Selected Perspectives on Ocean Acidification


Bubbles from the CO2 vent field at Ischia Island in the Bay of Naples, Source: (J. a. Hall-Spencer 2009)

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About the Research Paper

The multifaceted aspects of the Blue Economy sector are gaining attention from policymakers due to the vast untapped potential of the world's oceans and seas. The oceans are the next great economic frontiers. The marine ecosystems are more efficient and productive when they are healthy. However, the earth's resources are limited and the unsustainable production and consumption of earth resources are damaging the planet. Furthermore, pollution, unsustainable fishing, habitat destruction etc. harm marine life and are increasing day by day. The present research paper on "Selected Perspectives on Ocean Acidification" will act as a useful resource material for the planning and execution of audits related to Ocean Acidification. The research paper will guide the auditors in systematically gathering, analysing, and documenting data, as well as collecting essential audit evidence on Ocean Acidification. Additionally, the paper may serve as a valuable resource for the policymakers and researchers actively engaged in the evolving field of Ocean Acidification in India.

This research paper is a part of the Occasional Research Paper Series, with a special focus on Blue Economy sectors and marks iCED's new role as a Centre of Excellence on the Audit of the Blue Economy.

Feedback

We strive for constant improvement and encourage our readers to provide their valuable feedback/suggestions. Please send us your suggestions and comments about this Research Paper to **iced@cag.gov.in.**

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Declaration by the Research Associate

I, **Dr. Mahesh Kumar Saini,** hereby declare that the Research Paper titled **"Selected Perspectives on Ocean Acidification"** submitted to iCED, Jaipur is my own work and no part of it has been published anywhere else in the past. The facts, tables, figures and sources given in the paper are true, authentic and attributed properly to the best of my knowledge.

I concur with the modifications/corrections carried out during the report evaluation based on inputs provided by me.

21st March, 2024

(Dr. Mahesh Kumar Saini)
Research Associate, iCED

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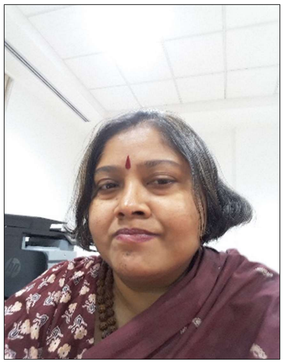
Foreword



The "Blue Economy" refers to a wide range of economic activities and sectors that are directly or indirectly related to the ocean. In recent times, the multifaceted aspects of the Blue Economy have gained special focus projecting its importance with respect to providing useful resources to the people.

These resources from the oceans, seas and coastal areas contribute to food security and poverty eradication. And yet, the oceans are under severe threat by anthropogenic activities, where economic benefits are aimed at the expense of environmental degradation. Ocean acidification, pollution, ocean warming, eutrophication and fisheries' depletion are some examples of the detrimental consequences of Climate Change and human interventions encountered by the marine ecosystems. These threats pose substantive risks to planet Earth and require immediate action to safeguard the ocean resources to enable their sustainable utilisation. Countries with long coastlines and oceanic islands are more susceptible to the consequences of environmental degradation. This is due to the fact that a significant portion of their population relies on the resources obtained from the oceans, seas, and coastal areas. According to Regional Information Centre for Western Europe (UN), 40 per cent of the world's population lives near coastal areas with approximately 3 billion people utilising the oceans for their livelihood. Maintaining the health of this vital ecosystem is of paramount importance (UN, 2022), therefore.

Our oceans also play the role of Carbon Sequesters, acting like huge sponge capturing, absorbing and storing atmospheric carbon dioxide units. This is how the oceans contribute towards reducing the impact of global warming and Climate Change. However, increased concentration of carbon dioxide in the ocean water leads to acidification of the oceans, which has several adverse impacts on the marine ecosystem. Ocean Acidification is often called "Climate Change's evil twin" and is projected to grow as carbon dioxide continues to be emitted into the atmosphere due to humans' anthropogenic activities.

The need of the hour is to understand the significance of our oceans and the adverse effects of Ocean Acidification on marine life and sectors that are socially and economically dependent on the oceans. India is home to a wide variety of marine life, including many species that are important for food security, livelihoods, and tourism.

The current situation calls for achieving a balance between economic and environmental concerns by focusing on cost-competitive, technology-driven environmentally sustainable solutions.

Thus, Honourable Comptroller and Auditor General of India, Shri Girish Chandra Murmu has designated iCED as a Centre of Excellence on Audit of the Blue Economy during SAI India's stellar Presidentship of the SAI20 in 2023. ICED seeks to contribute another vital resource on this subject in continuation of our earlier Specialised Papers on the Blue Economy viz. Sustainable Livelihood and Gender Equity in the Development of the Blue Economy with a Special Focus on Marine Fisheries, Use of Remote Sensing; GIS, DPSIR Framework and SWOT Analysis for Impact Assessment of Marine Renewable Energy Sector with a Focus on Floating Solar Photovoltaic Systems in India, and Marine Energy Resources: Some Perspectives for Planning Audits. This Research Paper on "Selected Perspectives on Ocean Acidification" is an outcome of iCED's continued vigorous and innovative efforts in research relating to various aspects of Climate Change-related factors in the Blue Economy.

Managing the inchoate and non-quantifiability of the sector is a challenge. In this context, it is hoped that this paper will be useful for the readers in giving them a first-hand idea of estimating Ocean Acidification in coastal regions and identifying the vulnerability of Ocean Acidification for the coastal regions. This approach will also empower auditors to prioritise crucial responsibilities and effectively communicate audit findings grounded to a greater extent in scientific precepts instead of abstract generalisations.

It is indeed very encouraging that this Research Paper has been developed by iCED's Research Associate, Dr. Mahesh Kumar Saini, in cooperation with the research team in iCED, and for this, I would like to congratulate the author Dr. Mahesh Kumar Saini, Research Associate. Incidentally, this is the 4th Research Paper on the Blue Economy under the Occasional Research Paper Series (ORPs), initiated in May-June 2022 at iCED and the 20th Paper in the entire research series at iCED.

I hope that, this Research Paper will be helpful for the auditing fraternity in reviewing the existing issues relating to Ocean Acidification and developing further auditing tools and techniques to sharpen auditing of this hitherto unexplored area. iCED hopes to continue developing ORPs, on related topics in Blue Economy in the upcoming months too. Feedback and suggestions are enthusiastically requested for, so that iCED can further enhance its research orientation in its challenging and intellectually stimulating journey of emerging as a Centre of Excellence on the Audit of the Blue Economy.

21st March 2024
Jaipur

(Ms. Sayantani Jafa)
Additional Deputy C&AG and Director General,
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Message from the Director (Training and Research)

Ocean Acidification is a serious threat to the marine environment, economy, and food security. It could have a devastating impact on fisheries, aquaculture, tourism, and coastal communities. Due to its extensive coastline and expansive Exclusive Economic Zone (EEZ), India is especially susceptible to the impacts of Ocean Acidification. India also has a large and growing coastal population, which relies heavily on resources obtained from the ocean.

There is an urgent need for us to address the threat of Ocean Acidification. This could include reducing greenhouse gas emissions, investing in marine research and development, and developing adaptation strategies for coastal communities.

This paper on Ocean Acidification has been developed to provide a fresh perspective and approach to assess the status of Ocean Acidification in the coastal areas of India, using satellite-based GIS data and analysis, with the help of the Quantum Geographic Information System (QGIS) software, which helped us understand the trend in Ocean Acidification and link them to plausible impacts on different sectors of Blue Economy.

This research paper is a valuable resource for anyone working to understand and mitigate the impacts of Ocean Acidification. It can be used by auditors, governments, businesses, and communities to understand different aspects of Ocean Acidification and take corrective measures.

I am sincerely grateful to Ms. Sayantani Jafa, Additional Deputy Comptroller and Auditor General and Director General, iCED, for her visionary leadership and constant encouragement during the development of this paper. I would also like to acknowledge the contributions of all those who directly or indirectly made this paper possible. I believe that this Occasional Research Paper will be a valuable resource for direct assessment of Ocean Acidification, which can be used at various stages of audits.

21st March, 2024
Jaipur

(Dr. Nanda Dulal Das)
Director (Training and Research), iCED

Abstract

Ocean Acidification poses a significant threat to both marine ecosystems and human communities. This study focuses on India's extensive coastline, emphasising the critical role it plays in supporting marine and coastal biodiversity and the well-being of its people. The research presents an in-depth analysis of Ocean Acidification levels across 66 selected beaches by developing some perspectives of auditing of Ocean Acidification.

This Paper calculates a composite value based on selected indicators such as Sea Surface Temperature (SST), Particulate Inorganic Carbon (PIC), Particulate Organic Carbon, Dissolved Oxygen (DO), and salinity. The Composite Index is used to rank beaches in terms of their Ocean Acidification levels. The study found Tamil Nadu beaches such as Mullakadu (66.08), Thiruvanmiyur (66.12), Muthunagar (65.06), Marina (64.24), and Shaheed Dweep Beach (61.57) in Andaman and Nicobar have the highest composite index, while Dandi Beach (18.33) in Gujarat has the lowest composite index.

The research underscores the importance of the Ocean Acidification thematic area as a valuable resource for assessing the trends and associated impacts of Ocean Acidification. It can be used to identify risk areas and prioritise action. The framework can be replicated to assess Ocean Acidification in other regions and countries.

Furthermore, the Paper is a resource that can help auditors, policymakers, and researchers assess and monitor Ocean Acidification and their plausible impacts in coastal areas. It provides a structured approach based on specific indicators and standard methods. The goal is to give stakeholders the information they need to make informed decisions, design or amend policies, and unlock the full potential of India's coastal regions, while being aware of the threats posed by Ocean Acidification.

Auditors and stakeholders can be encouraged to use QGIS-based techniques which is used in this paper to analyse data for Ocean Acidification. This approach could enable a fresh perspective on auditing relevant sectors of the Blue Economy.

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Abbreviations

CPCB	:	Central Pollution Control Board
DO	:	Dissolved Oxygen
INCOIS	:	Indian National Centre for Ocean Information Service
INTOSAI	:	International Organisation of Supreme Audit Institutions
IOC	:	Intergovernmental Oceanographic Commission
IOGOOS	:	Indian Ocean Global Ocean Observing System
MTE	:	Ministry of Ecological Transition
NASA	:	National Aeronautics and Space Administration
NCEI	:	National Centre for Environmental Information
PIC	:	Particulate Inorganic Carbon
POC	:	Particulate Organic Carbon
QGIS	:	Quantum Geographic Information System
SDG	:	Sustainable Development Goals
SIDS	:	Small Island Developing States
SST	:	Sea Surface Temperature
UN	:	United Nations
UNFCCC	:	United Nations Framework Convention on Climate Change
WGEA	:	Working Group on Environmental Auditing

Selected Perspectives on Ocean Acidification

1. Ocean Acidification

The Earth's oceans, covering approximately 70 per cent of its surface, is essential to life on Earth. They regulate the climate, support vast biodiversity, and provide livelihoods for billions of people. However, the oceans are facing a serious threat in the form of Ocean Acidification (Currie 2009). Increasing atmospheric CO_2 levels, linked to global warming and Ocean Acidification, pose significant threats to biological systems. Human-induced changes have rapidly elevated atmospheric CO_2 concentrations, currently at 380 ppm and increasing at an alarming rate of 0.5 per cent per year (NOAA 2020, Prentice 2018).

Ocean Acidification is a continuous decrease in the pH of the ocean water, caused by the increased absorption of Carbon Dioxide (CO_2) from the atmosphere. When CO_2 dissolves in seawater, it forms carbonic acid, lowering the pH of the seawater. The pH of the oceans has decreased by about 0.1 units since the pre-industrial era, which corresponds to a 30 per cent increase in acidity. If current trends continue, the pH of the oceans could drop by another 0.3 to 0.4 units by the end of this century (UNESCO 2023, AWI 2021).

Approximately, one-third of anthropogenic CO_2 emitted in the past 200 years has been absorbed by the oceans, impacting marine biodiversity through altered seawater chemistry and pH, thereby affecting calcification rates and metabolic physiology. This phenomenon, particularly studied in tropical coral reefs and planktonic coccolithophores, raises concerns about biodiversity, trophic interactions, and ecosystem processes (Mostofa 2016).

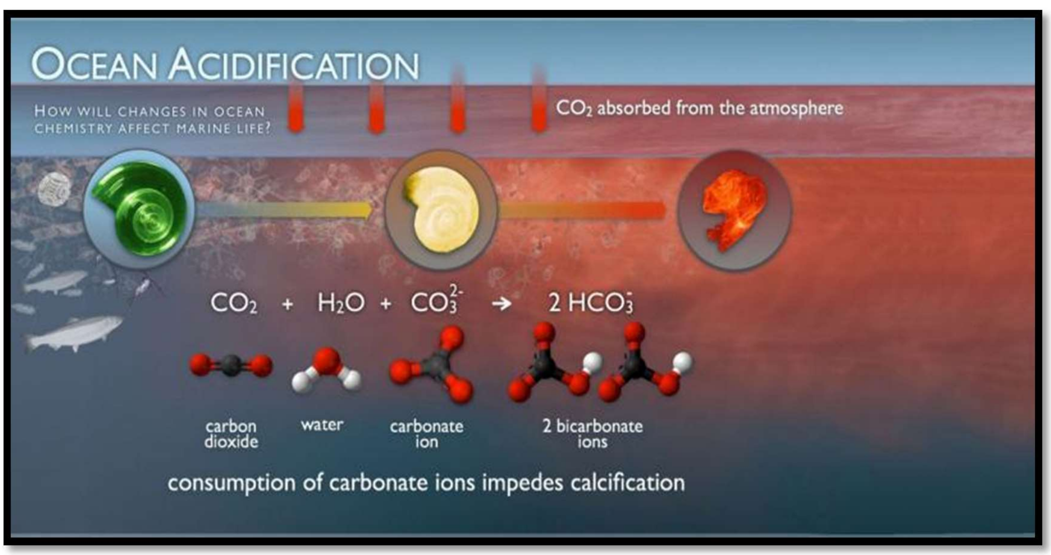


Figure 1:** Decrease in carbonate ions can make building and maintaining shells and other calcium carbonate structures difficult for calcifying organisms* ***Source: *(NOAA 2020)*

Rapid acidification is having a devastating impact on marine life. Calcifying organisms, such as corals, shellfish, and some types of plankton, are particularly vulnerable (Figure 1). These organisms rely on carbonate ions to build their shells and skeletons, but as acidity increases, carbonate availability decreases. This can lead to reduced growth, impaired reproduction, and death. Coral reefs, economically and biologically important marine ecosystems, are already threatened by increasing sea surface temperatures and associated bleaching, therefore, they face additional threats from Ocean Acidification. The Great Barrier Reef has shown a recent decline in calcification raising concerns that irreversible changes in marine ecosystems have already begun (Kimble, et al. 2009). Ocean Acidification is also disrupting the marine food web. Phytoplankton, the microscopic organisms at the base of the food web, are sensitive to changes in pH. As acidity increases, phytoplankton abundance declines, which can have cascading effects on higher-level predators (S. B. Doney 2020).

These changes in ocean chemistry can affect the behaviour of non-calcifying organisms as well. Certain fish's ability to detect predators is decreased in more acidic waters. When these organisms are at risk, the entire food web may also be at risk. Many economies are dependent on fish and shellfish and people worldwide rely on food from the ocean as their primary source of protein (NOAA, 2023).

The impacts of Ocean Acidification are not limited to the marine environment. Coastal communities are also at risk. Fisheries are also being adversely affected, as fish populations decline due to food availability and habitat changes (Hoegh-Guldberg 2017). Therefore, Ocean Acidification is a serious threat to the oceans' health and humanity's well-being. Urgent action is needed to reduce greenhouse gas emissions and mitigate the impacts of Ocean Acidification. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Approximately 20 per cent of the world’s population derives at least one-fifth of its animal protein intake from fish. Many jobs and economies around the world depend on the fish and shellfish that live in the ocean. Decline in ocean harvests can affect the most vulnerable communities particularly those in the least developed nations with limited agricultural alternatives. These challenges may influence migration to inland urban regions, which may lead to further social disruption and even conflict. Ocean Acidification reduces storm protection offered by reefs. The effects of acidification also extend to the tourism sector (NOAA n.d.). Several possible causes and consequences of Ocean Acidification are shown in Figure 2.

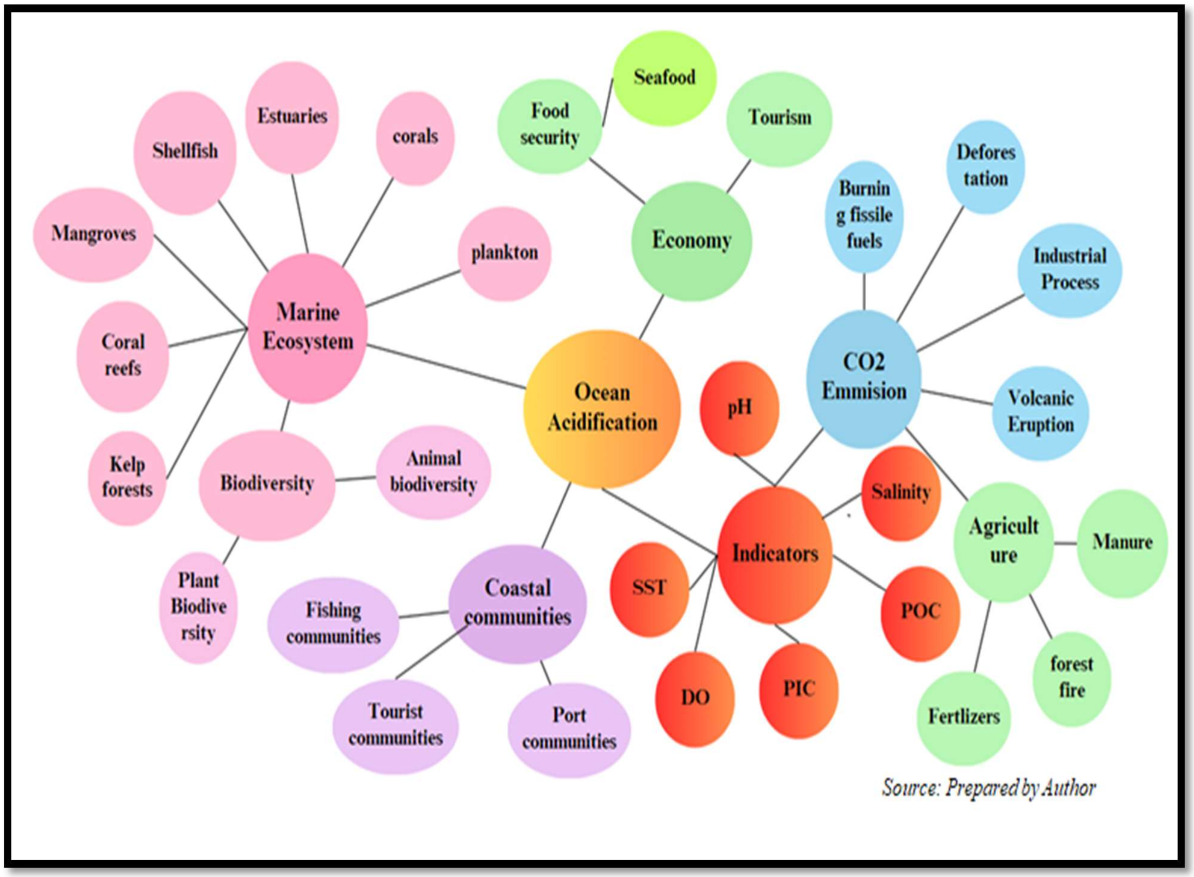


Figure 2: Causes and Impacts of Ocean Acidification

Despite progress, significant knowledge gaps persist, urging further research to understand and address the impending consequences of rising oceanic pCO_2[1] levels over the next century (Arundhathy 2021). The research paper on Ocean Acidification seeks to shed light on the environmental crisis threatening our oceans and coastal ecosystems. The intention is to provide a comprehensive understanding of the multifaceted impacts of Ocean Acidification, considering key indicators such as sea surface temperature, carbon absorption, dissolved oxygen, and salinity as discussed above. By developing a designed Ocean Acidification paper, this research endeavours to present a nuanced evaluation by offering a holistic perspective on the state of coastal and marine ecosystems.

[1] pCO_2 is the partial pressure of carbon dioxide, often used in reference to blood but also used in meteorology, climate science, oceanography, and limnology to describe the fractional pressure of CO_2 as a function of its concentration in gas or dissolved phases.

This paper offers a review of methodologies used in creating, applying, and improving composite indices, with a specific focus on their relevance in diverse initiatives to understand Ocean Acidification. Composite index depends on method of combining several variables or indicators to reflect overall assessment. Composite indices serve as statistical tools that combine various indices to create a comprehensive representation of overall sectoral performance. This study covers aspects such as exposure, mitigation, adaptive capacity, and vulnerability to Ocean Acidification.

Greyling, T, 2013 used a composite index to assess the quality of life in the Gauteng city region (Greyling, T 2013). Similar Composite Index was used by García-Sánchez, 2015 to develop a Composite Index of Environmental Performance (CIEP) tailored for countries (García-Sánchez 2015). Islam, M.M. et al. (2019), assessed Climate Change vulnerability for Bangladesh's fisheries sector using both composite index and GIS (Islam 2019).

Bandyopadhyay et al, 2009, used remote sensing GIS and Composite Index to assess the land suitability potential for agriculture (Bandyopadhyay 2009). Sahoo and Bhaskaran (2018), used a GIS-based approach for Multi-hazard risk assessment of coastal vulnerability for the Odisha coastline (Sahoo 2018).

In this study, GIS and Composite Index have been utilised to use data on selected indicators (SST, DO, PIC, POC, and Salinity), and generate a composite index to assess Ocean Acidification for the selected 66 beaches on the Indian coastline. Auditing Ocean Acidification can address achieving specific targets and indicators relating to specific SDGs, especially, **SDG 13: "Take urgent action to combat Climate Change and its impacts"**, as addressing Ocean Acidification contributes to climate action by raising awareness, integrating mitigation strategies, and building capacity to understand and address the interconnected nature of climate-related challenges and **SDG 14: "Conserve and sustainably use the oceans, seas and marine resources for sustainable development"**. Target 14.3 is especially focussed to minimise and address the impacts of ocean. As oceans are interconnected water-bodies, the global nature of Ocean Acidification requires dedicated efforts and international collaboration. By fostering partnerships, sharing knowledge, and mobilising resources, nations can collectively address the challenges posed by Ocean Acidification and work towards achieving the broader spectrum of SDGs.

In summary, addressing Ocean Acidification aligns with specific targets and indicators under **SDGs 13 and 14**. By integrating efforts to monitor, mitigate, and adapt to Ocean Acidification, countries contribute to the overall sustainable development agenda, recognising the interconnectedness of environmental, social, and economic goals.

1.1 Role of Oceans in Carbon Sequestration

The annual growth in global mean CO_2 during 1960-2015 was 399.4 parts per million (ppm) (NOAA 2016). At the present rate, Greenhouse gas emissions would reach almost 685 ppm CO_2- equivalents by 2050 (Virginie Marchal 2011). Oceans are the primary regulator of the global climate and an important sink for greenhouse gases and they provide water and oxygen. The atmospheric CO_2 levels can be stabilised by reducing Greenhouse Gas emissions and by the creation of new carbon sinks. Oceans and their constituent elements play a formidable role in carbon sequestration. Sediments act as a long-term sink for the atmospheric CO_2 captured by living biomass. Mangroves, seagrass and salt marsh sediments can store carbon for hundreds to thousands of years (UN n.d.).

Blue Carbon

Blue Carbon is simply the term used for carbon captured by world's ocean and coastal ecosystems. Blue carbon's broader perspective revolves around the conservation of coastal habitats. When these ecosystems suffer damage, a significant amount of carbon is released into the atmosphere, potentially contributing to climate change (NOAA 2023)**.**

Contribution of People to Ocean Acidification

Over the past 200 years, the world's oceans have absorbed more than 150 billion metric tonnes of carbon dioxide emitted from human activities. Worldwide, emitted CO_2, with an average of 15 pounds per person per week, is enough to fill a train long enough to encircle the equator 13 times every year. Ocean carbon dioxide concentrations are now higher than at any time during the past 800,000 years, and the current rate of increase is likely unprecedented. This increased contribution of anthropogenic CO_2 in the atmosphere accelerates the pace of Ocean Acidification (NOAA 2016).

India has significant potential for carbon sequestration, due to its large coastline, oceans, and expansive mangrove, sea-grass and salt-marsh systems, as shown in Table 1.

Table 1: Key aspects of carbon sequestration in India

Sl. No.	Potential
1.	Net C accrual of mangrove biomass is 1.69 tonnes C per hectare per year (NCSCM, 2023)
2.	A 20 per cent increase in mangrove area cover may create an additional sink of approx. 669 x 10^3 tonnes of CO_2 per year (NCSCM, 2023)
3.	Conservation and restoration of 100 ha of the degraded mangrove forest may reduce CO2 emissions of upto 144 x 103 tonnes CO2 per year (NCSCM, 2023)

4.	A 20 per cent increase in the seagrass area cover in India may create an additional sink up to approx. 82.4 x 10^3 tonnes CO_2 per year (approx.) (NCSCM, 2023)
5.	Conservation and restoration of 100 hectares of degraded seagrass may reduce CO_2 emissions of up to 52.2 x 10^3 tonnes CO_2 per year (NCSCM, 2023)
6.	Annual carbon sequestration by salt marshes in India is approx. 101 x 10 ^{3} tonnes C per year (NCSCM, 2023)

Oceans resources are increasingly threatened, degraded, or destroyed by human activities, reducing their ability to provide crucial ecosystem services, like carbon sequestration. Important classes of threats among others are Climate Change, marine pollution, unsustainable extraction of marine resources, physical alterations and destruction of marine and coastal habitats and landscapes. Ocean Acidification is a critical determinant of the health of the oceans and the vast array of life they support (Chivian 2022, NOAA n.d.).

1.2 Efforts at the International Forum

The International Atomic Energy Agency (IAEA) Ocean Acidification International Coordination Centre (OA-ICC) fosters global cooperation in addressing Ocean Acidification. This centre conducts training sessions in the Member States and facilitates access to data and resources, contributing to the progress of research on Ocean Acidification (IAEA n.d.).

An international effort on ocean carbon research and monitoring known as the International Ocean Carbon Coordination Project (IOCCP), is funded by the International Ocean Carbon (IOC) and Scientific Committee on Oceanic Research (SCOR). It creates an international network for technical assistance, strategy coordination, and observation. Given the importance of the Western Pacific region in supporting a multitude of coral species, IOC WESTPAC (IOC Western Pacific) seeks to establish regional research networks to track the effects of Ocean Acidification on coral reefs. IOC

Naturally Low pH Environments

There are several areas in the world's oceans which have a low pH or are already experiencing under saturation with respect to CaCO3 minerals, as is observed where volcanic processes cause CO_2 to vent from submarine sediments. In these areas, CO_2 reacts with the seawater, causing pH and chemistry changes. Such environments provide an ecosystem-scale validation of the predicted impacts of increasing p CO_2 and acidification on organisms and habitat structures, and can be examined to provide further information on the ecological tipping points at which principal groups of marine organisms are affected by increasing p CO_2 (J. R.-M. Hall-Spencer 2008).

WESTPAC raises awareness and strengthens the scientific capacity to address Ocean Acidification in the Western Pacific and surrounding regions through workshops (UNESCO-IOC 2024).

Initiatives by the National Oceanic and Atmospheric Administration (NOAA)

NOAA's Ocean Acidification Programme studies changes to ocean to understand changes in ocean chemistry, vulnerability of marine life and people to acidification and how can adaptations take place. An early warning system was developed in the United States of America (USA), using data from NOAA and its partner. This warning system signals the approach of acidified seawater, enabling hatchery managers to schedule production when water quality is right or to modify seawater intake to mitigate the effects of acidified waters (NOAA Fisheries n.d.).

The Ocean Acidification Programme plays an important role in promoting Ocean Acidification education, engaging in public outreach activities related to Ocean Acidification and its impacts, and working with ocean science partners and other agencies on Ocean Acidification activities. The programme also provides grants for critical research projects that will explore the effects of Ocean Acidification on marine organisms, ecosystems, and economies waters (NOAA Fisheries n.d.).

The Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organisation (UNESCO) is working with Ocean Acidification experts to develop the SDG indicator 14.3.1 methodology, which measures marine acidity at sampling stations (Julian Barbière 2019). The IOC supports the Global Ocean Acidification Observing Network (GOA-ON), which promotes science collaboration and capacity building in Ocean Acidification observations, encouraging members to collect and report relevant data. (UN 2023).

1.3 India's Strategic Role in Ocean Data Management and International Collaborations

The Indian National Centre for Ocean Information Services (INCOIS) has been designated as the National Oceanographic Data Centre by the International Oceanographic Data Exchange Programme (IODE) of the International Oceanographic Commission (IOC). Further, INCOIS serves as the National Argo Data Centre, Regional Argo Data Centre, and the regional data centre and clearing house for the Indian Ocean region for the Indian Ocean Global Ocean Observing System (IOGOOS) Programme. Ministry of Earth Sciences is the nodal data source agency for collection of data for the indicator 14.3.1. The periodicity of data collection is annual (MoSPI 2023).

India is a participant in the United Nations Framework Convention on Climate Change (UNFCCC), a global effort to combat Climate Change, including the reduction of carbon dioxide (CO_2) emissions. Given that Ocean Acidification is a consequence of elevated atmospheric CO_2 levels, actions taken within the UNFCCC framework can indirectly contribute to the welfare of the oceans (UN-Climate Change n.d.). India may also have specific domestic policies or action plans addressing Climate Change and marine conservation. While these might not explicitly target Ocean Acidification, they often encompass measures to curtail greenhouse gas emissions, aligning with global initiatives like the Net Zero Agenda 2070, which, in turn, can help mitigate the root causes of Ocean Acidification (Malhotra 2023).

In 2018, the Ministry for Ecological Transition (MTE), France and the Ministry of Environment, Forest, and Climate Change (MoEFCC), Government of India signed a Memorandum of Understanding (MoU), creating a working group focused on Climate Change, air quality, protected areas, and biodiversity (Iram, et al. 2019).

1.4 Funding for the Ocean Acidification mitigation

There are several ongoing projects focused on developing sustainability and mitigation plans. Various government ministries, including but not limited to the Ministry of Earth Sciences, the MoEFCC, and the Ministry of Ports, Shipping, and Waterways, are currently working on these financial allocations and programmes as part of a larger effort to combat Climate Change (MoEFCC 2022). The Interim Budget 2024-25 of India, highlights the 'Blue Revolution' with increased allocation from ₹ 2,025 crore in the fiscal year 2023-24 to ₹ 2,352 crore. This new scheme will promote climate-resilient practices and integrated coastal aquaculture and mariculture (DH 2024).

With a motive to explore Deep Ocean for resources, and to develop deep sea technologies, Cabinet Committee on Economic Affairs (CCEA) approved the proposal of Ministry of Earth Sciences (MoES) on “Deep Ocean Mission” at an estimated cost of ₹ 4,077 crore for a period of five years to be implemented in a phase-wise manner. The estimated cost for the first phase for the three years (2021-2024) would be ₹ 2,823.4 crore (MoES 2024). As per Budget Expenditure Profile 2023-24, Deep Ocean Mission (Central Sector Scheme) gets an allocation of ₹ 600 crore (Ministry of Finance 2024). Deep Ocean Mission will be a mission-mode project to support the Blue Economy Initiatives of the Government of India.

1.5 Composite Value for Ocean Acidification

Ocean Acidification happens due to increasing CO_2 level in sea water but in the current study, other than CO_2, numerous additional factors have been considered that can impact for the pH level in the water and result in Ocean Acidification. These factors are sea surface temperature, seawater salinity, particulate organic carbon, particulate inorganic carbon, and dissolved oxygen.

Using the selected indicators, we may assess the level of Ocean Acidification by creating a composite value, primarily for the selected 66 beaches along the Indian coastline.

The Composite Value for Ocean Acidification can serve as a valuable tool, to assess the susceptibility of marine environments to the effects of acidification. This Composite Value not only helps gauge the potential impact of rising acidity levels on various coastal areas but also offer critical insights into which regions may be most at risk and where mitigation efforts may be needed. Furthermore, it can also be helpful to policymakers, researchers, and conservationists to prioritise resources and develop strategies to protect vulnerable ecosystems and species facing the Ocean Acidification problem (S. F. Doney 2008).

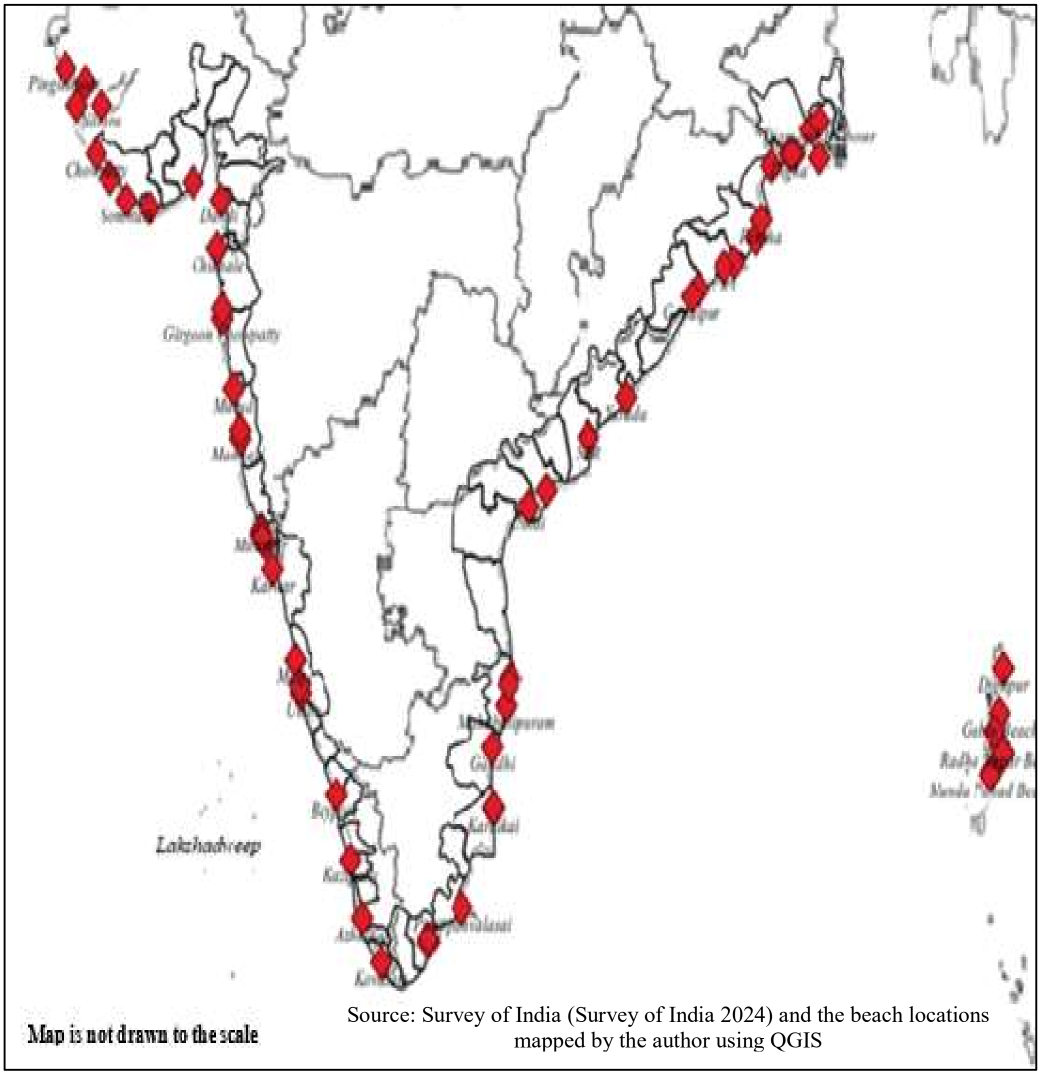
2. Objective

The objective of this study is to assess the extent of Ocean Acidification taking place in the water along the Indian coastline. Meeting this objective would help auditors study further impacts of Ocean Acidification on marine and coastal ecosystems along the Indian coastal regions.

3. Scope

The study covers 66 beaches along the Indian coastline, including the country's mainland, Andaman and Nicobar Islands, and the Union Territories (UTs). These beaches were carefully selected to reflect a variety of coastal habitats and were positioned to determine how vulnerable they were to Ocean Acidification.

Details of beaches are given in Appendix-I. The location of all the selected beaches is shown in the Figure 3 below:



Source: Survey of India (Survey of India 2024) and the beach locations mapped by the author using QGIS

Figure 3: Location of 66 beaches selected under the current study

4. Selected indicators and properties

Assessing Ocean Acidification on a global scale involves various methodologies that commonly rely on parameters like water pH, CO_2 levels, and sea surface temperature. However, due to the challenges in assessing CO_2 concentrations, some studies have used additional indicators such as Particulate Inorganic Carbon (PIC), Particulate Organic Carbon (POC), Dissolved Oxygen (DO), and salinity. This broader set of parameters, including sea surface temperature and salinity, along with PIC, POC, and DO, enables us to evaluate extent of Ocean Acidification. Table 2 shows the standard values of selected indicators for assessing the extent of Ocean Acidification.

Table 2: **Standard values for Ocean Acidification**

Indicators	Standard value	Effect on Ocean Acidification
Sea Surface Temperature (°C)	20.97°C (Copernicus 2024)	*The higher the value, higher the acidification*
Salinity (g/L)	35 g/l (de Oliveira Carvalho-Junior 2022, Gawande 2017)	*The higher the value, lower the acidification*
Particulate Organic Carbon (POC) mg m-3	60–75 mg m^{-3} (Rouf 2021)	*The higher the value, lower the acidification*
Particulate Inorganic Carbon (PIC) g m^{-2} y^{-1}	0.050 $gm^{-2}y^{-1}$ (Neukermans 2023)	*The higher the value, higher the acidification*
Dissolved oxygen (DO) *mg/L*	8.90 *mg/L* (EPA US 2023)	*The higher the value, lower the acidification*

The evaluation of the oceanic conditions was based on selected indicators such as Sea Surface Temperature (SST), Salinity, POC, PIC and DO are explained below:

4.1 Sea Surface Temperature (°C)

The higher the value, the higher the acidification.

As seawater temperature rises, the buffering capacity of seawater decreases, along with a decline in pH. Increased metabolic activity is caused by increasing seawater temperature and decreasing pH. Consequently, a temperature **increase of 2°C** leads to approximately a **10 per cent reduction** in carbon uptake in surface waters, primarily through phytoplankton photosynthesis (Baker-Austin 2013). That leads decline in photosynthesis and an increase CO_2 levels in sea water (Häder 2017).

4.2 Salinity (g/L)

The higher the value, the lower the acidification.

Salinity can buffer the pH of seawater, making it less acidic. This is because salt ions can bind to carbon dioxide molecules, making it more difficult for them to dissolve in seawater. Salinity can also exacerbate the effects of Ocean Acidification by increasing the toxicity of carbon dioxide to marine organisms. This is because salt ions can block marine organisms' channels to transport oxygen into their cells. The overall effect of salinity on Ocean Acidification is complex and depends on a few factors, including the temperature and the type of marine organism. However, in general, it is thought that the effects of Ocean Acidification are more pronounced in low salinity of sea water (Hansson 1973).

4.3 Particulate Organic Carbon (mg m-3)

The higher the value, the lower the acidification.

Particulate Organic Carbon (POC) is a form of carbon that is found in the ocean as suspended particles. It is made up of organic matter that is produced by marine organisms. There is a weak correlation between POC and Ocean Acidification (Kharbush 2020). However, some studies have shown no correlation or even a positive correlation between POC and Ocean Acidification (Brown 2014).

4.4 Particulate Inorganic Carbon (g m^{-2} y^{-1})

The higher the value, then higher the acidification.

Particulate Inorganic Carbon (PIC) is a form of carbon that is found in the ocean as suspended particles. It is made up of calcium carbonate and other minerals that are produced by marine organisms. There is a strong correlation between PIC and Ocean Acidification. As Ocean Acidification increases, the amount of PIC in the ocean decreases. This is because the increased acidity makes it more difficult for marine organisms to produce calcium carbonate. As a result, there are fewer particles of PIC in the sea water (Findlay 2011).

4.5 Dissolved Oxygen (DO) (mg/L)

The higher the value, the lower the acidification.

Aquatic plants generate oxygen through photosynthesis, which raises the water's oxygen level (Roman 2019). Through the influx of nutrients, particularly nitrogen and phosphorus, fuels the rapid growth of algae, leading to algal blooms. These blooms can form dense layers on the water's surface, blocking sunlight from reaching underwater plants; therefore, the dissolved oxygen concentration declines, and other aerobic organisms struggle to survive, leading to a decline in ecosystem biodiversity (Vaquer-Sunyer 2008). Thus, algal blooms decrease the oxygen level in the ocean water, which shows an increasing CO_2 level that leads to Ocean Acidification (Fu 2012).

5 Sources of Data

Sea surface temperature, PIC, and POC data for 66 beaches obtained from the National Aeronautics and Space Administration (NASA) website (data of MODIS satellite) and salinity and DO obtained from the National Centre for Environmental Information (NCEI) website are shown in Figure 4. The data pertaining to indicators were obtained from the following websites:

A. National Aeronautics and Space Administration (NASA) [Modis web] (EARTH DATA n.d.)

https://oceancolor.gsfc.nasa.gov/l3/order/

B. National Centre for Environmental Information (NCEI) (National Centre for Environmental Information 2023)

https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/

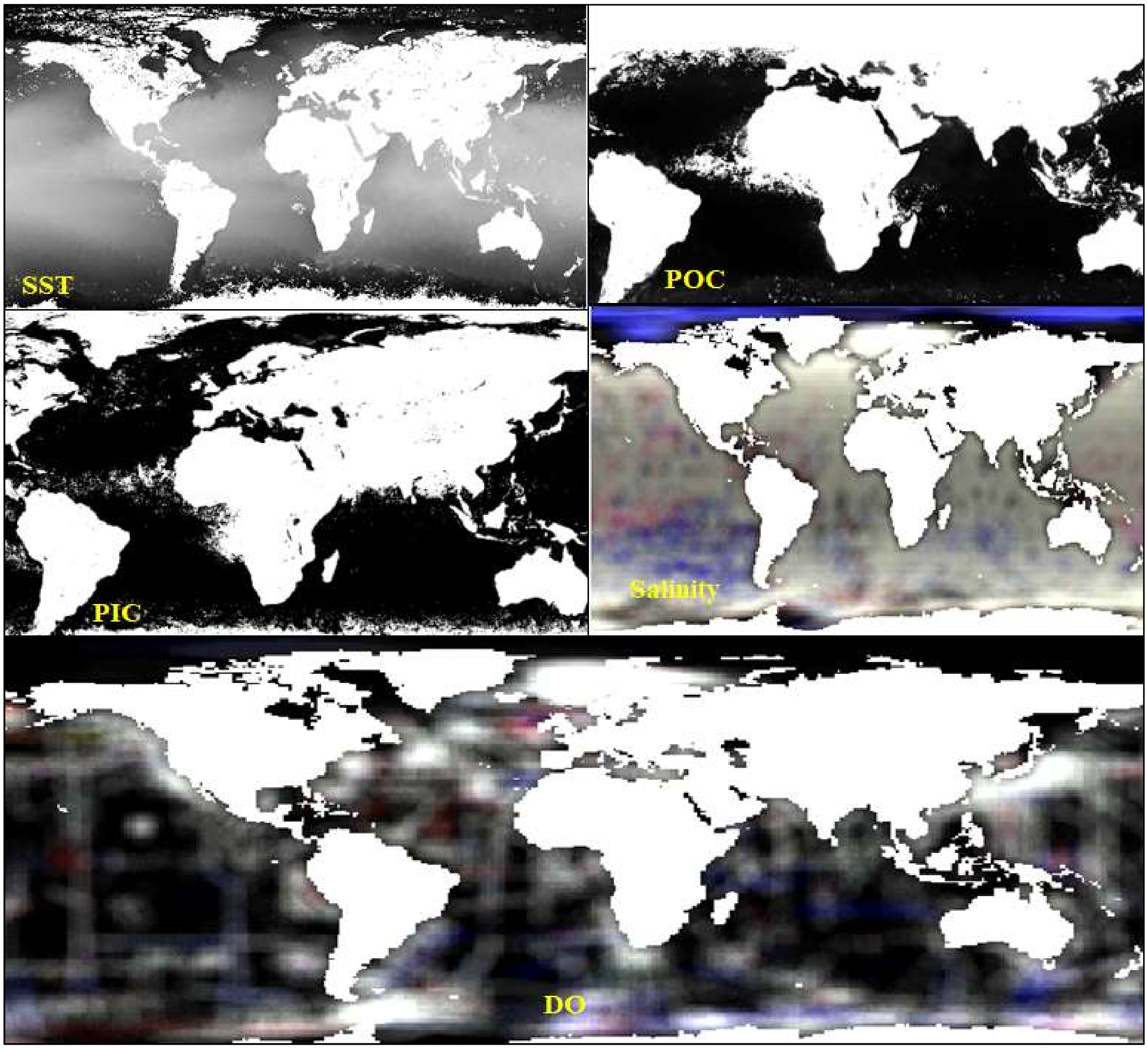


Figure 4: Satellite data obtained from the NASA and NCEI site

6. Methodology

In the current study, following methodology has been used to assess the state of Ocean Acidification along the Indian coastline:

- Literature study to gain insights into how Ocean Acidification affects ecosystems and biodiversity.

- Investigating the criteria for assessing Ocean Acidification.
- Choosing indicators that signify a decline in ocean pH, thus indicating increased Ocean Acidification and vice versa.
- Extracting data, from NASA and NCEI web resources relating to these selected indicators and deriving the mean values of them using QGIS software.
- Calculating the mean values for the indicators for the selected beach areas and preparing a Composite Index of Ocean Acidification along the Indian coastline.

7. Composite Index for Ocean Acidification: Results and Analysis

7.1 Mean Value of Selected Parameters

For the selected indicators, QGIS software was used to extract the mean values for the area comprising approx. 110 km from the beach, into the sea. For the selected areas, mean values have been used for further analysis. Table 3 represents some examples of the mean value for each selected indicator (all data shown in the Appendix-I).

***Table 3*: Mean value of selected indicators extracted using QGIS**

S. No.	Name of monitoring location/ Beaches	SST (°C)	Salinity (g/L)	POC (mg m-3)	PIC (g m^{-2} y^{-1})	DO (mg/L)
1.	Dandi	25.861	28.328	314.837	0.00006	23.328
2.	Ghoghla	25.880	27.150	294.298	0.00102	22.150
3.	Jhanjimer	27.472	26.600	322.042	0.00049	2.111
4.	Somnath	25.753	28.473	278.997	0.00034	22.983
5.	Chowpatty	24.972	29.144	273.285	0.00038	22.421

7.2 Calculation of the Composite Index on Ocean Acidification

7.2.1 Data Normalisation

Data normalisation is the process of organising data in a database in such a way that it is consistent, efficient, and easy to use. Normalisation is a complex process, but it is important for designing and maintaining efficient and reliable databases. Normalisation also helps to prevent data redundancy, which can waste space and make it difficult to update data (Quackenbush 2002). In this study, indicators such as SST and PIC progressively and other indicators regressively affected Ocean Acidification. The normalised value of progressive and regressive indicators is calculated by using the below formula:

For Progressive indicator = [(Actual Value-Lower value)/Highest Value-Lowest value] *100

For Regressive indicator = [(Highest Value-Actual value)/Highest Value-Lowest value] *100

Progressive indictors such as SST and PIC imply higher contribution to Ocean Acidification and Regressive indicators such as POC, DO and Salinity, if increased, imply lower contribution to Ocean Acidification. These analyses for the extraction emphasised on similar methodologies followed by the NITI Aayog (SDG India Index) and ORF in their recent indices (Renita D'Souza, and Debosmita Sarkar 2023).

7.2.2 Correlation Matrix

A correlation matrix is shown in Table 4 showing the correlations between each pair of variables in a dataset. It is a useful tool for figuring out how different variables are related to each other. By looking at the correlation coefficients between two variables, we can learn how they are related and how changes in one variable may affect the other variables. In this matrix, SST shows positive correlation with Salinity and negative correlation with POC, PIC, and DO. PIC and POC are opposite relations to each other. For the vulnerability performance of Ocean Acidification SST and PIC are used as progressive indicators, and Salinity, POC, and DO are used as negative indicators.

***Table 4*: Showing Correlation between Indicators**

Correlation Matrix (Pearson)					
Variables	**SST**	**Salinity**	**POC**	**PIC**	**DO**
SST	**1**	0.028	-0.252	-0.143	-0.469
Salinity	0.028	**1**	-0.040	-0.006	0.459
POC	-0.252	-0.040	**1**	0.265	0.437
PIC	-0.143	-0.006	0.265	**1**	0.082
DO	-0.469	0.459	0.437	0.082	**1**

7.2.3 Weightage for the indicators

A Principal Component Analysis (PCA)-based weight assignment technique was used to assign differential weights to indicators. In the current study, scale to 100 in PCA assigned almost equal weights for all indicators, except PIC, which has lowest weightage as 11, resulting in a different Composite Value obtained with the weights of selected indicators. While assigning the weight, it must be ensured that the weight or proportion assigned to all the indicators add up to 100 (Renita D'Souza, and Debosmita Sarkar 2023). The weight for each indicator as shown in Table 5.

Table 5: **Weightage for the selected indicators in current study**

Selected Indicators	Factor Loading			Squared Factor Loading			Weight	Weight at Scaled to 100
	F1	F2	F3	F1	F2	F3		
DO	0.752	0.55	-0.077	**0.565**	0.303	0.006	0.268	22
Salinity	-0.123	0.899	0.351	0.015	**0.807**	0.123	0.253	21
PIC	0.473	-0.326	0.783	0.224	0.106	**0.613**	0.130	11
SST	-0.736	-0.059	0.351	**0.541**	0.003	0.123	0.257	22
POC	0.774	-0.249	-0.014	**0.599**	0.062	0	0.284	24

7.2.4 Composite Value

A Composite Value is a calculated value that combines the values of two or more values. In this Research study, normalised values of all indicators have been combined to generate a Composite Value (McGahan 1986). For the Composite Value, following formula is used:

$$\textbf{Composite Value} = \textbf{Normalised value of } (\textbf{SST} + \textbf{PIC} + \textbf{Salinity} + \textbf{POC} + \textbf{DO})/5$$

A Composite Value serves as an indicator of Ocean Acidification, with a high Composite Value signifying elevated levels of Ocean Acidification, and a low Composite Value suggesting reduced Ocean Acidification. Some Composite Value of selected indicators are shown in Table 6 and all Composite Values are shown in Appendix-II.

Table 6: **Normalisation of indicator value for vulnerability index shown by the Composite Value**

S. No.	Name of monitoring location	State/UT	District	SST (°C) (P)	Salinity (g/L) (R)	POC (mg m-3) (R)	PIC (g m^{-2} y^{-1}) (P)	DO (mg/L) (R)	Composite Value
1.	Dandi	Gujarat	Navsari	19.2620	41.3449	22.0716	1.0289	0.0000	**18.330**
2.	Ghoghla	Dadra and Nagar Haveli and Daman and Diu	Diu	19.6628	46.9605	28.2406	20.7819	5.5516	**23.293**
3.	Jhanjimer	Gujarat	Bhavnagar	54.1652	49.5828	19.9077	9.8766	100.0000	**48.463**
4.	Somnath	Gujarat	Gir Somnath	16.9121	40.6509	32.8359	6.7902	1.6239	**21.388**
5.	Chowpatty	Gujarat	Porbandar	0.0000	37.4531	34.5515	7.6132	4.2760	**18.753**

* P is indicated as progressive, and R is indicated as regressive, for Ocean Acidification

7.2.5 Ocean Acidification along the Indian Coast as Obtained from the Study

Utilising the Composite Value scaling map, generated through QGIS (Kapsenberg 2015) (Agostini 2015), which signifies the Ocean Acidification levels at various beaches, enables us to assess the overall condition of these coastal areas by aggregating multiple individual factors or attributes. This composite value calls for enhanced actions in various aspects of beach management, tourism and recreation planning, environmental monitoring, policy formulation and enforcement, as well as community engagement. The application of this Composite Value to selected beaches provides a holistic view of their quality, ultimately enhancing decision-making, management strategies, and conservation efforts. Based on the composite value, prepared map is shown in Figure 5.

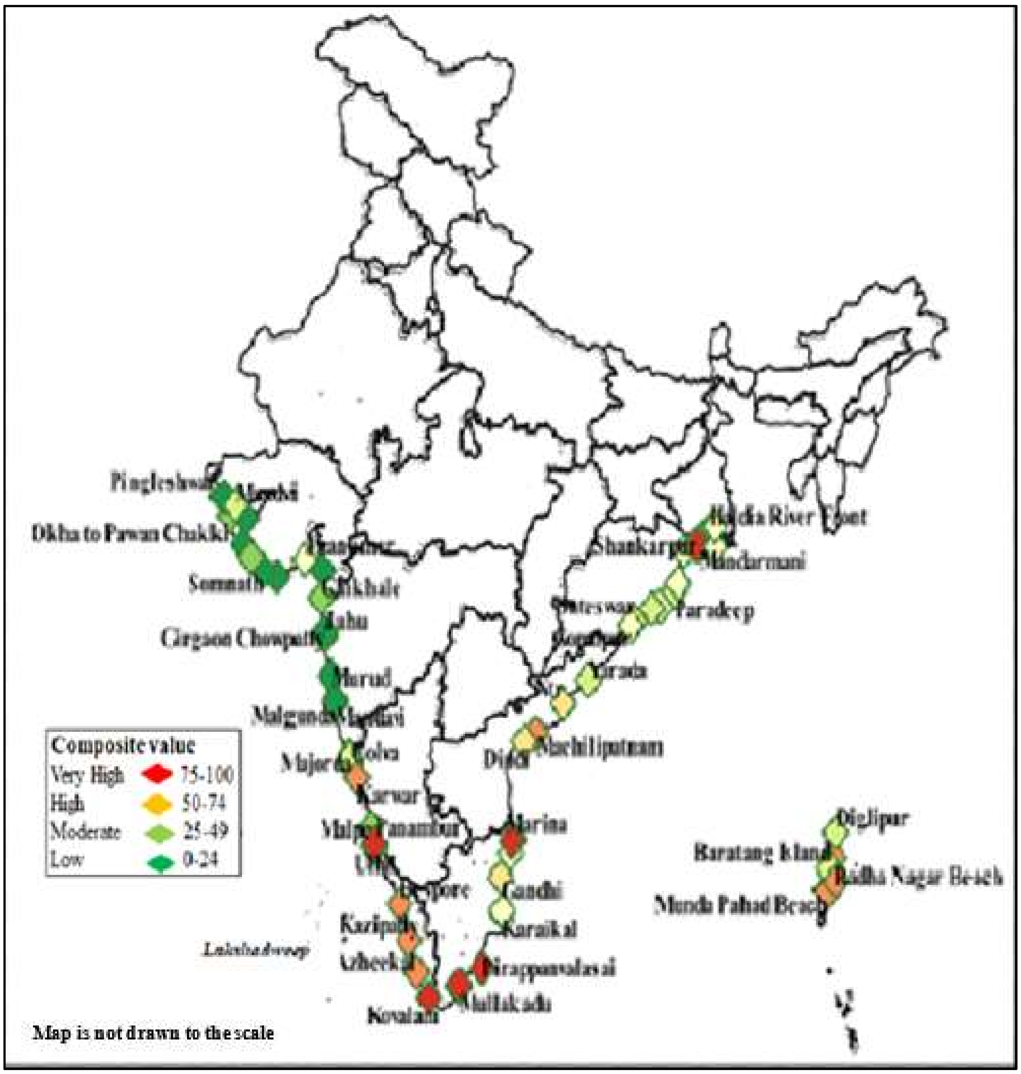


Figure 5: Composite Value showing for all 66 beaches

Source: Survey of India (Survey of India 2024) and the beach locations mapped by the author using QGIS

8. Outcomes

The Composite Value for assessing Ocean Acidification at 66 different beaches is determined by calculating the mean value of selected indicators, as outlined in Table 2. These Composite Values serve as an indicator of Ocean Acidification levels for each of the 66 beaches as shown in Table 5 and Appendix-II.

8.1 High Composite Values refer to high Ocean Acidification

Notably, the highest composite values are recorded for Tamil Nadu beaches such as Mullakadu (66.08), Thiruvanmiyur (66.12), Muthunagar (65.06), and Marina (64.24), and with Shaheed Dweep Beach (61.57) in Andaman and Nicobar, indicating that higher Ocean Acidification can be possible by pollution from plastics. The plastic litter in the sea beaches are contributed by tourists, shipping activities, and improper solid waste management practices (Krishnakumar 2020). The highest of the five Composite Values with locations is shown in Table 7.

***Table 7*: Beaches with the highest Composite Value and Ocean Acidification**

S. No.	Name of monitoring location	State/UT	District	SST (°C) (P)	Salinity (g/L) (R)	POC (mg m-3) (R)	PIC (g m^{-2} y^{-1}) (P)	DO (mg/L) (R)	Composite Value
1.	Mullakadu	Tamil Nadu	Tuticorin	84.3602	81.0488	89.5884	0.8231	81.6707	**66.801**
2.	Thiruvanmiyur	Tamil Nadu	Chennai	91.8948	75.6268	89.2053	0	71.8885	**66.124**
3.	Muthunagar	Tamil Nadu	Tuticorin	83.2307	76.9962	90.6231	1.0289	73.6578	**65.061**
4.	Marina	Tamil Nadu	Chennai	83.8419	76.2813	88.2261	0.4116	72.2442	**64.241**
5.	Shaheed Dweep	Andaman and Nicobar Islands	South Andaman	74.6811	33.2253	99.2311	0.5254	57.1901	**61.567**

8.2 Low Composite Values refer to low Ocean Acidification

The lowest Composite Value is found in Dandi Beach, located in the state of Gujarat, India. Gujarat has the highest number of clean beaches with low Ocean Acidification levels, as indicated in Table 8.

***Table 8*: Beaches with the lowest Composite Value and Ocean Acidification**

S. No.	Name of monitoring location	State/UT	District	SST (°C) (P)	Salinity (g/L) (R)	POC (mg m-3) (R)	PIC (g m^{-2} y^{-1}) (P)	DO (mg/L) (R)	Composite Value
1.	Narara	Gujarat	Devbhumi Dwarka	23.1799	26.5427	30.2963	21.1935	4.3113	**24.333**
2.	Ghoghla	Dadra and Nagar Haveli and Daman and Diu	Diu	19.6628	46.9605	28.2406	20.7819	5.5516	**23.293**
3.	Somnath	Gujarat	Gir Somnath	16.9121	40.6509	32.8359	6.7902	1.6239	**21.388**
4.	Chowpatty	Gujarat	Porbandar	0	37.4531	34.5515	7.6132	4.276	**18.753**
5.	Dandi	Gujarat	Navsari	19.262	41.3449	22.0716	1.0289	0	**18.33**

9. Way Forward

With its extensive range of indicators and data availability, this Ocean Acidification thematic outline can be a critical resource for assessing the degree of Ocean Acidification is potential audits. Furthermore, the Ocean Acidification Paper could be is a useful tool for determining the sensitivity of marine ecosystems and assessing the negative effects of Ocean Acidification on marine ecosystems. It may also help in marking risk areas with respect to the assessment of hazards and the identification of priority areas requiring immediate action by providing a standardised framework to control Ocean Acidification.

10. Pointers for Audit

10.1 Key Focus in Environment Audits on Climate Change and Ocean Acidification

The International Organisation of Supreme Audit Institutions (INTOSAI) Working Group on Environmental Auditing (WGEA) has shown longstanding concern for the marine environment. Following areas have been focussed in auditing relating to Climate Change and Ocean Acidification.

Assessing Risks and Vulnerabilities: This involves examining how governments assess risks and vulnerabilities in the marine environment. SAIs audits the approaches taken by governments in performing these assessments, evaluate the quality of the results, and analyse how governments subsequently utilise this information.

Adaptation Efforts: SAIs have concentrated on auditing government initiatives aimed at adapting to the impacts of Climate Change and Ocean Acidification on the marine environment. This includes scrutinising specific actions taken by governments. In some cases, SAIs have broadened their scope to include marine environment issues within audits that assess Climate Change adaptation activities or the implementation of international agreements on Climate Change.

Coordination among Entities: Another key focus has been the examination of coordination among government agencies and collaborations between governments and other entities. This encompasses activities designed to address the effects of Climate Change and Ocean Acidification on the marine environment (INTOSAI WGEA 2016).

10.2 Based on previous SAI's work, SAI's focus areas in Auditing Climate Change and Ocean Acidification can be summarised as the following:

The Federal Ocean Acidification Research and Monitoring Act (FOARAM) was established in 2009 by an interagency working group including NOAA, National Science Foundation, NASA, U.S. Fish and Wildlife Service, and U.S. Geological Survey. The plan aims to assess Ocean Acidification's impacts on marine organisms and ecosystems, develop adaptation and mitigation strategies, and coordinate research activities with international entities. NOAA conducts interdisciplinary research, the National Science Foundation supports research, and NASA ensures space-based monitoring assets are used for monitoring Ocean Acidification (GAO 2014).

In the United States of America (USA), the Federal Ocean Acidification Research and Monitoring initiative focuses on developing and implementing a comprehensive plan to monitor and research the effects of ocean and coastal acidification on marine ecosystems. It involves maintaining a program within the National Oceanic and Atmospheric Administration, assessing regional and national impacts, and researching strategies to adapt to and mitigate the effects on marine ecosystems (USCODE 2022)[2].

Federal Ocean Acidification Research and Monitoring

Office of the Law Revision Counsel United States Code is a consolidation and codification by subject matter of the general and permanent laws of the United States. It is prepared by the Office of the Law Revision Counsel of the United States House of Representatives under the Title 33: Navigation and Navigable Water; Chapter 50: Federal Ocean Acidification Research And Monitoring Section 3705: NOAA Ocean Acidification activities, Section 3706: NSF Ocean Acidification activities, Section 3707: NASA Ocean Acidification activities for the monitoring the Ocean Acidification activities (USCODE 2022).
(https://uscode.house.gov/view.xhtml?path=/prelim@title33/chapter50&edition=prelim)

[2]. The United States Code is the official codification of the general and permanent federal statutes of the United States

U.S. Government Accountability Office – Audit relating to Ocean Acidification

In a 2014 audit, the SAI of the United States evaluated its government's response to Ocean Acidification and the implementation of a 2009 law requiring the creation of an interagency working group on Ocean Acidification and the establishment of an Ocean Acidification programme. United States government agencies have joined and efforts to address Ocean Acidification have primarily focused on supporting various research and monitoring activities. As part of this audit, the SAI made recommendations to improve the government's response to Ocean Acidification, including recommending steps to strengthen coordination, such as clearly defining the roles and responsibilities of the agencies involved and designating the entity responsible for coordinating the next steps in the government's response (INTOSAI 2016).

10.3 Possible Approaches to Audit Ocean Acidification

In order to overcome the challenges associated with auditing Ocean Acidification, SAIs can adopt various strategic approaches. One effective method is to anchor audits in good governance criteria, and sound management principles. Additionally, SAIs can enhance their expertise by collaborating with independent domain experts, to access specialised knowledge not readily available within the SAI. For providing with a possible area of enquiry, a tentative audit design template has been provided in Appendix-III.

10.4 Challenges

- Separate Laws and Regulations are not available for guiding government actions concerning Ocean Acidification.
- The Central Pollution Control Board (CPCB) gathers fundamental seawater-related data annually. However, the publication of the report containing these data takes about a year. Therefore, there is a need for timely forecasting the data/information related to Ocean Acidification.
- Numerous programmes, such as energy policy, pollution control, infrastructure, fisheries, and ocean-protected areas, are intertwined with Climate Change and Ocean Acidification. However, addressing the pressing concern of Ocean Acidification requires specific programmes directly targeting this issue.

Key Challenges identified by SAIs in past while auditing Climate Change and Ocean Acidification:

Some of the Key challenges, SAIs have identified in auditing Climate Change and Ocean Acidification issues in the marine environment include:

- Limited extent of audit criteria and government action in some nations;
- Fragmentation of government's response in some nations;
- Limited experience and training among some SAIs;
- Competing audit priorities; and
- Limitations in the scope of some SAIs' audit mandates (INTOSAI 2016)

11. Conclusion

This Paper shows how Ocean Acidification causes concerns towards sustainability of the ocean ecosystems and highlights the areas for concern in and around the Indian coastal states through calculation of a composite value based on selected indicators such as SST, PIC, POC, DO, and salinity. The Composite Index shows that Tamil Nadu beaches such as Mullakadu (66.08), Thiruvanmiyur (66.12), Muthunagar (65.06), Marina (64.24), and Shaheed Dweep Beach (61.57) in Andaman and Nicobar have the highest composite index, while Dandi Beach (18.33) in Gujarat has the lowest composite index.

This research underscores the importance of the Ocean Acidification thematic area as a valuable resource for assessing the trends and associates impacts of Ocean Acidification. It can be used to identify risk areas and prioritise action. The framework can be replicated to assess Ocean Acidification in other regions and countries.

Furthermore, the Paper can help auditors, policymakers, and researchers assess and monitor Ocean Acidification and their plausible impacts in coastal areas. It seeks to provide stakeholders the information they need to make informed decisions, design or amend policies, and unlock the full potential of India's coastal regions, while being aware of the threats posed by Ocean Acidification. Further, use of Remote Sensing and GIS techniques can further exacerbate the impact of audit relating to Ocean Acidification.

Appendix-I: Mean value of selected indicators extracted using QGIS

S. No.	Name of monitoring location/ Beaches	SST (°C)	Salinity (g/L)	POC (mg m-3)	PIC ($g\ m^{-2}\ y^{-1}$)	DO (mg/L)
1.	Dandi	25.861	28.328	314.837	0.00006	23.328
2.	Ghoghla	25.880	27.150	294.298	0.00102	22.150
3.	Jhanjimer	27.472	26.600	322.042	0.00049	2.111
4.	Somnath	25.753	28.473	278.997	0.00034	22.983
5.	Chowpatty	24.972	29.144	273.285	0.00038	22.421
6.	Narara	26.042	31.433	287.453	0.00104	22.413
7.	Okha to Pawan Chakki	26.297	26.600	188.392	0.00038	13.500
8.	Pingleshwar	26.374	27.960	293.401	0.00014	20.147
9.	Madhavpur	27.655	17.144	359.655	0.00015	15.072
10.	Mandvi	27.635	16.070	371.632	0.00083	14.535
11.	Murud	27.147	17.679	388.326	0.00006	15.340
12.	Girgaon Chowpatty	26.523	21.876	288.846	0.00102	17.727
13.	Juhu	26.637	24.852	281.964	0.00049	19.568
14.	Chikhale	26.783	26.600	188.392	0.00038	13.500
15.	Mandavi	27.147	27.096	261.769	0.00034	19.808
16.	Malgunda	27.209	28.000	230.637	0.00038	18.000
17.	Majorda	27.236	25.312	180.998	0.00104	15.375
18.	Miramar	27.263	24.957	151.543	0.00014	15.273
19.	Baina	27.188	24.580	181.027	0.00015	15.003
20.	Velsao	27.103	24.539	160.043	0.00083	15.000
21.	Colva	27.172	24.155	172.139	0.00006	15.000
22.	Bogmalo	27.443	24.000	148.078	0.00006	15.000
23.	Ullal	25.890	19.952	128.980	0.00102	12.249
24.	Malpe	26.308	26.600	188.392	0.00038	13.500
25.	Karwar	26.447	19.433	114.037	0.00049	10.217
26.	Panambur	26.954	16.025	103.075	0.00034	8.025
27.	Beypore	26.884	19.654	101.056	0.00038	9.327
28.	Kazipally	26.549	25.112	94.806	0.00104	8.711
29.	Azheekal	26.826	23.723	62.212	0.00014	7.569
30.	Kovalam	27.295	22.000	107.173	0.00015	5.000
31.	Mahabalipuram	28.847	26.600	188.392	0.00038	13.500
32.	Pirappanvalasai	27.760	22.000	171.410	0.00083	5.000
33.	VOC Harbour	28.810	26.600	294.342	0.00487	13.500
34.	Mullakadu	28.866	20.000	90.037	0.00005	6.000

35.	Muthunagar	28.814	20.850	86.592	0.00006	7.700
36.	Marina	28.842	21.000	94.573	0.00003	8.000
37.	Thiruvanmiyur	29.213	21.137	91.312	0.00001	8.075
38.	Machilipatnam	28.463	29.000	81.059	0.00002	12.000
39.	Kakinada	28.525	29.000	84.192	0.00001	12.098
40.	NTR	28.357	29.000	79.079	0.00001	13.000
41.	Dindi	28.370	29.000	82.996	0.00003	13.000
42.	Yarada	28.015	26.600	188.392	0.00038	13.500
43.	Bateswar	27.843	23.009	122.943	0.00003	13.009
44.	Gopalpur	28.600	26.600	188.392	0.00038	13.500
45.	Chandrabhaga	28.449	29.000	103.464	0.00001	15.000
46.	Puri	28.363	29.000	110.533	0.00006	17.000
47.	Paradeep	28.398	29.000	131.190	0.00003	17.000
48.	Pentha	28.889	28.000	135.994	0.00001	15.000
49.	Chandipur	28.847	30.013	130.290	0.00002	15.402
50.	Haldia River Front	28.785	26.547	120.853	0.00001	14.156
51	Digha	28.670	26.600	188.392	0.00038	13.500
52.	Mandarmani	29.056	26.600	188.392	0.00038	13.500
53.	Shankarpur	29.588	23.030	184.770	0.00001	10.009
54	Bakkhali Sea	29.563	23.642	321.520	0.00006	10.000
55.	Diamond Harbour	29.340	25.862	283.072	0.00003	10.000
56.	Karaikal	29.111	26.600	188.392	0.00038	13.500
57.	Kilinjalmedu	29.111	26.000	247.209	0.00001	10.000
58.	Gandhi	29.018	26.000	231.477	0.00002	9.482
59.	Shaheed Dweep	28.419	30.031	57.931	0.00004	11.194
60.	Burmanallah Beach	28.249	30.438	59.376	0.00017	11.708
61.	Munda Pahad Beach	28.247	30.540	55.878	0.00018	11.640
62.	Gablu Beach	28.323	30.001	55.726	0.00004	12.000
63.	Radha Nagar Beach	28.269	30.000	188.800	0.00001	12.000
64.	Baratang Island	28.445	37.000	55.371	0.00002	12.000
65.	Diglipur	28.427	37.000	56.950	0.00002	12.000
66.	Shaheed Dweep	28.419	30.031	57.931	0.00004	11.194
	Minimum Value	**24.972**	**16.025**	**55.371**	**0.00001**	**2.111**
	Maximum Value	**29.588**	**37.000**	**388.326**	**0.00487**	**23.328**
	Average Value	**27.777**	**25.854**	**174.465**	**0.00034**	**13.288**

Appendix-II: Normalised Indicator values and Composite Value of Ocean Acidification

S. No.	Name of monitoring location	State/UT	District	SST (°C) (P)	Salinity (g/L) (R)	POC (mg m-3) (R)	PIC (g m^{-2} $y^{-1)}$ (P)	DO (mg/L) (R)	Composite Value
1.	Dandi	Gujarat	Navsari	19.2620	41.3449	22.0716	1.0289	0.0000	**18.330**
2.	Ghoghla	Dadra and Nagar Haveli and Daman and Diu	Diu	19.6628	46.9605	28.2406	20.7819	5.5516	**23.293**
3.	Jhanjimer	Gujarat	Bhavnagar	54.1652	49.5828	19.9077	9.8766	100.0000	**48.463**
4.	Somnath	Gujarat	Gir Somnath	16.9121	40.6509	32.8359	6.7902	1.6239	**21.388**
5.	Chowpatty	Gujarat	Porbandar	0.0000	37.4531	34.5515	7.6132	4.2760	**18.753**
6.	Narara	Gujarat	Devbhumi Dwarka	23.1799	26.5427	30.2963	21.1935	4.3113	**24.333**
7.	Okha to Pawan Chakki	Gujarat	Jamnagar	28.6948	49.5828	60.0483	7.6132	46.3213	**40.435**
8.	Pingleshwar	Gujarat	Kachchh	30.3599	43.1012	28.5099	2.6749	14.9934	**25.797**
9.	Madhavpur	Gujarat	Porbandar	58.1232	94.6637	8.6110	2.8807	38.9114	**32.414**
10.	Mandvi	Gujarat	Kachchh	57.6959	99.7876	5.0138	16.8725	41.4442	**33.553**
11.	Murud	Maharashtra	Ratnagiri	47.1108	92.1122	0.0000	1.0289	37.6502	**27.443**
12.	Girgaon Chowpatty	Maharashtra	Mumbai City	33.5913	72.1052	29.8778	20.7819	26.3986	**31.337**
13.	Juhu	Maharashtra	Mumbai Suburban	36.0590	57.9147	31.9448	9.8766	17.7202	**29.267**
14.	Chikhale	Maharashtra	Palghar	39.2370	49.5828	60.0483	7.6132	46.3213	**42.754**
15.	Mandavi	Maharashtra	Ratnagiri	47.1158	47.2185	38.0104	6.7902	16.5894	**32.567**
16.	Malgunda	Maharashtra	Ratnagiri	48.4601	42.9082	47.3605	7.6132	25.1117	**37.072**
17.	Majorda	Goa	South Goa	49.0575	55.7235	62.2691	21.1935	37.4846	**44.998**
18.	Miramar	Goa	North Goa	49.6394	57.4158	71.1157	2.6749	37.9627	**45.317**
19.	Baina	Goa	South Goa	47.9988	59.2150	62.2604	2.8807	39.2356	**43.133**
20.	Velsao	Goa	South Goa	46.1555	59.4067	68.5628	16.8725	39.2514	**45.783**
21.	Colva	Goa	South Goa	47.6534	61.2373	64.9299	1.0289	39.2514	**43.498**
22.	Bogmalo	Goa	South Goa	53.5230	61.9785	72.1564	1.0289	39.2514	**46.524**
23.	Ullal	Karnataka	Dakshina Kannada	19.8799	81.2777	77.8922	20.7819	52.2154	**45.524**
24.	Malpe	Karnataka	Udupi	28.9448	49.5828	60.0483	7.6132	46.3213	**40.490**
25.	Karwar	Karnataka	Uttara Kannada	31.9512	83.7518	82.3802	9.8766	61.7971	**50.165**
26.	Panambur	Karnataka	Dakshina Kannada	42.9292	100.0000	85.6724	6.7902	72.1277	**55.303**

27.	Beypore	Kerala	Kozhikode	41.4181	82.6965	86.2790	7.6132	65.9887	**53.856**
28.	Kazipally	Kerala	Ernakulam	34.1600	56.6747	88.1560	21.1935	68.8913	**54.842**
29.	Azheekal	Kerala	Kollam	40.1609	63.3008	97.9453	2.6749	74.2740	**57.659**
30.	Kovalam	Kerala	Thiruvananthapuram	50.3352	71.5137	84.4417	2.8807	86.3839	**59.344**
31.	Mahabalipuram	Tamil Nadu	Kanchipuram	83.9462	49.5828	60.0483	7.6132	46.3213	**52.590**
32.	Pirappanvalasai	Tamil Nadu	Ramanathapuram	60.3979	71.5137	65.1488	16.8725	86.3839	**58.466**
33.	VOC Harbour	Tamil Nadu	Tuticorin	83.1555	49.5828	28.2273	100.0000	46.3213	**54.942**
34.	Mullakadu	Tamil Nadu	Tuticorin	84.3602	81.0488	89.5884	0.8231	81.6707	**66.801**
35.	Muthunagar	Tamil Nadu	Tuticorin	83.2307	76.9962	90.6231	1.0289	73.6578	**65.061**
36.	Marina	Tamil Nadu	Chennai	83.8419	76.2813	88.2261	0.4116	72.2442	**64.241**
37.	Thiruvanmiyur	Tamil Nadu	Chennai	91.8948	75.6268	89.2053	0.0000	71.8885	**66.124**
38.	Machilipatnam	Andhra Pradesh	Krishna	75.6381	38.1406	92.2848	0.2058	53.3912	**59.240**
39.	Kakinada	Andhra Pradesh	Kakinada	76.9705	38.1406	91.3440	0.0000	52.9306	**59.183**
40.	NTR	Andhra Pradesh	East Godavari	73.3446	38.1406	92.8795	0.0000	48.6779	**57.818**
41.	Dindi	Andhra Pradesh	East Godavari	73.6141	38.1406	91.7030	0.4116	48.6779	**57.641**
42.	Yarada	Andhra Pradesh	Vishakhapatnam	65.9295	49.5828	60.0483	7.6132	46.3213	**48.627**
43.	Bateswar	Odisha	Ganjam	62.1963	66.7050	79.7054	0.4116	48.6374	**52.240**
44.	Gopalpur	Odisha	Ganjam	78.6029	49.5828	60.0483	7.6132	46.3213	**51.415**
45.	Chandrabhaga	Odisha	Puri	75.3220	38.1406	85.5557	0.0000	39.2514	**54.422**
46.	Puri	Odisha	Puri	73.4618	38.1406	83.4325	1.0289	29.8250	**51.542**
47.	Paradeep	Odisha	Jagatsinghpur	74.2327	38.1406	77.2286	0.4116	29.8250	**50.155**
48.	Pentha	Odisha	Kendrapara	84.8629	42.9082	75.7857	0.0000	39.2514	**54.176**
49.	Chandipur	Odisha	Baleshwar	83.9520	33.3096	77.4986	0.2058	37.3564	**53.993**
50.	Haldia River Front	West Bengal	East Midnapore	82.6138	49.8371	80.3332	0.0000	43.2285	**55.648**
51.	Digha	West Bengal	East Midnapore	80.1229	49.5828	60.0483	7.6132	46.3213	**51.749**
52.	Mandarmani	West Bengal	East Midnapore	88.4899	49.5828	60.0483	7.6132	46.3213	**53.590**
53.	Shankarpur	West Bengal	East Midnapore	100.0000	66.6035	61.1362	0.0000	62.7757	**59.166**
54.	Bakkhali Sea	West Bengal	South 24 Parganas	99.4748	63.6838	20.0644	1.0289	62.8177	**49.315**
55.	Diamond Harbour	West Bengal	South 24 Parganas	94.6275	53.0990	31.6119	0.4116	62.8177	**50.952**
56.	Karaikal	Puducherry	Karaikal	89.6667	49.5828	60.0483	7.6132	46.3213	**53.849**
57.	Kilinjalmedu	Puducherry	Karaikal	89.6799	52.4434	42.3832	0.0000	62.8177	**52.404**

58.	Gandhi	Puducherry	Puducherry	87.6620	52.4434	47.1083	0.2058	65.2581	**53.653**
59.	Shaheed Dweep	Andaman and Nicobar Islands	South Andaman	74.6811	33.2253	99.2311	0.5254	57.1901	**61.567**
60.	Burmanallah Beach	Andaman and Nicobar Islands	South Andaman	70.9975	31.2848	98.7971	3.2579	54.7674	**60.420**
61.	Munda Pahad Beach	Andaman and Nicobar Islands	South Andaman	70.9542	30.7986	99.8477	3.4636	55.0879	**60.756**
62.	Gablu Beach	Andaman and Nicobar Islands	South Andaman	72.6009	33.3683	99.8934	0.6449	53.3912	**60.446**
63.	Radha Nagar Beach	Andaman and Nicobar Islands	South Andaman	71.4309	33.3730	59.9258	0.0000	53.3912	**50.525**
64.	Baratang Island	Andaman and Nicobar Islands	North and Middle Andaman	75.2444	0.0000	100.0000	0.1961	53.3912	**61.004**
65.	Diglipur	Andaman and Nicobar Islands	North and Middle Andaman	74.8544	0.0000	99.5258	0.1258	53.3912	**60.796**
66.	Shaheed Dweep	Andaman and Nicobar Islands	South Andaman	74.6811	33.2253	99.2311	0.5254	57.1901	**61.567**

* **P is indicated as progressive, and R is indicated as regressive, for Ocean Acidification.**

Appendix-III: Audit Design Matrix Template on Ocean Acidification

Audit questions		Audit Criteria	Data collection and analysis method	Audit evidence
1. Assessment of Ocean Acidification				
1.1 Research and Data Collection	**1.1.1** Whether the data collection methods used for monitoring Ocean Acidification are standardised and follow best practices?	Relevant resources by the Indian National Centre for Ocean Information Services	Satellite based data	CPCB data
	1.1.2 Whether the research studies and scientific data on Ocean Acidification are peer-reviewed and from reputable sources?	Relevant Acts/ Rules/ Notifications/ Circulars on Ocean Acidification	Scrutiny of the related files and data	Data available with respective department
1.2 Monitoring and Observation Systems	**1.2.1** Whether there is a well-established and coordinated Ocean Acidification monitoring network in place?	Relevant Acts/ Rules	Scrutiny of the related files and data	GIS based and Data available with respective department
	1.2.2 Whether the monitoring systems adequately cover different ocean regions and depths to capture spatial and temporal variability?			
1.3 Ocean Carbon Cycle and CO_2 Uptake	**1.3.1** Whether the understanding of the ocean carbon cycle and CO_2 uptake processes is based on robust scientific evidence and research?	Relevant Acts/ Rules	Scrutiny of the related files and data	Data available with respective department
	1.3.2 Whether the models used to estimate CO_2 absorption rates and future projections			

Audit questions		Audit Criteria	Data collection and analysis method	Audit evidence
	are regularly updated and validated?			
1.4 Ocean Chemistry and indicators Variability	**1.4.1** Whether ocean pH levels and chemical composition are regularly measured and reported to identify variations and trends?	Relevant Acts/ Rules	Scrutiny of the related files and data	GIS system based, Data available with respective department
	1.4.2 Whether the factors contributing to spatial and temporal pH variability have been identified and studied?			GIS system based, Data available with respective department
	1.4.3 Whether POC in the ocean is regularly measured and reported to identify variations and trends?			
	1.4.4 Whether the PIC of ocean is regularly measured and reported to identify variations and trends?			
	1.4.5 Whether the salinity of the ocean is regularly measured and reported to identify variations and trends?			
	1.4.6 Whether the sea surface temperature of the ocean is regularly measured and reported to identify variations and trends?	Relevant Acst/ Rules/ Notifications/ Circulars on Ocean Acidification	Scrutiny of the related files and data	Data available with respective department

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