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DEVELOPMENT OF A COASTAL OCEAN ACIDIFICATION VULNERABILITY INDEX (COAVI)

Jamil Tajam^{1*}, Nurul Hidayah Rosmee¹, Mohd Azlan Mohd Ishak¹, Sabiha Hanim Saleh², Aileen Tan Shau Hwai³, Mazlin Mokhtar⁴, Khairul Naim Abd. Aziz¹, Sharir Aizat Kamaruddin¹ and Md Nizam Ismail⁵

¹ Marine Research Station (MARES), Faculty of Applied Sciences, Universiti Teknologi MARA, Arau Campus, 02600 Arau, Perlis, Malaysia

Email: jamiltajam@uitm.edu.my, hidayahrosmee@gmail.com, azlanishak@uitm.edu.my,
khairul87@uitm.edu.my, shariraizat@uitm.edu.my

² School of Chemistry and Environment, Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

Email: sabihahanim@uitm.edu.my

³ Centre For Marine and Coastal Studies, Universiti Sains Malaysia, Penang, Malaysia

Email: aileen@usm.my

⁴ United Nations Sustainable Development Solutions Network (UN SDSN) Asia Headquarters, Sunway University, Sunway City Kuala Lumpur, 5 Jalan Universiti, Petaling Jaya 47500, Selangor, Malaysia

Email: mazlin.mokhtar@unsdsn.org

⁵ Fisheries Research Institute, 11960, Batu Maung, Pulau Pinang, Malaysia

Email: mdnizam@dof.gov.my

* Corresponding Author

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Abstract:

Coastal ocean acidification (COA), driven by rising atmospheric CO₂ levels and localized stressors such as eutrophication and freshwater inputs, poses significant risks to marine ecosystems, fisheries, and coastal communities. Despite its increasing impact, there is limited assessment of COA vulnerability at regional and local scales. This study proposes the development of a Coastal Ocean Acidification Vulnerability Index (COAVI) to systematically quantify and map the susceptibility of coastal environments. The COAVI integrates three key components: (i) Exposure, which includes coastal Total Alkalinity, pH variability, Sea Surface Temperature, Salinity, fCO₂, Aragonite and Calcite Saturation State (Ω_{Ar} & Ω_{Cal}), (ii) Sensitivity, which considers the presence of calcifying species and calcification rates and (iii) Adaptive Capacity, which evaluates socioeconomic resilience, and mitigation strategies. Data will be collected from remote sensing sources, in-situ monitoring, scientific literature, and national reports, followed by normalization, weighting, and spatial analysis using Geographic Information System (GIS) tools. The resulting index will identify high-risk coastal



regions, providing a valuable tool for policymakers, researchers, and conservationists to prioritize intervention strategies. By systematically assessing COA vulnerability, this study aims to support sustainable coastal management and enhance climate resilience in marine-dependent communities.

Keywords:

Ocean Acidification, Coastal Area, Exposure, Sensitivity, Adaptive Capacity

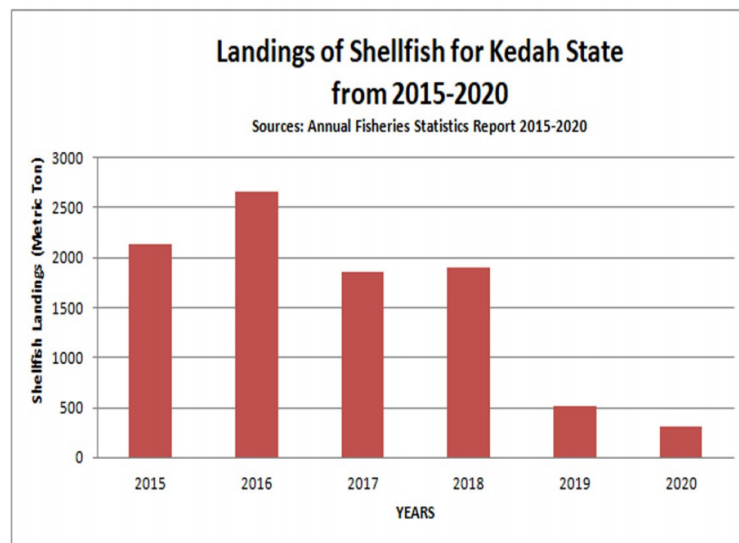
Introduction

The global ocean's carbonate chemistry is undergoing swift transformation because of the absorption of human-generated carbon dioxide (CO₂). This phenomenon, known as ocean acidification (OA), is causing detrimental effects on numerous marine species and ecosystems (Feely, 2023). The origin of ocean acidification is caused by a type of gas known as excess carbon dioxide in the atmosphere. Carbon dioxide (CO₂) is a major greenhouse gas that traps heat in Earth's atmosphere, contributing to climate change (Soeder, 2021; Nadeau et al., 2021; Reichle, 2020). Therefore, this has contributed to the case of global warming and continues further with the effect of ocean acidification.

Among the causes of increased carbon dioxide concentration in the atmosphere are human activities, such as the burning of fossil fuels (coal, oil, and natural gas) for energy, deforestation and industrial processes (Doney et al., 2009; Gruber et al., 2019). Almost 50% more atmospheric carbon dioxide (CO₂) is present today than in pre-industrial times, with 2019 values exceeding 409 ppm (Friedlingstein et al., 2020). Since the pre-industrial era, the ocean has absorbed about one-third of the CO₂ emitted by humans into the atmosphere, causing a decrease in ocean pH of about 0.1 units and a reduction in carbonate ion concentration ([CO₃²⁻]) of almost 20%. (Doney et al., 2009; Feely et al., 2009; Friedlingstein et al., 2019).

According to Vargas (2022), the oceans are currently acidifying at the fastest rate in at least 55 million years. The biggest problem is that increased emissions will lead to even higher rates and higher concentrations of ocean acidification (OA), which will have negative impacts on marine life. This will include inhibited growth of marine animals that rely on calcium carbonate to build their skeletons or shells, as well as the creatures' roles in food webs, nutrient cycling, and habitat development, such as coral reefs (Milita et al., 2023). It is estimated that corals will continue to calcify even after reef water chemistry moves from net precipitation to net dissolution, which is anticipated to happen by 2050 (Eyre et al., 2018)

According to Annual Fisheries statistical report (Figure 1), over the past 6 years, the significant change in the number of cockles landings has been alarming from (2015-2020) with a drastic decline of 85%. Moreover, the declination of shellfish landings was 314 metric ton (2020) compared to the 2,130 metric ton of shellfish landings recorded in 2015. This shows that the cockles which made from calcium carbonate as same as coral reefs also affected by the phenomenon of this ocean acidification which will make the sea condition become more worse.



**Figure 1: Landing Of Shellfish for Kedah State
from 2015 to 2020**

(Source: Annual Fisheries Statistic Reports 2015 to 2020)

A primary cause is ocean acidification, driven by human activities that release carbon dioxide (CO_2) into the atmosphere. About 30% of this CO_2 dissolves into the ocean, forming carbonic acid, which lowers seawater pH and reduces carbonate ion availability (Azetsu-Scott, 2019). These ions are essential for forming calcium carbonate, the material that builds coral skeletons and shells of other marine organisms. The declining carbonate ion concentrations impede coral growth and resilience, jeopardizing the survival of reef ecosystems (Marubini et al., 2003; Guo et al., 2020).

Therefore, the development of a Coastal Ocean Acidification Vulnerability Index (COAVI) is critical to systematically assess and quantify the susceptibility of coastal ecosystems and communities to the growing threat of ocean acidification. A COAVI would serve as a structured, data-driven tool that integrates diverse factors such as chemical trends (pH, carbonate saturation states), biological sensitivities (species resilience), socio-economic dependencies (fisheries, tourism), and adaptive capacity (governance, technology)—into a unified metric. By synthesizing complex ecological and socio-economic information, this index would enable policymakers, researchers, and local stakeholders to identify hotspots of vulnerability, prioritize mitigation efforts, tailor adaptation strategies, and monitor the effectiveness of interventions over time. Furthermore, a well-designed COAVI could enhance public awareness, drive resource allocation, and inform international cooperation on coastal climate resilience initiatives.

Literature Review

Ocean Acidification and Marine Life

The rising atmospheric concentration of CO_2 is the main cause of ocean acidification. The amount of CO_2 in the atmosphere has been greatly increased by human activities such the burning of fossil fuels (coal, oil, and natural gas), deforestation, and the manufacture of cement. Therefore, water all over the planet absorbs a very large percentage of this CO_2 . According to (Jiang et al., 2023), in about 20% to 30% of all anthropogenic carbon dioxide (CO_2) released since the start of global industrialization has been absorbed by the ocean as a result of the burning

of fossil fuels, the manufacture of cement, and changes in land use. (Friedlingstein et al., 2022; Gruber et al., 2019, 2023; Sabine et al., 2004; Terhaar, Frölicher, & Joos, 2022). All this absorption of carbon dioxide by the ocean has led to a chemical reaction, forming carbonic acid that lowers the pH of seawater, a process known as ocean acidification.

Ocean acidification occurs when the process of sea water takes excess carbon dioxide (CO_2) from the atmosphere and makes it more acidic. The term "ocean acidification" refers to a long-term, typically decades-long drop in the pH of the ocean caused mostly by the ocean's absorption of CO_2 from the atmosphere, though other chemical additions or removals from the water can also cause it (Riebesell et al., 2010; Jean-Pierre Gattuso, Lina Hansson; 2011). The future severity of ocean acidification will largely depend on rising atmospheric CO_2 levels (Figure 1). Bindoff et al., (2019) stated, if greenhouse gas emissions follow the high-emission RCP8.5 pathway, seawater acidity could rise by as much as 0.4 pH units by the end of the century.

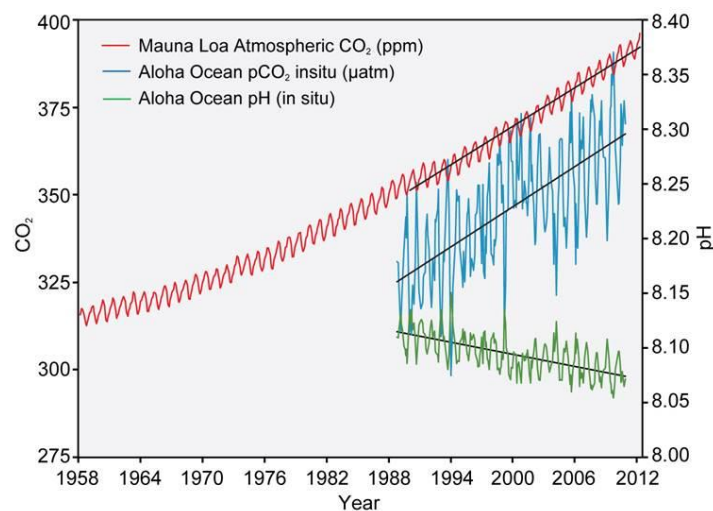


Figure 1: Trends In Atmospheric and Seawater CO_2 Concentrations and Their Impact on Seawater pH in Hawaiian Waters, North Pacific, From 1958 to 2019

Source: (Dore et al., 2020)

The optimum pH value is in range 8.1-8.3 to maintain the health and stability of marine ecosystems, while for the value for the alkalinity in the range of 2.2 to 2.5 meq/L, which is the best value particularly to support calcareous species and as a buffer against pH fluctuations (Middelburg et al., 2020). According to Signorini et al., (2024), animals that are now recognized to be vulnerable to the negative effects of ocean acidification are marine animals that produce calcareous structures, such as shells, exoskeleton and calcareous endoskeleton, such as mollusks, corals and echinoderms. On the other hand, species that rely on calcium carbonate for their shells and skeletons, such as corals, mollusks, and some plankton, find it harder to maintain and build their structures in more acidic conditions (Kroeker et al., 2020). Corals, mollusks, and some forms of plankton find it more difficult to maintain and develop their calcium carbonate-containing shells and skeletons in more acidic conditions (Figure 2).



Figure 2: Dissolution Of Pteropod Shell in Acidified Water, With Near-Complete Dissolution Occurring After 45 Days of Exposure to Seawater Reflecting The pH and Carbonate Concentrations Projected for The Year 2100.

Source: © David Liittschwager/National Geographic Creative.

In addition, ocean acidification can affect the growth, development, population size, and survival of marine organisms (Figure 3). Early life stages tend to be particularly sensitive, with some juvenile fish struggling to find suitable habitats (Heuer et al., 2019). According to Duarte et al., (2021), responses to acidification vary among and within marine species and can be both positive and negative, most scientists agree that ocean acidification will play a significant role in reshaping ocean ecosystems during this century.

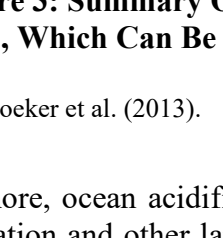
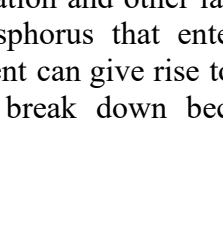
Group		Main response
Algae		Fleshy algae
		Diatoms
		Calcifying algae
Molluscs		Clams, scallops, mussels, oysters, pteropods, abalone, conchs and cephalopods (squid, cuttlefish and octopuses)
Echinoderms		Sea urchins, sea cucumbers, starfish
Corals		Warm and cold water coral
Crustaceans		Shrimps, prawns, crabs, lobsters, copepods, and their relatives contributing to zooplankton
Finfish		Small (herrings, sardines, anchovies), large (tuna, bonitos, billfishes), demersal (flounders, halibut, cod, haddock), etc.

Figure 3: Summary Of the Ocean Acidification Effects Among Major Taxonomic Groups, Which Can Be Represented as Positive (Green) Or Negative (Red) Percentage Changes.

Source: Kroeker et al. (2013).

Furthermore, ocean acidification could also a result of altered land use and nitrogen runoff. Deforestation and other land-use practices can increase the amount of nutrients like nitrogen and phosphorus that enter the ocean. The eutrophication that results from this nutrient enrichment can give rise to algal blooms. Local acidification is exacerbated when these algae die and break down because the process depletes oxygen and carbon dioxide. Ocean

acidification is largely caused by eutrophication, which is the excessive growth of algae as a result of nutrient inputs from humans (Sunda & Cai, 2012). This process is especially noticeable in coastal areas, where the risk of acidification is increased by the input of pollutants from terrestrial ecosystems (Zeng 2015). Eutrophication has been associated with increasing rates of subsurface respiration, primary production, and phytoplankton biomass in the Southern California Bight. This has resulted in a notable loss of oxygen and acidification (Kessouri et al., 2021). Moreover, these impacts of ocean acidification may be intensified by ocean deoxygenation, which is already having consequences for marine life in certain areas (Breitburg et al., 2018). These results highlight the necessity of efficient management plans to lessen the influence of ocean acidification caused by eutrophication.

In short, we need to understand and reduce the process of ocean acidification because it is important for the health of our marine ecosystems and marine world because of the benefits we can get from the sea to maintain the human food supply chain. Ocean acidification is one of the significant environmental problems caused by increasing levels of carbon dioxide gas in the atmosphere. It will result in serious threats to marine ecosystems, biodiversity, and human industries that depend on the oceans. Addressing the issue of ocean acidification requires global cooperation and continuous efforts to reduce carbon emissions and protect the marine environment especially in the unique North Straits of Malacca area with its coral reef ecosystem.

Societal Impacts of Ocean Acidification

Ocean acidification, fuelled by increased anthropogenic carbon dioxide uptake in the world's oceans, has been expected to trigger profound changes in marine ecosystems (Bindoff et al., 2019), having far-reaching impacts on human communities, especially those highly dependent on ocean services and products. Coastal and island communities, industries dependent on fisheries, tourism, and coastal protection, are highly prone to these impacts. Ocean ecosystem service degradation risks not only harming biodiversity and environmental health but also threatening food security, economic stability, and human well-being worldwide Moritz et al., 2023; NOAA, 2020).

According to FAO (2022) and Barange et al., (2018), one of the most direct concerns relates to food security, as globally more than three billion people depend on seafood as a main source of protein, and fisheries and aquaculture in the seas provide livelihoods to millions of people worldwide. Furthermore, ocean acidification makes fundamental physiological functions in sea creatures, such as calcification, respiration, reproduction, and larval development, more difficult (Kroeker et al., 2020). Calcifying animals, like molluscs (e.g., oysters, mussels, and clams), echinoderms, and a number of crustaceans, are most sensitive because these animals depend on calcium carbonate structures, which become harder to produce as seawater pH levels fall (Hennige et al., 2020; Waldbusser et al., 2023). Narita et al., (2018) was stated that, a high-emissions scenario (RCP8.5), we project a global economic loss from reductions in mollusc populations of more than US\$100 billion by 2100, independently of other impacts of ocean change on fisheries production. Acidification has further potential to harm fish larvae and planktonic populations that are at the base of sea foodwebs, resulting in additional decreases in fish stock productivity and overall dependability of seafood supplies (IPCC, 2019; Stiasny et al., 2019).

Coastal protection is also a critical ecosystem service threatened. Mangroves, together with seagrass beds and coral reefs, confer natural protection from waves, storm surges, and erosion. These ecosystems are particularly significant in small island nations and densely populated coastal areas. Coral reefs, for example, can reduce up to 97% of wave energy, thus minimizing potential cyclonic- and storm-related damage, as well as that from other extreme weather phenomena (Ferrario et al., 2018). Ocean acidification lowers the density of coral skeletons, decreases calcification rates, and drives mass bleaching, all of which impair the structure of the reefs and its efficiency as a natural barrier (Hoegh-Guldberg et al., 2019; Cornwall et al., 2021). Disabling this protective service would put millions of individuals, along with billions of dollars' worth of infrastructure, at increased hazard. Its annual economic benefit has been estimated at around US\$9 billion, not incorporating the long-term costs of socioeconomic relocation, rebuilding, and increased susceptibility to disasters (Spalding et al., 2020).

The recreation and tourism industries are also set to be severely hit by ocean acidification. Reef-related tourism is a significant economic force in most areas, creating jobs and generating enormous revenue. Acidification of reefs, along with other stresses like warming and pollution, lowers their aesthetic, as well as ecological, appeal, hence curtailing potential for tourism (Pendleton et al., 2016). GBRMPA, (2019) reported, the Great Barrier Reef Marine Park in Australia, for instance, welcomes a record 1.9 million tourists per annum and generates more than A\$5.4 billion annually in revenue to the country. The same situation is expected in these reef-dependent nations in the Pacific, Southeast Asia, and the Caribbean, where a significant proportion of GDP and employment comes from tourism (Spalding et al., 2017).

Finally, ocean acidification compromises the ocean's capacity to modulate the worldwide climate. Currently, oceans take up 25–30% of anthropogenic CO₂ emissions, serving as a key carbon sink (Friedlingstein et al., 2022). As surface waters become acidified, though, the carbonate buffering system starts to lose its power, making the ocean's capacity to take up more CO₂ weaker (IPCC, 2021). Such a weakened uptake might allow more CO₂ to remain in the atmosphere, potentially speeding up the advance of global climate change. Additionally, alterations in phytoplankton and microbiome composition and productivity under acidified waters might weaken the biological carbon pump, which stores carbon in deeper ocean layers over extended periods of time (Hutchins & Fu, 2017). Overall, persistent ocean acidification poses a multifarious threat to human communities by weakening fundamental marine ecosystem services. From fisheries and coastal protection to tourism opportunities and climate regulation, cascading impacts of acidification underscore the importance of lowering overall CO₂ emissions, as well as increasing adaptation capacity in already vulnerable areas. Holistic policy responses, integrated ocean management, and investment in climate-resilient marine practice will be necessary in order to reduce these impacts and protect the welfare of today as well as future generations."

Coastal Ocean Acidification Vulnerability Assessment

Tropical coastal oceans, highly valued for their richness in biodiversity and contributing significantly to livelihoods of millions of people, face an ever-increasing threat due to the global phenomenon of ocean acidification (OA) (Vargas et al., 2022). According to Hall-Spencer & Harvey, (2019), OA, fuelled mainly by increasing atmospheric CO₂, decreases seawater pH and carbonate ion content, impairing marine organisms' ability to construct and sustain calcium carbonate structures, such as corals, shellfish, and some plankton. In tropical

areas, where coral reef ecosystems represent the pillar of coastal productivity and protection, these chemistry changes can have strong ecological, economic, and social impacts.

Furthermore, Hoegh-Guldberg et al., (2019) was stated, these effects of ocean acidification are further compounded in tropical coastal areas by local stressors such as land-use change, warming sea surface temperatures, and nutrient runoff. Synergies between these factors can promote coral bleaching, modify fish behavior and numbers, and compromise the resilience of ecosystems and supporting communities. To be able to evaluate and address these risks, it is essential to develop a Vulnerability Index (Kroeker et al., 2020). The Coastal Ocean Acidification Vulnerability Index (COAVI) synthesizes exposure to acidification, sensitivity of local populations and ecosystems, and their adaptation capacity. This index, by synthesizing scientific information and socio-economic factors, identifies areas of high risk, ranks conservation and policy interventions, and directs adaptation measures. This index offers an implementable, evidence-based decision-support tool to address long-term ocean acidification impacts in at-risk tropical coastal environments.

The Coastal Ocean Acidification Vulnerability Index (COAVI) is determined by applying a weighted sum technique that incorporates three main components, i.e., Exposure (E_i), Sensitivity (S_i) and Adaptive Capacity (A_i). The overall formula is given as:

$$\text{COAVI} = E_i + S_i - A_i \text{-----} (1)$$

All input components (E_i , S_i and A_i) are normalized to a common range of (0 to 1) to make them comparable and deal with unit bias. This composite index allows vulnerability to be assessed spatially and supports priority areas of high risks to be identified and focused adaptation or management interventions. Importantly, adaptive capacity typically functions to reduce vulnerability. Therefore, its contribution is subtracted in the formula, reflecting its mitigating effect on the combined influence of exposure and sensitivity. This structure enables the COAVI to serve as a robust, spatially explicit tool for identifying and prioritizing areas at higher risk from ocean acidification impacts.

Recently, various parameters and categories have been developed and tested across different regions to assess the vulnerability to ocean acidification. Some of the key ones that have garnered attention are listed in Table 1. As for example, Cheung et al. (2022) established a framework of vulnerability to estimate the effects of ocean change on deep-sea ecosystems. The framework uses three primary components: Exposure, Sensitivity, and Adaptive Capacity. Exposure is quantified by four significant parameters: temperature, dissolved oxygen content, pH level, and export particulate organic matter, which represent the physical and chemical stressors to which deep-sea organisms are subject. Sensitivity is determined by four parameters of biological response: growth, calcification, survivorship, and reproduction, representing how species or communities react to environmental stressors. The Adaptive Capacity is calculated by the level of diversity of the system, with increased richness of species and functional diversity bolstering the resilience of the system and recovery following disturbances. By integrating these parameters in a composite index, this researcher can identify the most at-risk areas and communities of the deep sea and provide a scientific rationale to prioritize conservation and adaptation measures in response to ocean change.

While a study by Johnson et al. (2015) investigated vulnerabilities of fisheries and aquaculture in the tropical Pacific region, covering an area of more than 27 million km² and comprising 22 Pacific Island Countries and Territories (PICTs). The livelihoods, economic incomes, food security, and culture of these communities depend highly on marine ecosystems. The research identifies that climate change and ocean acidification would highly impact coastal and oceanic environments, changing the distribution and productivity of marine organisms and, hence, fisheries and aquaculture sustainability. The study uses the following formula in order to measure vulnerability

$$V = (PI \times AC \text{ index}) + 1 \text{ -----(2)}$$

where V is Vulnerability Index, 'PI' is Potential Impact combining exposure and sensitivity, and AC refers to Adaptive Capacity. The '+1' provides a minimum level of vulnerability, recognizing that no system can be invulnerable. The higher degree of PI or lesser AC level implies higher vulnerability, highlighting increased need to overcome projected impacts in these ecologically. In conclusion, tropical coastal oceans experience increasing threats due to ocean acidification and local stressors of warming, nutrient runoff, and land-use change. Such impacts weaken coral reef ecosystems and undermine associated livelihoods, food security, and marine biodiversity. Therefore, Coastal Ocean Acidification Vulnerability Index (COAVI) was introduced to dictate vulnerability by combining exposure, sensitivity, and adaptive capacity. Normalized metrics facilitate spatial risk assessment and response prioritization. This such tools inform guiding conservation and policy actions to further increase resilience and protect marine ecosystems and associated communities in threatened tropical coastal areas.

Table 1: Categories And Parameters Used from Previous Study to Assess Ocean Acidification Vulnerability

Author	Category (No. of parameters)	Parameter	Location
M. Zulian et al., (2025)	Exposures (5)	pH and Dissolved oxygen data, sensitive to changing thresholds, seasons and biogeography	California
I. Working O. Acidification et al., (2023)	Exposure (3)	Ocean and Coastal Acidification Monitoring, Ocean and Coastal Acidification Modeling	Northeast Region, Mid -Antlantic Region, Southeast and Caribbean Region, Gulf of Mexico Region, Alaska Region, West Coast Region, Pacific Islands Region
	Biological Response (3)	Species and Habitats, Important Species, Populations	
	Social Vulnerability (2)	Economic and Cultural Communities,	

Author	Category (No. of parameters)	Parameter	Location
R. Losciale et al., (2023)	Exposures (3)	Spatial scale, Frequency, trend	Temperate Antlantic, Tropical Atlantic, Mediterranean, Temperate Pasific, Tropical Indo-pasific, Temperature Southern
	Sensitivity (4)	Functional impact, resistance, recovery time, certainty	
	Adaptive capacity (1)	Diversity	
	Potential Impacts (3)	Bioregion, Climate change and Direct-Antropogenic	
T. Rouleau et al., (2022)	Ecological (4)	Geology/water, Climate, Ecosystem, Fisheries	Castries, Saint Lucia, Kingston and Jamaica
	Financial (3)	Economics, Major industries, Infrastructure	
	Political (3)	Social/Demographics, Governance, Stability	
W. Cheung et al., (2022)	Exposure (4)	Temperature, Dissolve oxygen concentration, pH level, export particle organic matter	Northern Atlantic Ocean and the Indo-Pacific region
	Sensitivity (4)	Growth, calcification, survivorship and reproduction	
	Adaptive capacity (1)	Diversity	
P. Steward-Sinclair et al., (2020)	Exposure (4)	Sea surface temperature, ocean acidification, primary productivity, extreme weather	Antartica
	Sensitivity (3)	Specles sensitivity, economic dependence, nutritional dependence	
	Adaptive capacity (2)	Diversity, governance	
J. Johnson et al., (2015)	Exposure (2)	aragonite saturation and area of reef to land area	Pacific Islands
	Sensitivity (4)	Food security (coastal population, annual fish consumption, projected coastal fisheries declines, and distance of reefs from population centres) Number of aquaculture jobs, Tourism and household earnings	

Author	Category (No. of parameters)	Parameter	Location
	Adaptive capacity (4)	Health, education, economy and governance	
D. Cyrus et al., (2011)	Exposure (1)	each country received a fraction of a point based on the number of years until the Ω Ar transition decade	All nations
	Sensitivity (2)	Provide more than 0.001% of the GDP, Protein insufficient and citizens' protein	
	Adaptive capacity (5)	required increase in production by 2050 is more than 100%, the country currently does not have mollusc aquaculture, countries also received points based on the rank of their average adaptabilities, economic and governance data	

Methodology

The method used in the current study is quantitative, as it involves the systematic collection, analysis, and integration of numerical data to develop the Coastal Ocean Acidification Vulnerability Index (COAVI). The study quantifies key environmental parameters such as pH, total alkalinity, sea surface temperature, salinity, fugacity of CO₂ (f CO₂), and saturation states of aragonite and calcite (Ω Ar and Ω Cal), along with biological indicators like calcification rates and the presence of calcifying species, and socioeconomic indicators such as income diversity, education level, and governance strength. Several studies have explored the development of composite vulnerability indices to assess climate change impacts. These indices typically integrate indicators of exposure, sensitivity, and adaptive capacity, normalized to a common scale and weighted based on relevance (Balaganesh et al., 2020; Yu et al., 2021; McIntosh & Becker, 2020; Edmonds et al., 2020). These variables were normalized to a common scale, weighted based on scientific relevance, and mathematically integrated into a composite index using the formula $COAVI = Exposure + Sensitivity - Adaptive Capacity$.

Conceptual Framework for Assessing Coastal Ocean Acidification Vulnerability

The Coastal Ocean Acidification Vulnerability Assessment is an integrative framework to assess the risk to coastal marine ecosystems and human societies posed by ocean acidification (OA). It is structured around three interconnected elements: exposure, sensitivity, and adaptive capacity. Exposure is defined as the degree to which an area is subject to chemical and physical alterations of OA. Of particular relevance exposure indicators are total alkalinity (TA), an indication of seawater buffering capacity; pH, an indication of acidity; aragonite and calcite saturation states (Ω Ar and Ω Cal) as critical to shell and coral formation; fugacity of CO₂ (f CO₂) as an indication of dissolved CO₂ pressure; and sea surface temperature, exacerbating OA impacts and coral bleaching. Lastly, salinity, shifts in salinity impact seawater chemistry and marine organism stress responses. Sensitivity represents the degree to which ecosystems can be impacted, highlighting the presence and diversity of calcifying organisms such as corals,

cryptofauna, coral reefs, and mollusks. Their biological function, particularly calcification and accretion rates, is directly impacted by acidification and therefore represent critical indicators. The assessment of adaptive capacity is concerned with how well human and ecological components can adapt to OA impacts. This ranges from socioeconomic resilience in terms of infrastructure, education level, and diversification of incomes, to local mitigation actions like marine protected areas, sustainable fishing and coastal construction practices, and OA monitoring. Individually, these indications are integrated within an index that enables spatial assessment of exposure, guiding priorities and targets of conservation, policy-level decisions, and adaptability actions aimed at protecting tropical coastal ecosystems and societies. The framework and components are summarized in Figure 4.

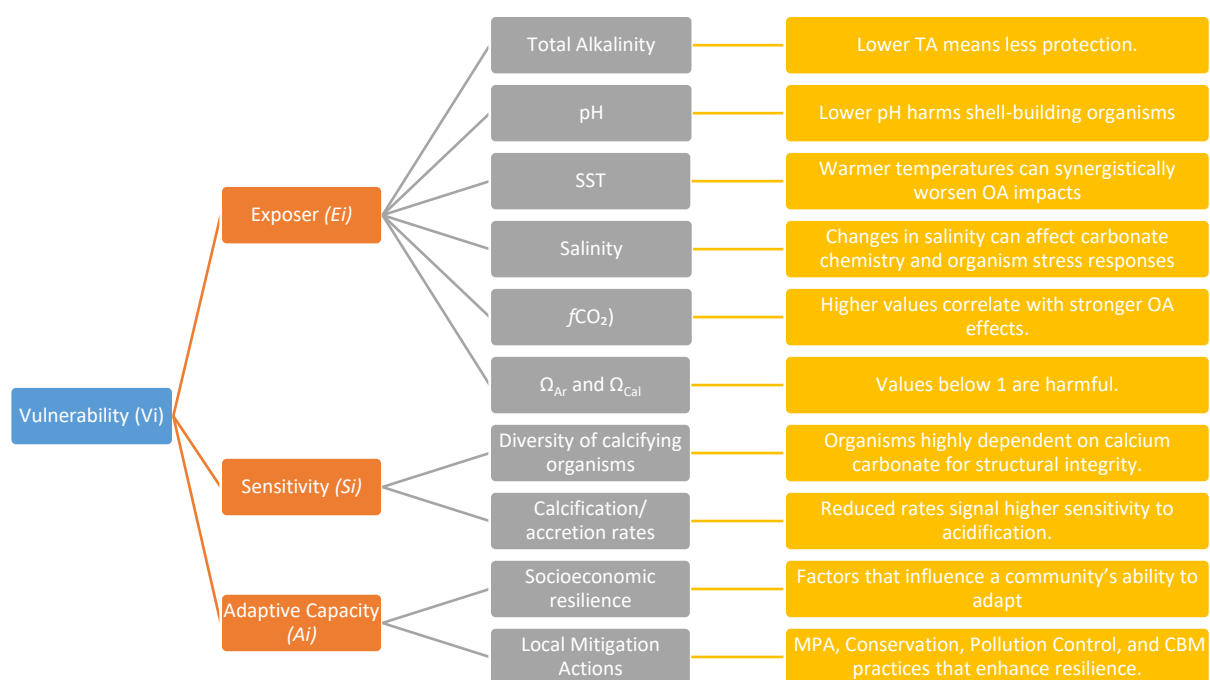


Figure 4. A Schematic Representation of The Vulnerability Assessment Framework, Demonstrating That Overall Vulnerability Is Determined by The Combination of Three Factors: Exposure, Sensitivity, And Adaptive Capacity, Each of Which Includes Subfactors.

Exposure Indicator

Exposure metrics are primary parameters employed to measure the extent to which coastal ecosystems are exposed to the stresses of ocean acidification (OA). According to Gledhill et al., (2021), these indicators capture essential elements of seawater chemistry and physical status that control marine organisms' biological response, especially calcifiers like corals, molluscs, and some planktonic organisms. Among exposure indicators, there is Total Alkalinity (TA) that crucially reflects seawater's ability to buffer (Fassbender et al., 2020). Moreover, Jiang et al., (2019) was stated, decreased TA suggests poorer buffering capacity and greater susceptibility to pH decreases due to higher atmospheric CO₂ content. This is significant in coastal environments affected by freshwater input, which usually reduces TA and amplifies acidification impacts. Next parameter was pH, a direct measure of seawater acidity level, is

another vital indicator (Feely et al., 2020). As increasing amounts of CO₂ enter the ocean, it reacts to form carbonic acid, decreasing pH and disrupting carbonate chemistry. This transition decreases carbonate ion content, disrupting calcification functionality in shell- and skeleton-producing organisms (Gomez et al., 2020). pH is closely related to aragonite (Ω_{Ar}) and calcite (Ω_{Cal}) saturation states, and these control thermodynamic potential of these minerals to be formed or dissolved. According to Sharp et al., (2022), aragonite is particular significance to tropical reef environments since most coral organisms depend upon supersaturated aragonite states ($\Omega_{Ar} > 3$) to sustain growth and structural integrity. In addition, if Ω_{Ar} drops below then one (1), it's means environments are corrosive where aragonite will dissolve at rates higher than it can be produced, and reef sustainability will be compromised (Hofmann et al., 2020). Likewise, Ω_{Cal} indicates conditions suited to organisms that form calcite such as coccolithophorids, foraminifera, and coralline algae, where calcite is generally stable though still susceptible to prolonged low-saturation states (Kapsenberg & Cyronak, 2019).

Another significant chemically relevant indicator is fCO_2 , or the effective concentration or pressure of seawater CO₂ (Takahashi et al., 2021). High values of fCO_2 relate to increased acidification potential and both reflect and inform about atmospheric CO₂ uptake and local biogeochemical processes like respiration and upwelling. Concurrently, sea surface temperature (SST) is a salient physical forcing that acts synergistically with OA. Dutkiewicz et al., (2020) was define, an increased temperature will decrease the solubility of water's CO₂ content and can boost marine organism's metabolic and stress response, and high SST values result in coral bleaching (Hughes et al., 2019) as well as decreased resilience of already stressed reef ecosystems due to low pH and carbonate saturation. Finally, salinity affects both carbonate chemistry and organism health. Alterations in salinity due to rainfall, river input, or evaporation impact ion concentration and buffering capacity (Jiang et al., 2021). Lower salinity generally decreases carbonate ion availability, resulting in lower saturation states and preventing calcification. On the other hand, lower salinity also contributes osmotic stress (Waldbusser et al., 2020), and modelling these additional stressors to marine organisms in acidifying environments exacerbates the physical challenges to organisms.

Overall, exposure indicators give a multi-aspect view of environmental drivers of ocean acidification. Measuring and monitoring these parameters which include TA, pH, Ω_{Ar} , Ω_{Cal} , fCO_2 , SST, and salinity enable scientists to assess coastal ecosystems' vulnerabilities to a higher degree, predict biological impacts, and inform the creation of adaptation measures to counteract long-term risks (Pacella et al., 2020). The integration of these indicators in vulnerability frameworks is particularly crucial when it comes to managing tropical marine ecosystems' health and sustainability (Doney et al., 2020), where there is high ecological richness and human reliance on marine resources.

Sensitivity Indicators

Sensitivity indicators are used to evaluate how vulnerable ecological systems are to stressors (Kroeker et al., 2020). Indicators reflect the intrinsic biological and ecological properties that dictate to what degree an organism or habitat is sensitive to chemistry changes in seawater, particularly decreased pH and carbonate saturation states. The sensitivity of a system is higher when it is most likely to be affected by the adverse impacts of decreased growth, structural damage, and loss of diversity. According to Fabry et al., (2018) and Foo & Byrne, (2019), one of the crucial sensitivity indicators is biodiversity of calcifying organisms, representing an array of marine taxa depending on calcium carbonate (CaCO₃) to form their shells or skeletons.

Moreover, Chan et al., (2019) emphasizes, among the most sensitive of these are foraminifera (calcium carbonate-containing microscopic protists with calcareous tests), cryptofauna (dwellers hidden within reefs that are invertebrates), coral reef organisms, and mollusks (bivalves and gastropods). Either aragonite or calcite the dominant crystalline types of CaCO_3 are used by these organisms, and both become harder to form as ocean pH decreases and carbonate ions become less available. Decline or loss of these taxa's abundance and range harms them, of course, as well as disturbing associated higher-order ecosystem processes like habitat development, nutrient cycling, and web of life dynamics.

Another significant sensitivity indicator is reef-building organism and habitat calcification and accretion rate. Calcification rate is the rate at which organisms, particularly corals and calcifying algae, deposit calcium carbonate to form and repair skeletal tissue. Accretion rate takes this principle to reef-scale and measures the net accumulation of calcium carbonate structure over time. Acidification of oceans lowers carbonate mineral saturation state and hence reduces energy efficiency and biochemical pathways associated with calcification. As the rates of these processes slow down, reef structure becomes weakened and prone to erosion and bio-erosion, undermining protective and habitability functions (Enochs et al., 2020). Decline in calcification and accretion rates is thus an unambiguous biological metric of rising ecological sensitivity to OA.

In tropical areas, where coral reefs have an ecological and economic keystone role, lower biodiversity and decreasing calcification translate immediately to increased sensitivity (Hall-Spencer et al., 2020; Agostini et al., 2021). Such environments not only lose structural resilience and complexity, but also imperil those benefits they offer in coastal protection, fisheries, and tourist revenue. By incorporating these measures of sensitivity into assessments of OA impacts, scientists can more accurately forecast both how much and in what way OA will affect them (Cornwall & Hurd, 2019), where best to prioritize conservation actions, and how to create more focused mitigation and adaptation initiatives.

Adaptive Capacity Indicator

Scientifically, adaptive capacity indicators reflect human and ecological systems' capability to adapt to, cope with, or recover from ocean acidification impacts (Bindoff et al., 2019). Indicators of adaptive capacity play a crucial role in distinguishing between vulnerability and exposure and sensitivity since they reduce the detrimental impacts related to exposure and sensitivity. Cinner et al., (2018) stated, a main adaptation capacity measure is socioeconomic resilience, in terms of diversity of incomes, access to education, good governance, and economic resilience. Community ability to absorb losses due to declining tourism or fisheries improvement where there is diversity of incomes. Education improves awareness and capacity to adapt, and good governance and sound economies enable application of policies and investment appropriate to adapt. Furthermore, another significant sign is the application of local mitigation measures. According to Pendleton et al., (2016), among them are marine protected areas (MPAs) that mitigate ecological stress and enable recovery of biodiversity; reef restoration initiatives, which restore coral resilience and structural integrity; and pollution control practices like mitigation of land-based nutrients that can increase acidification by eutrophication. Community-based management reinforces adaptive capability by engaging local actors in making decisions and combining traditional knowledge and scientific methods (Schoeman et al., 2020). In ecological communities, functional diversity and resilient species with an ability to tolerate acidification can be an indication of adaptive capacity (Graham et

al., 2015). With high adaptive capacity, long-term exposure to threats is decreased by enhancing recovery of ecosystems and retaining ecosystem functions.

Vulnerability Analysis

Vulnerability Analysis of coastal ocean acidification is usually done by adopting a structured, multi-step procedure that merges environmental, biological, and socio-economic information (Figure 5). The initial step is to specify the scope and objective of assessment by considering particular coastal areas, reef system, or dependent societies. After defining the scope, respective parameters of components of vulnerability and corresponding indicators for them are chosen. The exposure indicators (e.g., TA, pH, SST, Salinity, fCO_2 , Ω_{Ar} and Ω_{Cal} and sensitivity indicators (e.g., diversity of calcifying organisms and Calcification/ accretion rates) and adaptive capacity indicators (e.g., socioeconomic resilience and local mitigation actions) are typically considered. The chosen indicators are then normalized to the same range, usually between 0 and 1, to facilitate comparability between units and types of data. Following normalization, weights to the indicators are then determined by literature review and expert input. The resulting index values can then be spatialized using Geographic Information System (GIS) software such as QGIS to map high-risk areas. The results should finally be tested with expert knowledge or historical impact records, and sensitivity analysis is advised to examine index robustness. This integrated strategy enables decision-makers to rank areas of intervention, facilitate adaptation planning, and inform coastal resource use in response to ocean acidification

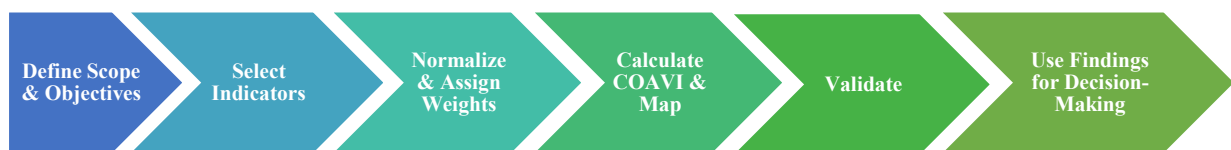


Figure 5. Workflow of the Coastal Ocean Acidification Vulnerability Assessment Framework.

Conclusion

In conclusion, based on the document titled “Development of a Coastal Ocean Acidification Vulnerability Index (COAVI)”, the study's objectives were clearly achieved, as it successfully created a comprehensive index that combines exposure, sensitivity, and adaptive capacity to evaluate the vulnerability of coastal environments to ocean acidification. Using indicators such as pH, aragonite saturation, CO_2 levels, biodiversity, and socioeconomic resilience, the framework offers a practical tool for policymakers and researchers to identify high-risk areas, allocate resources, and strengthen climate adaptation strategies. Although the approach is methodologically strong, it faces limitations in data availability, temporal variability, and measuring factors like governance capacity. Future work should focus on empirical validation, expanding to other regions, integrating climate projections, and including stressors such as pollution and overfishing for a more complete assessment. Overall, the study makes a valuable and timely contribution to marine science, offering both a diagnostic and strategic framework to safeguard coastal ecosystems and dependent communities from the escalating impacts of ocean acidification.

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