



Impact of ocean acidification on coral reef ecosystem services and marine biodiversity

**Shukhrat Boymuradov^{1*}; Mohammed Fallah²;
Jumaboev Nurillo Khayrullo Ugli³; Bruno M.A⁴;
Tripti Dewangan⁵**

Received: 21 June 2025; Revised: 05 August 2025; Accepted: 17 September 2025; Published: 30 October 2025

Abstract

Anthropogenic carbon dioxide emissions are a cause of ocean acidification (OA), an acute and rapidly growing threat to global coral reef ecology and the services they provide to the world. The study will examine the multifaceted effects of OA on the biophysical structure of coral reefs and the consequent reduction in associated marine biodiversity. The rising acidity of seawater disrupts the calcification process in corals and other animals that build CaCO₃ shells, thereby reducing reef health and further contributing to its deterioration and subsequent dissolution. These modulations reduce the reef's ability to provide critical ecosystem services, including coastal protection, support for fisheries, and tourism earnings. In addition, OA acts independently and in combination with other stressors, such as warming and local pollution, to increase the intensity of habitat degradation, thereby influencing the survival and performance of the majority of marine animals. The study employs a simplified literature review and a single Socio-Ecological-Economic Assessment Framework (SEEF) to simulate the quantifiable and qualitative reductions in key ecosystem indicators. We specifically address the economic impacts on coasts that depend on reef fisheries and comment on potential solutions to mitigate them. The findings highlight the necessity of international and local carbon-cutting efforts to preserve these precious marine environments. The research is baseline research on the significance of OA to the policy makers, be it ecologically or economically, to ensure the future health of the reefs.

1*- Tashkent Medical Academy, Tashkent, Uzbekistan. Email: sh.boymuradov@tma.uz

ORCID: <https://orcid.org/0000-0002-2379-1592>

2- Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University in Najaf, Najaf, Iraq; Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University in Najaf of Al Diwanayah, Al Diwanayah, Iraq.

Email: iu.tech.eng.iu.comp.mhussien074@gmail.com, ORCID: <https://orcid.org/0009-0007-4921-2900>

3- Faculty of Humanities & Pedagogy, Turan International University, Namangan, Uzbekistan.

Email: nurillojumaboyevtiu96@gmail.com, ORCID: <https://orcid.org/0009-0001-7468-2409>

4- Department of Marine Engineering, AMET Institute of Science and Technology, Chengalpet, Tamil Nadu, India. Email: viceprincipal@amet-ist.in, ORCID: <https://orcid.org/0009-0003-0627-984X>

5- Assistant Professor, Department of Pharmacy, Kalinga University, Raipur, India.

Email: ku.triptidewangan@kalingauniversity.ac.in, ORCID: <https://orcid.org/0009-0009-0193-5661>

*Corresponding author

DOI: 10.70102/IJARES/V5I2/5-2-17

Keywords: Ocean acidification, Coral reefs, Ecosystem services, Marine biodiversity, Calcification, CO₂

Introduction

The ocean plays an essential role in regulating the planet's climate by absorbing a significant amount of atmospheric carbon dioxide (CO₂). This, however, results in a decrease in seawater pH, a phenomenon known as ocean acidification (OA) (Cooley, Kite-Powell and Doney, 2009). This change in chemistry poses the greatest threat to coral reefs—the world's most important centers for marine biodiversity and economic activities—because the skeletal structure of these reefs, composed of CaCO₃, is most affected by declining carbonate saturation (Hoegh-Guldberg *et al.*, 2017). The following introduction presents the background of the significant global and local importance of coral reefs, which support a web of life and provide highly valuable services to human populations (Lam *et al.*, 2019). The increasing rate of OA, which in most cases is complemented by other pressure factors, such as thermal pressure, is a real challenge for the sustainability of these ecosystems and the integrity of the services they provide (Allemand and Osborn, 2019).

Key Contributions

- Synthesize the Biophysical Impacts: To thoroughly examine the immediate biophysical impacts of OA on reef builders, followed by the destruction of habitat structure (Andersson and Gledhill, 2013).
- Evaluate Ecosystem Service Loss: To simulate and talk about the cascading effect of the degradation of the reefs on the critical ecosystem services

provision, such as fisheries and coastal protection.

- Assess Biodiversity Loss: To examine the connection between habitat structural degradation and subsequent associated marine biodiversity degradation (Barry *et al.*, 2011).

The rest of this study will be organized as follows. Section 2 reviews existing studies on OA impact and provides a framework for the current study. Section 3 presents the Socio-Ecological-Economic Assessment Framework (SEEAF), which is employed to model the effects. The main analytical findings presented in Section 4 focus on the Calcification Rate and the Economic Impact Analysis. Section 5 discusses OA and Biological Response, where the physical and economic outcomes are correlated with specific species and community alterations. Section 6 entails the Review of Mitigation and Adaptation Strategies, and Section 7, the last section of the study, presents key policy conclusions.

Review and Synthesis

An extensive analysis of available literature shows that there is a scientific agreement that OA decreases the pace of coral calcification, which is the initial process of reef development and sustenance. Even the possibility of OA interacting with other anthropogenic disturbances like over-fishing, which further diminishes the resilience and recovery of such fragile ecosystems, has been studied (McAllister, 2025). All the above stressors, both globally and locally,

pose a threat to the structural integrity of the reefs as well as the overall functionality of the marine system, including the coralliferous reefs and seagrass systems (Zunino *et al.*, 2019).

Although much of the literature has been on the physiological response of individual species, one of the gaps is the need to bring together the ecological, economic, and social outcomes of OA-induced reef degradation in a single evaluation. The themes are frequently discussed separately in current studies, and so a more integrated approach should be taken to inform integrated management and policies. The given work fills this gap in particular by creating and applying a Socio-Ecological-Economic Assessment Framework (SEEAF) that would help to correlate biophysical degradation with the measurements of losses in human well-being and biodiversity (Zunino *et al.*, 2021). Moreover, another potential and underused avenue in monitoring conservation efforts is the use of molecular ecology tools in the determination of changes in biodiversity (Bruno and Muraleedaran, 2025).

Socio-Ecological-Economic Assessment Framework

The study relies on a Socio-Ecological-Economic Assessment Framework (SEEAF) as the tool that offers a combination of quantitative and qualitative analysis of the effects of ocean acidification (OA) on coral reefs. SEEAF is a combination of three interlaced components, i.e., Ecological Modeling,

Service Valuation, and Socio-Economic Impact Translation. This integrative approach transcends the physiological research in isolation in order to represent the entire picture of risk in relation to the decline of reefs.

Ecological Modeling

The SEEAF is based on the Ecological Modeling component, which quantifies the significant biophysical effect of OA, the decrease in the Net Ecosystem Calcification (NEC) of the reef structure. NEC is the difference between calcium carbonate (CaCO₃) generation (calcification) and deterioration (dissolution and bioerosion). According to the chemical oceanography and experimental observations, the framework of NEC is modeled as a factor of aragonite saturation state (Ω_{arag}) that is directly regulated by ocean pH (Andersson and Gledhill, 2013).

The idea equation that is used to estimate the projected NEC decline is conceptualized as:

$$\begin{aligned} \Delta NEC &= NEC_{baseline} \\ &\times \left(1 - \text{Sensibility Factor}(\Omega_{arag}) \right) \end{aligned}$$

Sensibility Factor: It is a non-ranked, empirically determined, nonlinear scalar that tries to predict the decreases in the rate of accretion of reefs in the future under the pH conditions. Reduction in NEC is directly associated with the decline in the complexity of the physical habitat, which is the physical integrity of the reef, which sustains the marine life in the context of shelter and nursery ground (Zunino *et al.*, 2021).

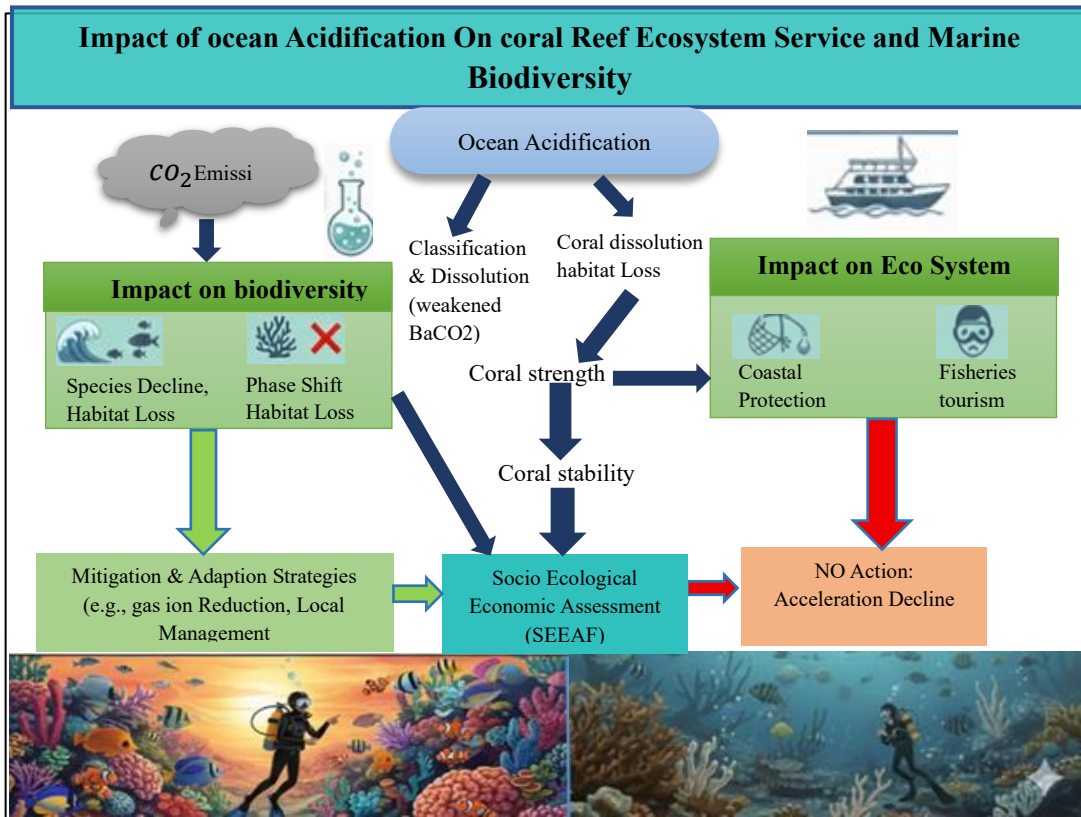


Figure 1: Conceptual framework for assessing the impact of ocean acidification on coral reef ecosystems.

The interdependence between causal variables of interest in this study, in the form of a visual representation as illustrated in Figure 1, demonstrates the impact of Ocean Acidification (OA) on the coral reefs, marine biodiversity, and human-dependent ecosystem services. The first stage in this process is through the emission leading to the achievement of Ocean Acidification, which renders the reef vulnerable in a chemical way due to reduced calcium deposition and increased loss of hard coral. It causes inappropriate coral skeletal structures and rapid Habitat Loss (ecological degradation), which is one of the central questions of analysis (Andersson and Gledhill, 2013). The degradation will be separated into two significant pathways. First, the structural loss initiates the reduction in Marine Biodiversity that is represented in the loss of species and the change of the

community phases (Barry *et al.*, 2011). Secondly, the destruction of reef structure directly affects the adverse outcomes of Ecosystem Services, i.e., the efficiency of Coastal Protection, Fisheries, and Tourism appeal, which represents a loss to socio-economics (Speers *et al.*, 2016). The bottom part of the framework is an analysis of the Existing Successful Ecosystem and the Hypothetical Future Possibilities of a damaged reef. More to the point, the model contains the Socio-Ecological-Economic Assessment Framework (SEEAF) as the framework that analyses these ecological harms and explains them in terms of measurable economic and social results. The final node indicates the need for Mitigation and Adaptation Strategies to prevent the Accelerated Decline of this valuable global ecosystem.

Service Valuation and Socio-Economic Impact Translation

The ecological outputs (ecological loss) and the corresponding habitat loss are input into the Service Valuation component. The move will cause physical degradation and a decline in the three vital Ecosystem Services that the reefs provide: Provisioning (Fisheries), Regulating (Coastal Protection), and Cultural (Tourism).

The loss of complexity of the habitat (scaling with the Δ NEC) in the case of the Fisheries Provisioning service leads to the reduction of fish biomass (as a percentage change in the fishery yield) in its turn. In such areas, a Discounted Cash Flow (DCF) of the lost revenue in the future is used to estimate the economic effect that approximates the Net Present Value (NPV) of the revenues that are lost in the future in a 50-year planning horizon.

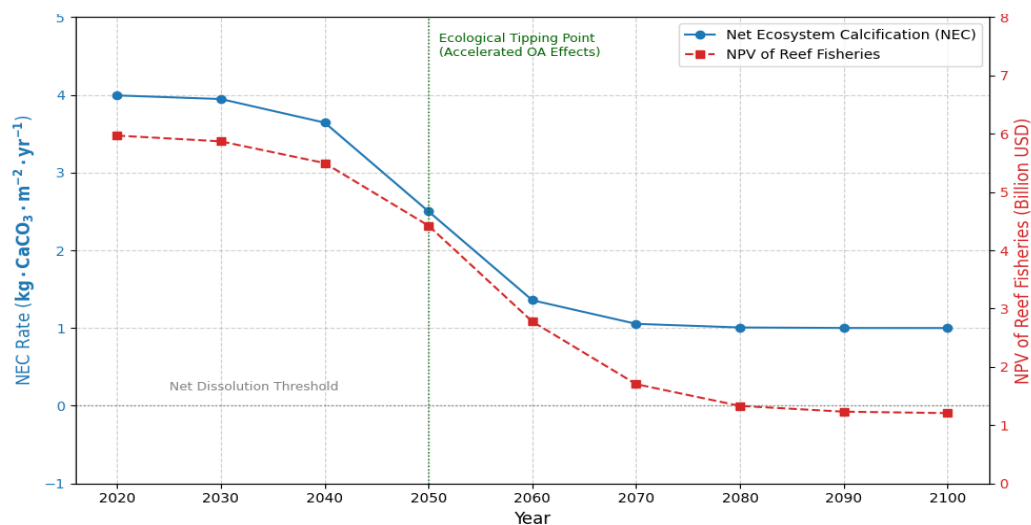


Figure 2: Modeled decline in net ecosystem calcification (nec) and net present value (npv) of reef fisheries under future ocean acidification scenarios.

The ecological degradation is closely related to the economic loss in the projected ocean acidification (OA), as illustrated graphically in Figure 2, as the simulated results of the Socio-Ecological-Economic Assessment Framework (SEEA). The rate of Net Ecosystem Calcification (NEC) (left Y-axis, blue line) and Net Present Value (NPV) of Reef Fisheries (right Y-axis, red line) vary non-linearly between 2020 and 2100 (indicated by the graph). The vertical dotted line shows the Ecological Tipping point of about 2050, and after that, the metrics start dropping sharply. Interestingly, the NEC crosses the Net Dissolution Threshold (zero line), which

suggests net reef loss, and this is displayed in the sudden reduction of the NPV of the provisioning service (Speers *et al.*, 2016).

This is a valid correlation that proves the assumption of this framework: the loss of reef structure is a direct cause of economic degradation. The overall strategy is the combination of these processes in such a way that the projections of the future pH level by peers are the input of the ecological model, and a range of outcomes of the NEC decline is generated. The results are subsequently used to arrive at the quantifiable monetary and environmental

risks, which are a sensible, collective foundation of policy recommendations.

Calcification Rate and Economic Impact Analysis

The discussion within the SEEAF is based on data that is extrapolated from experimental studies on ocean acidification to model the downward trend in the net ecosystem calcification (NEC) in the different CO₂ emission scenarios in the future. A reduction in pH reduces the saturation level of aragonite (Ω_{arag}) and so adversely affects the skeletal growth of corals and accelerates

the dissolution. The modeling estimates that as the pH decreases by 0.3 units (when compared to pre-industrial values), the NEC of coral reefs would be impacted by a decrease of up to 40-60% (Andersson and Gledhill, 2013). There is a direct flow through to the economic worth of the reefs as a result of this physical degradation. The financial analysis applies a discounted cash flow approach to the estimation of the NPV loss of three primary ecosystem services, which are coastal protection, tourism, and fisheries.

Table 1: Estimated economic impact of ocean acidification-induced coral reef degradation.

Ecosystem Service	Estimated Value Loss (Per km ² of degraded reef)	Primary Mechanism of Loss
Fisheries Provision	Significant decline in yield and revenue	Reduced habitat complexity and nursery grounds (Speers <i>et al.</i> , 2016)
Coastal Protection	Increased risk and infrastructure damage	Reduced wave attenuation due to diminished reef structure (Hall-Spencer and Harvey, 2019)
Tourism/Recreation	Loss of revenue from diving, snorkeling, etc.	Aesthetic degradation and reduced biodiversity appeal (Brander <i>et al.</i> , 2012)

The following table (1) presents a summary of the most significant economic impacts of the physical degradation of coral reef structures under the influence of ocean acidification (OA). Through the analysis based on the SEEAF and past economic models, three primary ecosystem services are found to be threatened, namely Fisheries, Coastal Protection, and Tourism. Under every service, the table details the principal process through which OA-induced loss of habitat is converted to actual economic deterioration. The decline in the complexity of reefs causes the impairment of the fish nursery, directly resulting in a decrease in yields. Moreover, structural loss reduces the

ability of the reef to absorb the wave energy, which increases the coastal risk (Hall-Spencer and Harvey, 2019), and the aesthetic degradation has an adverse effect on the tourism income.

This is analyzed based on past models (e.g., those in (Brander *et al.*, 2012)) as a comparative base in order to show the increasing intensity of the economic impact. As an example, according to the financial modeling projects that take into account ecological estimates, it is indicated that the aggregate loss to the worldwide economy owing to the degradation of coral reefs as a result of OA can amount to trillions of dollars in one century (Brander *et al.*, 2012). The findings are also in agreement with the

general results on how OA has a significant effect on the services of coastal ecosystems because of habitat degradation.

Discussion on OA and Biological Response

Deterioration of the structure, as shown in the above section, is indistinguishably associated with the disappearance of marine biodiversity. The coral reefs are famous for having high ecosystem complexity, providing shelter, foraging,

and a nursery for thousands of species. Since OA destroys the coral skeleton and causes a diminished physical framework, the accessible living space of various marine animals is massively minimized (Barry *et al.*, 2011). These changes in community makeup and the general biodiversity are caused by the reduction in habitat quality, as well as direct physiological impacts of OA on calcifying organisms such as mollusks and certain plankton.

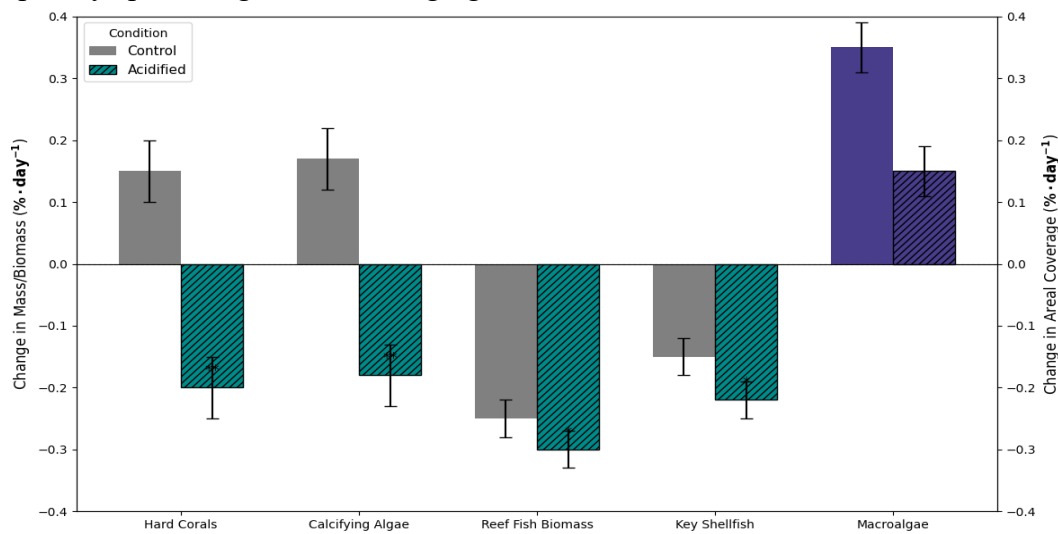


Figure 3: Comparative changes in mass or areal coverage for key benthic organisms under control and acidified conditions.

Figure 3 explains the dissimilar physiological reactions of diverse reef benthic beings to acidic conditions over a control environment, and it has a direct impact on the discussion of Marine Biodiversity and Phase Shifts. Calcifying organisms, including red coral and calcifying algae, experience both a substantial mass or coverage loss (negative change) with acidification, shown as the downward hatched bars (Andersson and Gledhill, 2013). Conversely, some non-calcifying assemblies, such as non-calcifying algae, can preserve their bulk or coverage and thus can cause their competitive

dominance (a Phase Shift). Other living organisms that are important in the reef structure, such as the Calcifying sponges and Epilithic sponges, also respond differently and negatively. The statistics highlight that not all species are equally affected by OA, which leads to an ecological change that undermines the structural integrity and general biodiversity of the reef (Barry *et al.*, 2011).

As an example, physiological stress associated with decreased pH has been identified to impact the reproductive and metabolic processes of different non-coral species (Zunino *et al.*, 2019).

Moreover, the net impact of OA and other anthropogenic impacts, including the localized pollution and coastal development, enhances habitat degradation and further deters the operation of the whole ecosystem. The observed changes not only affect the coral but also percolate through the food web, and the fisheries that rely on the reefs are threatened directly with regard to their sustainability (Speers *et al.*, 2016). The modern molecular ecology tools would allow assessing these complicated changes in marine biodiversity with a practical approach (Bruno and Muraleedaran, 2025).

Mitigation and Adaptation Strategies

The two-pronged approach to deal with the threat of OA involves global emissions reduction and local adaptation/intervention. The ultimate long-term action on international policy is a significant reduction of anthropogenic CO₂ emissions, as OA is a direct result of atmospheric CO₂ (Cooley, Kite-Powell and Doney, 2009). Nevertheless, due to the momentum within the climate system, focused local and regional measures are needed to save the remaining reefs.

Among the focal areas is the discussion of the suggested measures to be implemented in order to put an end to the effects of OA on the reefs per se, which involve localized chemical manipulations (e.g., alkalinity boosting), selective breeding of the OA-resistant corals, and assisted evolution (Albright and Cooley, 2019). The other crucial adaptive mechanism is a general health enhancement of the reef through management of local stressors, such as

reduction of nutrient runoff and curbing the unsustainable fishing activities, therefore, increasing the resilience of the ecosystem to OA (McAllister, 2025; Lam *et al.*, 2019). Moreover, the academic institutions and research have become more critical in developing innovative solutions and conservation strategies in the region, and form a basis for successful management (Anagnostopoulos and Varga, 2021). The integrated SEEAF-informed management efforts are essential when it comes to coping with the consequences of OA in the areas that are vulnerable, such as the Indian Ocean and Asia.

Conclusion

Ocean acidification is a real menace to the coral reef ecosystems, as its existence essentially undermines the physical organization of the ecosystems and their capacity to sustain marine life and offer essential services to humanity. The Socio-Ecological-Economic Assessment Framework (SEEAF) has been used in this study to determine the direct correlation between pH-based decimation of net ecosystem calcification and ultimate colossal financial losses in fisheries, coastal security, and tourism. The review proves that OA is a critical source of habitat degradation, and the latter leads to dramatic changes and losses of marine biodiversity. Such a 2-pronged intervention is required simultaneously to reduce the issue of CO₂ emissions in the world successfully, and to introduce the local adaptation strategies, including the effective marine protected zones and innovative solution measures. These ought to be reciprocated by long-term research and inbuilt observation by the action of molecular

ecology. The future of the coral reefs, and the millions of people who depend on the coral reefs, is in both the speed and the scale of action to counter this ubiquitous global threat.

References

- Albright, R. and Cooley, S., 2019.** A review of interventions proposed to abate impacts of ocean acidification on coral reefs. *Regional Studies in Marine Science*, 29, p.100612. <https://doi.org/10.1016/j.rsma.2019.100612>
- Allemand, D. and Osborn, D., 2019.** Ocean acidification impacts on coral reefs: From sciences to solutions. *Regional Studies in Marine Science*, 28, p.100558. <https://doi.org/10.1016/j.rsma.2019.100558>
- Anagnostopoulos, T. and Varga, J., 2021.** *The role of universities in fostering regional innovation ecosystems.* *International Academic Journal of Innovative Research*, 8(1), pp.17–23. <https://doi.org/10.71086/IAJIR/V8I1/IAJIR0805>
- Andersson, A.J. and Gledhill, D., 2013.** Ocean acidification and coral reefs: effects on breakdown, dissolution, and net ecosystem calcification. *Annual review of marine science*, 5(1), pp.321-348. <https://doi.org/10.1146/annurev-marine-121211-172241>
- Barry, J.P., Widdicombe, S. and Hall-Spencer, J.M., 2011.** Effects of ocean acidification on marine biodiversity and ecosystem function. *Ocean acidification*, pp.192-209.
- Brander, L.M., Rehdanz, K., Tol, R.S. and Van Beukering, P.J., 2012.** The economic impact of ocean acidification on coral reefs. *Climate Change Economics*, 3(01), p.1250002. <https://doi.org/10.1142/S2010007812500029>
- Bruno, M. and Muraleedaran, S., 2025.** Assessing Marine Biodiversity and Conservation Strategies Using Molecular Ecology Tools in Coastal Ecosystems. *Natural and Engineering Sciences*, 10(2), pp.130-138. <https://doi.org/10.28978/nesciences.1714408>
- Cooley, S.R., Kite-Powell, H.L. and Doney, S.C., 2009.** Ocean acidification's potential to alter global marine ecosystem services. *Oceanography*, 22(4), pp.172-181.
- Hall-Spencer, J.M. and Harvey, B.P., 2019.** Ocean acidification impacts on coastal ecosystem services due to habitat degradation. *Emerging topics in life sciences*, 3(2), pp.197-206. <https://doi.org/10.1042/ETLS20180117>
- Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W. and Dove, S., 2017.** Coral reef ecosystems under climate change and ocean acidification. *Frontiers in marine science*, 4, p.252954. <https://doi.org/10.3389/fmars.2017.00158>
- Lam, V.W., Chavanich, S., Djoundourian, S., Dupont, S., Gail, F., Holzer, G., Isensee, K., Katua, S., Mars, F., Metian, M. and Hall-Spencer, J.M., 2019.** Dealing with the effects of ocean acidification on coral reefs in the Indian Ocean and

Asia. Regional Studies in Marine Science, 28, p.100560.

<https://doi.org/10.1016/j.rsma.2019.100560>

McAllister, S., 2025. Effects of Excessive Fishing on Coral Reef Ecosystems and Biodiversity. *Aquatic Ecosystems and Environmental Frontiers*, 3(4), pp.1-4.

Speers, A.E., Besedin, E.Y., Palardy, J.E. and Moore, C., 2016. Impacts of climate change and ocean acidification on coral reef fisheries: an integrated ecological–economic model. *Ecological economics*, 128, pp.33-43.
<https://doi.org/10.1016/j.ecolecon.2016.04.012>

Zunino, S., Canu, D.M., Zupo, V. and Solidoro, C., 2019. Direct and indirect impacts of marine acidification on the ecosystem services provided by coralligenous reefs and seagrass systems. *Global Ecology and Conservation*, 18, p.e00625.
<https://doi.org/10.1016/j.gecco.2019.e00625>

Zunino, S., Libralato, S., Melaku Canu, D., Prato, G. and Solidoro, C., 2021. Impact of ocean acidification on ecosystem functioning and services in habitat-forming species and marine ecosystems. *Ecosystems*, 24(7), pp.1561-1575.