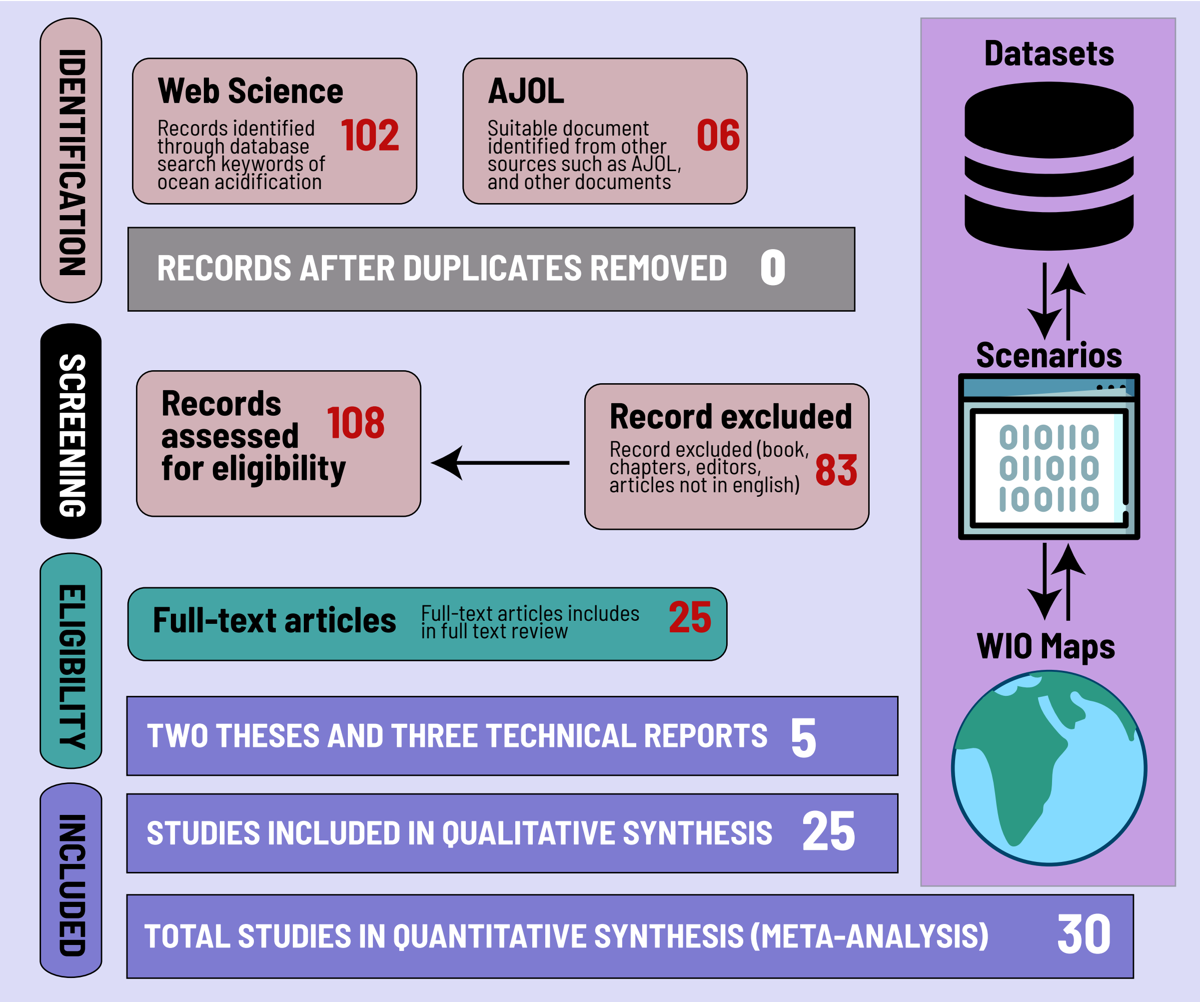

Figure 4: Conceptual framework for literature review and global dataset analysis of OA indicators under various SSPs.

2.3 Trends of OA Indicators in the WIO

2.3.1 Data Source

Due to the short-term and inconsistent nature of monitoring data for OA indicators in the WIO region, it is not possible to determine reliable trends, which require long-term data. To address this challenge, we have opted to use global datasets from the National Centers for Environmental Information at National Oceanic and Oceanographic Authority (NOAA) to compute OA trends in the WIO. These datasets include historical simulations covering 164 years, from 1850 to 2014. The modelled data used in this study were accessed at this link.

2.3.2 A Comparative Analysis of Shared Socioeconomic Pathways

In this review, four scenarios of Shared Socioeconomic Pathways (SSPs) shown in Table 1 were applied. These scenario represent a range of potential future social and economic conditions for the WIO countries to analyze trends in selected OA indicators, using the framework developed by Riahi et al. (2017) for the period from 2015 to 2100. The scenarios include SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, each reflecting different pathways for emissions and global development. SSP1-2.6 reflects sustainable development with low emissions, while SSP2-4.5 follows a "middle of the road" path that extends current global development trends, resulting in moderate radiative forcing by the end of the century.

SSP3-7.0, marked by regional rivalry, predicts a rise in nationalism and conflicts, leading to higher emissions as global cooperation weakens. This scenario also features increased aerosol and methane emissions due to declining forest coverage and expanding pasture lands. In contrast, SSP5-8.5 assumes a future with high fossil fuel use and extremely high CO_2 emissions, a decline in aerosols, and rising methane concentrations. The year 2050 was chosen for each scenario, aligning with the timeframe of climate change strategies adopted by most WIO countries. This timeframe allows for a meaningful assessment of potential impacts under varying development and emission pathways. The selection of OA indicators was based on available measured data from the WIO region, ensuring relevance to local conditions.

Table 1: Summary of Shared Socioeconomic Pathways (SSPs) applied to WIO countries for OA indicator trends from 2020-2100.

	Scenario Overview		
Scenario	Description	Key Characteristics	Emissions Path
SSP1-2.6	Sustainable Development	Low emissions, global cooperation, focus on sustainability	Low CO_2 emissions
SSP2-4.5	Middle of the Road	Moderate emissions; current trends in global development continue	Moderate CO_2 emission
SSP3-7.0	Regional Rivalry	Rise in nationalism, conflicts, weakened global cooperation, increasing aerosol and methane emissions	High CO_2 emissions, deforestation, and pasture expansion
SSP5-8.5	Fossil-Fueled Development	High fossil fuel use, very high CO_2 emissions, declining aerosols, increasing methane emissions	Extremely high CO_2 emissions

3 RESULTS AND DISCUSSION

3.1 The State of OA Knowledge in the WIO

The available documents related to OA in the WIO region are predominantly composed of journal articles, which account for 83.3% with 25 documents (Figure 5). This is followed by the report, which accounts for 10% with three documents (WIOMSA, 2022a; WIOMSA, 2022b; WIOMSA, 2024) and the remaining 6.7% are theses with two documents (Figure 5 a). The large proportion of journal articles suggests a strong research focus on scientific analysis and peer-reviewed studies in the region, providing credible, detailed insights into OA and its impacts. However, the number of published articles from the WIO region is significantly lower compared to other regions globally, contributing very little to the global database of OA research (Yang et al., 2024). The majority of study sites with archived data are located in the North Atlantic Ocean, North Pacific Ocean, South Pacific Ocean, and Mediterranean Sea, while the Indian Ocean, including WIO, remain relatively underrepresented (Figure 5 b). These results highlight a significant imbalance in global OA research, underscoring the need for increased efforts, particularly in the WIO region, to address this gap and improve the situation.

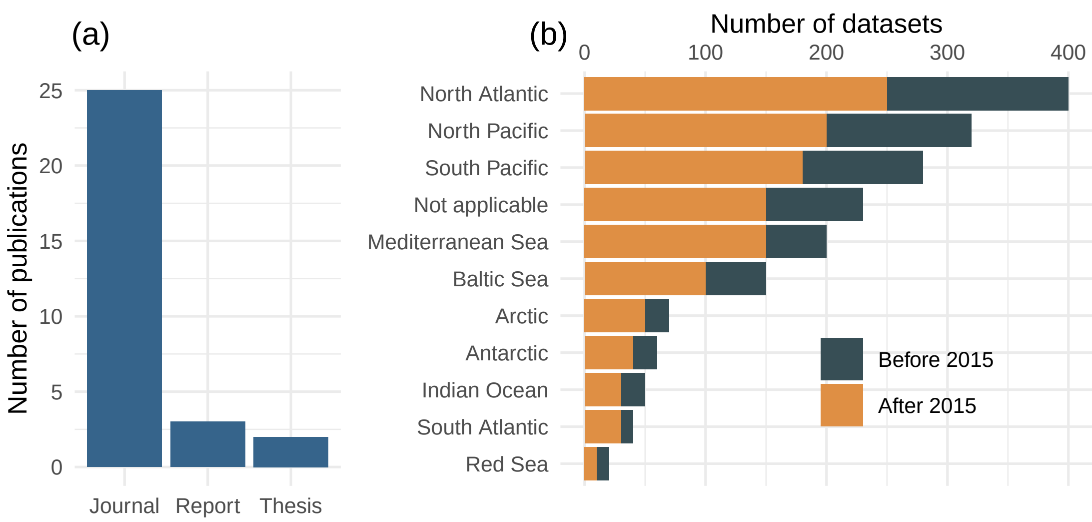

Figure 5: a) The number of document type of the available OA information in the WIO region, b) Geographical distribution of datasets included in the Ocean Acidification International Coordination Centre (OAICC) data compilation, compared to those archived before 2015.

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 the way, 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, with a predominant focus on a temperate region. This highlights a significant knowledge gap regarding the response 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. There is a complete absence of OA data and information for both Somalia and Comoros.

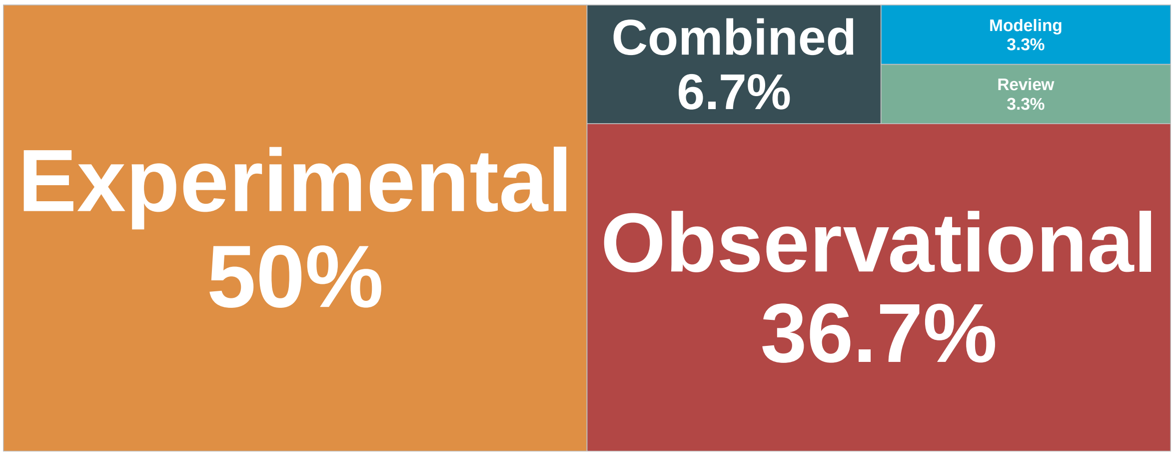

Figure 6: Share of OA in the WIO by study type.

Together, these findings indicate a significant limitation in OA knowledge within the WIO region. Most countries lack comprehensive OA data and information, and the available data are heavily concentrated in certain countries, such as South Africa, lacking geographical representation. While WIOMSA established a regional working group on OA in 2019, involving six WIO countries, this initiative contributed to advancing OA knowledge in the region (WIOMSA, 2022b). It helped to establish a baseline for developing an integrated science strategy for OA monitoring and impact assessment in the region. However, the lack of continued funding beyond the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO) project in 2022 has hindered ongoing OA monitoring efforts in most countries.

The scarcity of OA data and information, particularly in many WIO countries, underscores the urgent need for expanded OA research in the region. By increasing research efforts in experimental, observational, and modeling studies, they could help develop a comprehensive understanding of the status and trends of OA, along with its associated impacts in the region. This knowledge will be essential for informing effective mitigation and adaptation strategies in the WIO region.

3.2 Status and Trends of OA

The current state of ocean pH reflects an ongoing trend of acidification, driven by the absorption of atmospheric carbon dioxide (CO_2). Since the late 1980s, the average global surface ocean pH has been decreasing by approximately 0.017 to 0.027 units per decade. This decline is primarily attributed to the uptake of CO_2, which forms carbonic acid when dissolved in seawater, thus lowering pH levels. In particular, coastal waters are subject to more pronounced acidification (Figure 7) due to a combination of natural processes (e.g., freshwater inflows, biological activity) and anthropogenic influences (e.g., agricultural runoff and industrial nutrient input). While some regions, particularly the open ocean, have been well-monitored, gaps remain in long-term observations in coastal areas, limiting the full understanding of acidification's impact.

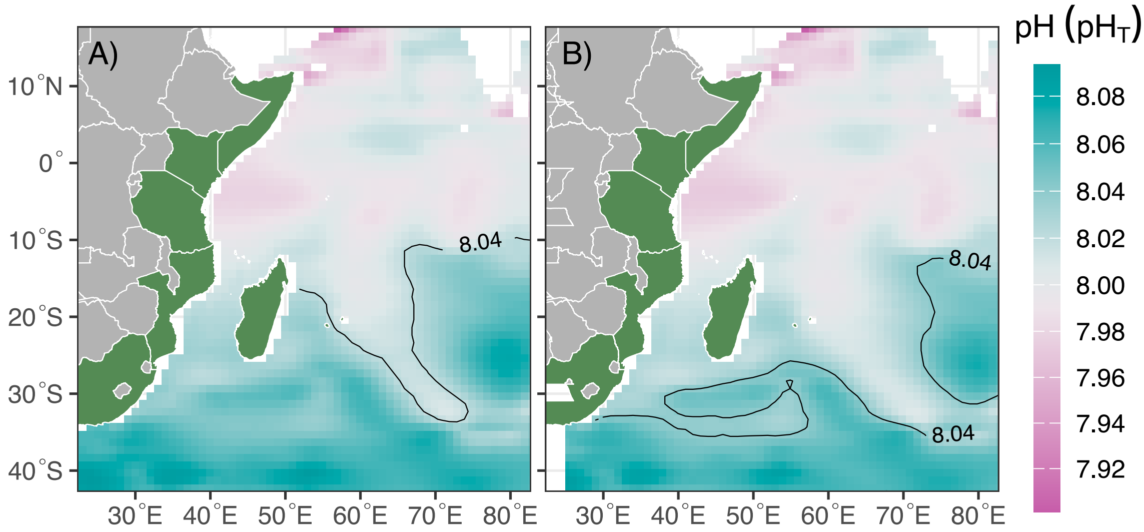

Figure 7: The spatial distribution of pH across the WIO region for a) 2020 and b) 2030.

3.2.1 State of OA in the WIO

Table 2 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. Average pH levels in the open waters of the WIO countries are between 8.0 and 8.1, a decrease from pre-industrial levels of around 8.2, indicating the region is experiencing OA. However, the lack of observational studies in many WIO countries prevented documentation of OA indicator status in those countries (Table 2).

Table 2: Status of OA indicators in selected open ocean environemnet within the WIO region. The reference source(s) for each data point is also included.

Indicator	WIO Countries					
	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±131.41 (Job, 2022)	396–435 (WIOMSA, 2022b)	993±268 (OA Report 2022)	-	1673.48±28.32 (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)

Daily mean pH in coastal waters varies significantly depending on habitat type (George and Lugendo, 2022). Seagrass habitats generally exhibit higher pH and dissolved oxygen (DO) levels compared to adjacent mangrove and coral reef habitats. Upwelling regions, such as the Tanga-Pemba Seascape in Tanzania (George et al., 2024) and the northern KwaZulu-Natal Bight in South Africa (Roberts and Nieuwenhuys, 2016), are experiencing significant fluctuations in pH, temperature, and DO. pH and DO levels during upwelling events drop to 7.6, which aligns with the conditions predicted for future OA scenarios by the year 2100. As a result, these areas are particularly vulnerable to OA impacts and require special conservation attention. More efforts are needed to identify OA hotspots within the WIO region.

3.2.2 Trends of OA in the WIO

The absence of long-term monitoring data on OA in WIO countries has prevented the ability to discern trends in OA indicators using regional raw data. Consequently, the trends presented for selected OA indicators are derived from a global dataset that includes the WIO region (Figure 8). However, this approach has limitations, as it may not fully reflect the actual conditions observed in raw data from within the WIO region itself. Nonetheless, it remains the best available dataset for describing the trends of OA indicators in the region over time and space across different scenarios of SSPs. Figure 8 shows that a) $_fCO_2$, pH, aragonite saturation state, DIC, and temperature significantly change over time in the WIO region, with more pronounced changes under higher carbon emission scenarios.

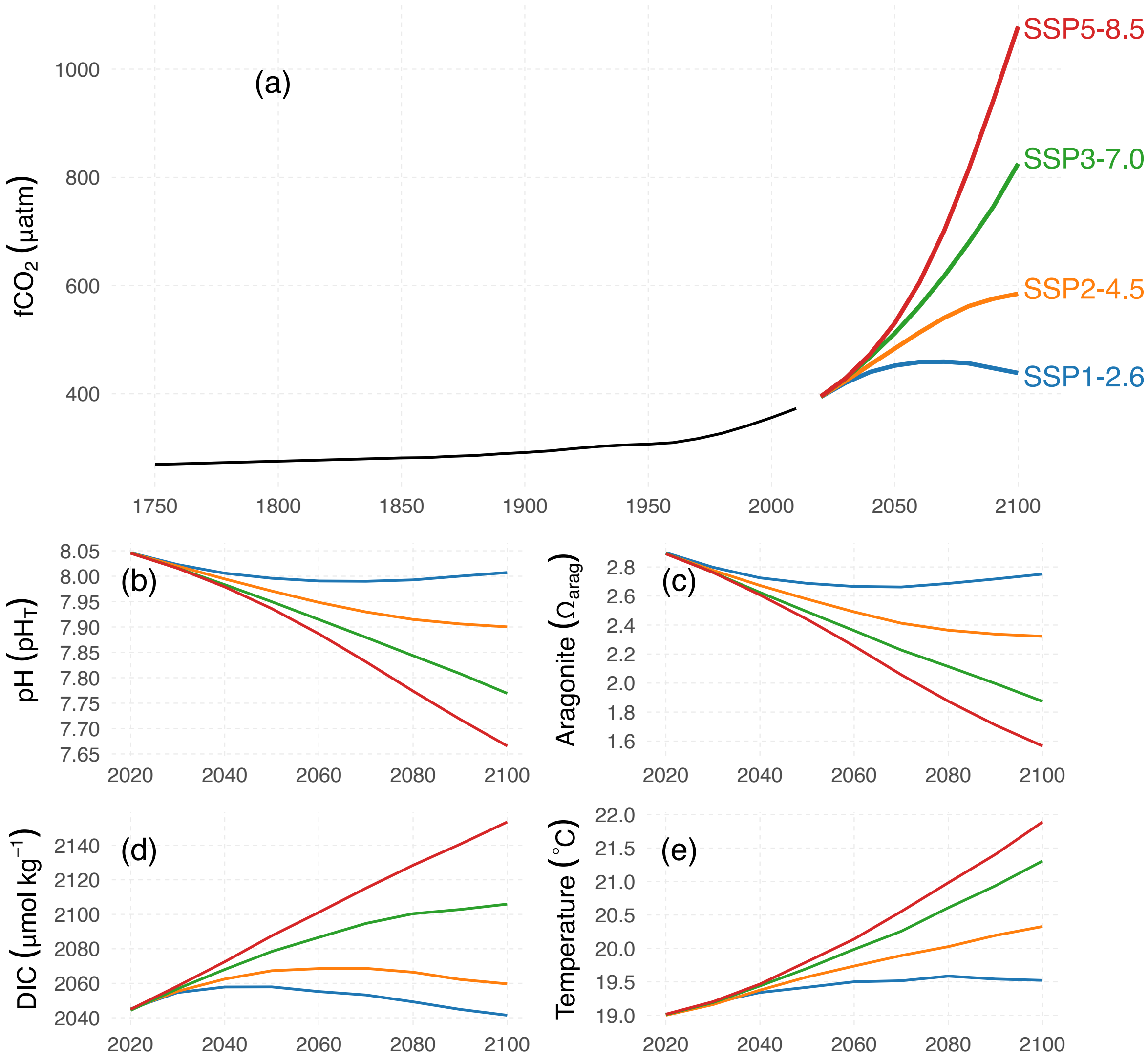

Figure 8: Trends in OA indicators for the WIO region under various SSP scenarios, including (a) fugacity of carbon dioxide ($_fCO_2$), (b) pH, (c) aragonite saturation state, (d) Dissolved Inorganic Carbon (DIC), and (e) temperature.

The fugacity of CO_2 increased from 2030 to 2100 across all SSPs (Figure 9), with the smallest increase observed in SSP1-2.6 and the largest in SSP5-8.5. This trend indicates that SSP5-8.5 will result in the most substantial rise in CO_2 fugacity, leading to a more pronounced increase in OA and its impacts in the WIO region

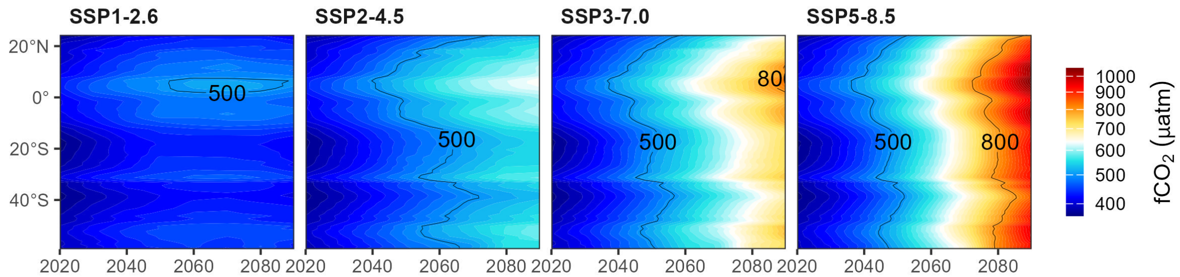

Figure 9: CO_2 fugacity trends in the WIO region across various SSPs.

Between 2030 and 2100, pH (pH_T) levels decreased across all SSP scenarios, with the smallest reduction in SSP1-2.6 and the largest in SSP5-8.5 (Figure 10). In the SSP1-2.6 scenario, a slight decline is expected, with pH dropping from the current 8.1 to 8.01. Conversely, under SSP5-8.5, the reduction is much more pronounced, with pH falling from 8.1 to 7.67 (Figure 9). This trend highlights the increasing severity of OA CO_2 emissions rise.

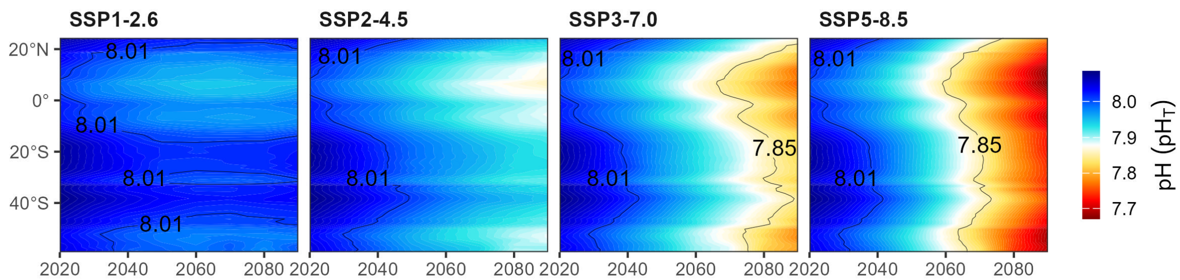

Figure 10: pH trends in the WIO region across various SSPs.

DIC increased from 2030 to 2100 across all SSP scenarios (Figure 11), with the lowest levels seen in SSP1-2.6 and the highest in SSP5-8.5. The southern part of the WIO region experienced a faster rate of increase compared to the northern part. This accelerated rise in the southern WIO is linked to lower temperatures in the region (Figure 13), which enhance the absorption rate of CO_2 in seawater.

The Arag showed a consistent decline from 2020 to 2100 across all SSP scenarios in the WIO region (Figure 12). By 2100, this decline varied significantly depending on the SSP scenario. SSP1-2.6, experienced only a minor decrease in aragonite saturation, while SSP3-7.0 and SSP5-8.5, showed a much more pronounced decline. This suggests that under higher emission scenarios, the WIO region becomes increasingly undersaturated with aragonite, particularly in the southern part. Interestingly, even under SSP1-2.6, lower aragonite saturation levels were observed in the southern WIO, with the northern side maintaining higher levels. However,

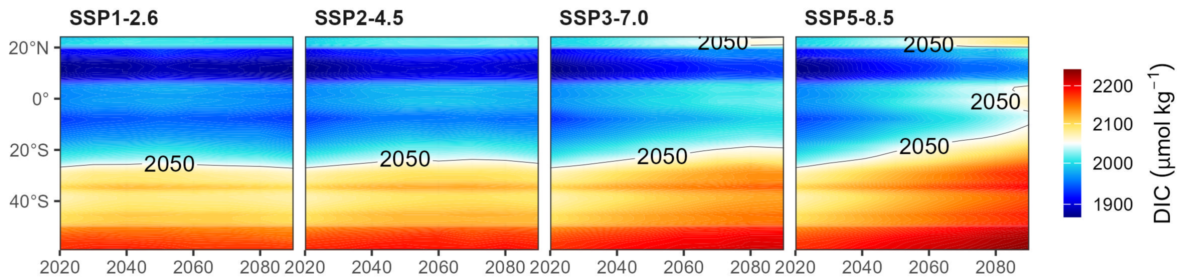

Figure 11: DIC trends in the WIO region across various SSPs.

under SSP2-4.5, SSP3-7.0, and SSP5-8.5, the zone of lower aragonite saturation expanded from the southern WIO to the northern regions, indicating a broader geographic spread of the impacts in these more severe carbon emission scenarios. Arag levels below 1 are critical, as they no longer support calcification processes and instead trigger the dissolution of calcium carbonate structures, posing a serious threat to marine organisms that rely on calcification for their skeletal development (Kroeker et al., 2013).

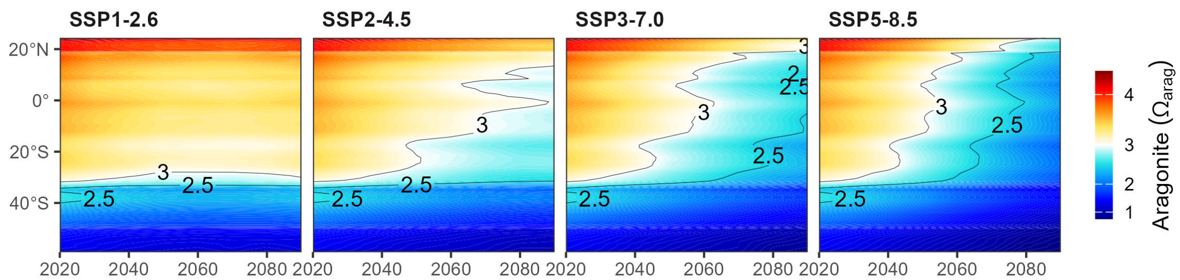

Figure 12: Arag trends in the WIO region across various SSPs.

Temperature increased from 2030 to 2100 across all SSPs, indicating ocean warming in the WIO (Figure 13). The smallest temperature increase occurred under SSP1-2.6, while SSP5-8.5 showed the largest increase. This contrast highlights the influence of different carbon emission pathways on global temperatures, with more extreme warming associated with higher emissions. The effects of rising temperatures, such as coral bleaching, are expected to be more severe in the northern WIO compared to the southern region, as temperatures have reached the critical threshold of 31°C for most tropical corals across all scenarios of SSPs.

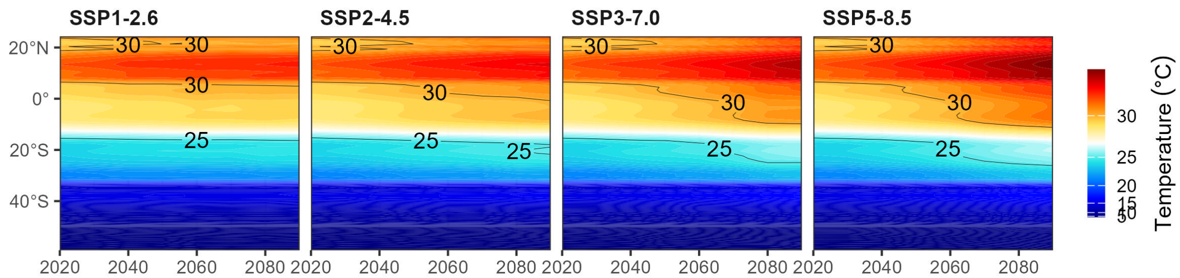

Figure 13: Temperature trends in the WIO region across various SSPs.

3.3 OA Impacts on 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 state (Cornwall et al., 2023). These effects can be intensified by additional climate change stressors such as warming and deoxygenation (Kroeker et al., 2023; Kroeker et al., 2013). However, the response of marine organisms and ecosystems to these stressors depends on their adaptive capacity (Foo and Byrne, 2016). The following subsections explore the potential impacts of OA on marine environments and food security in the WIO region, based on findings of experimental studies primarily conducted in this region.

3.3.1 OA Impacts on 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). Species like corals, shellfish, crabs, mussels, gastropods, certain plankton species, and many others form hard calcium carbonate shells or skeletons through calcification, a process highly sensitive to changes in calcite and aragonite saturation states (Semesi et al., 2009b). pH reduction decreases carbonate ions availability, disrupting calcification, which impairs growth and development and increases vulnerability to disease and depredation of affected organisms (Doney et al., 2020; Kroeker et al., 2013).

When calcite and aragonite saturation states drop below 1, calcification ceases, and the dissolution of existing shells and skeletons begins (Kroeker et al., 2013). This can lead to devastating impacts on marine organisms and ecosystems, resulting in the loss of critical ecosystem services they provide (Cornwall et al., 2023; Kroeker et al., 2013; Lutier et al., 2022). Table 3 presents potential impacts of OA on marine organisms in the WIO. 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 3: 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)
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)

The impacts of OA on marine organisms can have cascading effects on marine ecosystems (Doney et al., 2020; Kroeker et al., 2013). Reduced coral growth and weakened skeletons (which are more susceptible to breakage due to strong waves) can hinder coral reef development and the provision of associated ecosystem services (Andersson and Gledhill, 2013). The loss of coral reefs can have a significant impact on the availability, presence, and abundance of reef fish (Samoilys et al., 2022), supporting more than 70% of artisanal fisheries (Samoilys et al., 2022). For example, the significant loss of coral reefs in Papua New Guinea resulted in a 75% reduction in reef fish populations and the extinction of some fish species (Jones et al., 2019). Reduced larval production, altered dispersal patterns, and changes in gene flow, which can result from affected marine organisms, can impact recruitment, population replenishment, and species persistence (Doney et al., 2020; Kroeker et al., 2013). These changes may lead to significant shifts in ecosystem community structure and their associated socioeconomic values.

3.3.2 OA Impacts on Food Security

OA threatens the development of the fisheries sector, vital to food security in the WIO Region (Sumaila et al., 2014). OA directly impacts foundation species like corals, compromising reef health and 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 threaten 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, oysters, and sea cucumbers often used in agriculture are highly vulnerable to OA. For instance, an experimental study on rock oysters (*Saccostrea cucullata*) in Mozambique showed that reduced pH levels decreased fertilization success of this species. Similarly, future pH conditions of 7.7 and 7.4 negatively affected the growth of two sea cucumbers (*Holothuria scabra*) from Madagascar, further jeopardizing aquaculture production in the country.

3.3.3 Future Impacts of OA under Different Emissions Scenarios

Future OA conditions under the SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios (Figures 8-13) are expected to severely affect marine organisms, ecosystems, and the services they provide, such as fisheries, agriculture and coastal protection. These impacts could undermine food security in the WIO region. The severity of these impacts will largely be determined by the SSP pathway adopted in the region. Under SSP1-2.6, the effects are expected to be minimal, while under SSP5-8.5, the impacts will be severe, posing potential threats to ecosystem services and food security in the WIO region.

4 CONCLUSIONS and RECOMMENDATIONS

4.1 Conclusions

Based on the findings of this review, the following conclusions were drawn:

- OA knowledge in the WIO region is limited, with a significant lack of data and information available for most countries. Even the available OA information is heavily skewed, with South Africa contributing a disproportionate share of published articles.
- OA monitoring programs in WIO countries are currently limited and only cover a subset of OA indicators, leaving many key aspects undetermined. This narrow focus hinders a comprehensive understanding of OA and its impacts within the WIO region.
- The average pH levels in the open ocean of WIO have decreased from pre-industrial levels of approximately 8.2 to between 8.0 and 8.1, indicating that the region is experiencing OA.
- OA in the coastal waters of the WIO is influenced by a variety of drivers. These include biogeochemical processes such as calcification, photosynthesis, and respiration, as well as freshwater inputs and underground discharges, upwelling, land-based pollution, and sewage discharge.
- Declines in pH and carbonate mineral saturation states, as well as changes in other OA indicators, are projected to range from minimal under SSP1-2.6 to maximal under SSP5-8.5.
- To mitigate the impacts of OA in the WIO, intervention efforts should prioritize meeting the SSP1-2.6 climate goals. Achieving these goals is expected to result in minimal OA impacts and could help support the survival of marine organisms, ecosystems, and the ecosystem services they provide.
- A wide range of marine organisms and ecosystems in the WIO are vulnerable to the detrimental effects of OA, particularly when exposed to lower pH levels and reduced carbonate mineral saturation states. These impacts can be further intensified when combined with other climate change-related stressors, such as warming and deoxygenation, as well as local factors like pollution, seagrass habitat loss, freshwater influx during heavy rains and flooding events, and sewage discharge. However, the resilience of affected organisms to these stressors, whether individually or in combination, will depend on their ability to adapt.
- Given that the WIO region relies heavily on marine and coastal resources for substance and livelihoods, the potential impacts of OA on fisheries and aquaculture could significantly compromise food security in the region.

4.2 Recommendations

Based on the findings of this review, the following recommendations are proposed for the WIO region to improve understanding of OA, enhance its capacity to address its impacts, and promote sustainable development in the context of climate change.

4.2.1 Enhance OA Research and Monitoring Program

This can be achieved through the following actions:

- Continue and expand monitoring of OA indicators at existing sites to build long-term datasets. This will improve understanding of OA and allow future predictions of OA indicators across the WIO region;
- Enhance research efforts by prioritizing experimental studies to better understand the impacts of OA on marine organisms, especially those targeted for agriculture in the WIO region;
- Increase funding and support for OA research across the WIO region, with a focus on WIO countries that currently lack data and information on OA. This would not only enhance our understanding of OA but also ensure the sustainability of ongoing OA monitoring programs, which often face challenges due to limited funding after initial implementation.
- Promote collaborative research efforts to address the data gap and strengthen OA research capacity among WIO countries;
- Develop and implement standardized monitoring protocols to ensure consistency and comparability of data across different WIO countries.
- Establish a regional OA working group in the WIO to facilitate the sharing of knowledge, resources, and best practices related to OA research and monitoring;
- Establish regional networks or platforms to facilitate data sharing and joint research initiatives; and;
- Engage with international organizations and research institutions to support OA research and capacity building in the WIO region.

4.2.2 Promote Mitigation Strategies

This can be achieved through the following actions:

- Advocate for and support national initiatives to achieve the SSP1-2.6 climate goals, which are associated with minimal impacts on OA. This involves implementing policies and strategies aligned with the Paris Agreement to reduce emissions and mitigate climate

change and ensuring these policies are integrated into broader climate change and sustainable development frameworks; and;
- Adopt nature-based solutions to protect and restore vital habitats, such as mangroves and seagrass meadows, which are significant carbon sinks.

4.2.3 Address Food Security Concerns

This can be achieved through the following actions:

- Assess the potential impacts of OA on fisheries and aquaculture and develop strategies to ensure the resilience and sustainability of these industries in a changing ocean;
- Support community-based initiatives and adaptive management approaches that help mitigate the impacts of OA on livelihoods and local food security;
- Encourage sustainable fishing practices, aquaculture, and coastal development to minimize human-induced stressors on marine habitats; and;
- Ensure that policies related to fisheries, aquaculture, coastal development, and climate change are aligned to address OA effectively.

4.2.4 Build Capacity and Awareness

This can be achieved through the following actions:

- Conduct trainings to equip local communities, researchers, and policymakers with the knowledge and skills needed to address OA impacts;
- Raise public awareness about OA and its impacts on marine organisms, ecosystems and livelihoods; and;
- Provide technical support to WIO countries to strengthen their capacity for OA research, monitoring, and mitigation.

4.2.5 Develop and Implement OA Action Plan in the WIO Region

Developing a regional action plan for OA in the WIO is crucial for coordinating and implementing collective responses among WIO countries. This action plan will serve as a comprehensive framework for implementing joint initiatives across the region, facilitating collaborative monitoring, assessment, and mitigation of OA impacts.

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APPENDIX

Appendix A

Table 4 shows projections for several OA indicators across three years (2030, 2050, 2100) under four different scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-8.5). The indicators include Aragonite saturation (Arag), Dissolved Inorganic Carbon (DIC), temperature, surface ocean CO_2 flux ($_fCO_2$), and total pH (pH_T). For each indicator, the table displays corresponding values for the specified years and scenarios, allowing comparison of how these OA indicators change over time under different emission pathways.

Table 4: Median values for selected Ocean OA in the Western Indian Ocean region for 2030, 2050 and 2100 under four Shared Socioeconomic Pathways (SSPs).

		Shared Socioeconomic Pathways			
Year	Parameters	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP4-8.5
2030	Arag	2.8	2.8	2.8	2.8
2050		2.7	2.6	2.5	2.4
2100		2.8	2.3	1.9	1.6
2030	DIC	2054.7	2055.4	2056.9	2058.5
2050		2057.9	2067.3	2078.5	2087.6
2100		2041.5	2059.7	2105.9	2153.5
2030	Temperature	19.2	19.2	19.2	19.2
2050		19.4	19.6	19.7	19.8
2100		19.5	20.3	21.3	21.9
2030	fco2	420.2	423.4	428.3	428.5
2050		452.2	483.7	511.9	530.8
2100		438.5	584.8	825.4	1078.8
2030	pHt	8.0	8.0	8.0	8.0
2050		8.0	8.0	7.9	7.9
2100		8.0	7.9	7.8	7.7

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