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International Journal of Marine Science, 2024, Vol.14, No.4, 285-294
http://www.aquapublisher.com/index.php/ijms

Review and Progress Open Access

Eutrophication Mechanisms and Their Impacts on Coastal Marine Ecosystems

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International Journal of Marine Science, 2024, Vol.14, No.4, doi: 10.5376/ijms.2024.14.0032

Received: 29 Jun., 2024

Accepted: 10 Aug., 2024

Published: 28 Aug., 2024

Preferred citation for this article:

Wang W.F., 2024, Eutrophication mechanisms and their impacts on coastal marine ecosystems, International Journal of Marine Science, 14(4): 285-294 (doi: 10.5376/ijms.2024.14.0032)

Abstract Eutrophication is a process driven by the excessive input of nutrients, primarily nitrogen and phosphorus, which severely threatens the health of coastal marine ecosystems. With the increase in human activities, eutrophication has become increasingly severe, leading to the depletion of dissolved oxygen and the formation of hypoxic and anoxic zones. These changes have profound impacts on primary producers, species composition, biodiversity, and food web structure. This study systematically reviews the mechanisms of eutrophication and its physical, chemical, and ecological impacts on coastal marine ecosystems, exploring its long-term consequences and discussing mitigation and management strategies. Additionally, by analyzing case studies of coastal eutrophication in both developed and developing countries, this study summarizes effective management experiences and best practices. The significance of this research lies in providing a scientific basis for the development of more effective policies and management strategies, promoting the sustainable development of global coastal ecosystems.

Keywords Eutrophication; Coastal marine ecosystems; Hypoxic zones; Biodiversity; Management strategies

1 Introduction

Eutrophication is a process driven by the excessive accumulation of nutrients such as nitrogen (N) and phosphorus (P) in water bodies, leading to a range of ecological issues. This phenomenon is primarily caused by anthropogenic factors such as agriculture, urbanization, and industrial activities, which increase nutrient runoff into aquatic systems (Wilkinson et al., 2017; Wurtsbaugh et al., 2019; Wang et al., 2021). As a result, the nutrient overload stimulates the excessive growth of algae and other aquatic plants, disrupting the natural balance of aquatic ecosystems. Eutrophication not only leads to harmful algal blooms (HABs) and hypoxia but also causes a decline in water quality, significantly impacting biodiversity and ecosystem services (Ferrera et al., 2016; Glibert et al., 2017; Malone and Newton, 2020).

Coastal ecosystems are particularly vulnerable to eutrophication due to their proximity to human activities and the cumulative impact of nutrient inputs from upstream sources. The effects of eutrophication in these areas are profound, including the formation of hypoxic "dead zones," loss of biodiversity, and an increase in harmful algal blooms, which threaten marine life and human health (Wilkinson et al., 2017; Wurtsbaugh et al., 2019; Wang et al., 2021). Understanding the mechanisms of eutrophication in coastal ecosystems is crucial for developing effective management strategies to mitigate these impacts. However, the complexity of nutrient dynamics, influenced by various factors such as nutrient ratios and forms, adds to the challenge of managing eutrophication (Yan et al., 2016; Glibert et al., 2017).

This study synthesizes current research on the mechanisms of eutrophication and its impacts on coastal marine ecosystems, exploring the sources and trends of nutrient inputs contributing to coastal eutrophication and analyzing the effects of nutrient enrichment on ecosystems, including changes in biodiversity and the occurrence of harmful algal blooms. Additionally, the study evaluates the effectiveness of different management strategies in controlling nutrient inputs and mitigating eutrophication and identifies knowledge gaps and areas for further research, aiming to provide scientific evidence for the health and sustainable management of coastal ecosystems.

2 Mechanisms of Eutrophication

2.1 Nutrient enrichment sources

Nutrient enrichment, primarily from nitrogen (N) and phosphorus (P), is a key driver of eutrophication in coastal marine ecosystems. These nutrients originate from various anthropogenic sources, including agricultural runoff, urban wastewater, industrial discharges, and atmospheric deposition. Agricultural activities contribute significantly to nutrient loading through the use of fertilizers, which are rich in N and P. These nutrients are transported via runoff into water bodies, leading to increased nutrient concentrations in coastal areas (Korpinen and Bonsdorff, 2015; Wurtsbaugh et al., 2019). Urbanization and industrialization also play crucial roles, with sewage and industrial effluents being major sources of nutrient pollution (Zhou et al., 2019; Malone and Newton, 2020). Additionally, atmospheric deposition of nitrogen compounds, resulting from fossil fuel combustion and other industrial processes, further exacerbates nutrient enrichment in coastal waters (Korpinen and Bonsdorff, 2015; Wang et al., 2021).

2.2 Biogeochemical cycles and nutrient dynamics

The biogeochemical cycles of nitrogen and phosphorus are central to understanding nutrient dynamics in coastal ecosystems. Nitrogen undergoes various transformations, including nitrification, denitrification, and nitrogen fixation, which influence its availability and impact on eutrophication. Phosphorus, on the other hand, is primarily introduced through direct runoff and is less mobile than nitrogen. The interaction between these nutrients and the biotic and abiotic components of the ecosystem determines the extent and impact of eutrophication (Korpinen and Bonsdorff, 2015). For instance, the presence of nitrogen-fixing cyanobacteria can increase nitrogen availability, while denitrification processes can reduce it. The balance between these processes is crucial in regulating nutrient levels and mitigating eutrophication (Romanelli et al., 2020).

2.3 Role of human activities in accelerating eutrophication

Human activities have significantly accelerated the process of eutrophication. The intensification of agriculture, urbanization, and industrialization has led to increased nutrient inputs into coastal ecosystems. The use of artificial fertilizers in agriculture has dramatically increased nutrient runoff, while urban wastewater and industrial discharges have added substantial amounts of nutrients to water bodies (Wurtsbaugh et al., 2019; Zhou et al., 2019; Malone and Newton, 2020). Additionally, climate change exacerbates eutrophication by altering hydrological patterns, increasing water temperatures, and affecting nutrient cycling processes. These changes can enhance nutrient loading and reduce the resilience of ecosystems to eutrophication impacts (Wang et al., 2021; Meerhoff et al., 2022). Effective management and mitigation strategies are essential to address the anthropogenic drivers of eutrophication and protect coastal marine ecosystems from further degradation (Zhou et al., 2019; Malone and Newton, 2020; Wang et al., 2021).

3 Physical and Chemical Processes in Eutrophication

3.1 Dissolved oxygen depletion

Dissolved oxygen (DO) depletion is a critical process in eutrophication, primarily driven by the increased microbial respiration that accompanies the decomposition of organic material. This process is exacerbated by the stratification of water columns, which limits the reoxygenation of deeper waters. For instance, in the East China Sea off the Changjiang Estuary, marine-sourced organic matter formed by eutrophication-induced primary production was identified as the dominant oxygen consumer, leading to significant DO depletion (Wang et al., 2016). Similarly, in eutrophic estuaries like western Long Island Sound and Jamaica Bay, high rates of respiration in both surface and bottom waters contribute to persistent hypoxia, with DO concentrations dropping below 2 mg L^{-1} (Wallace and Gobler, 2021).

The impact of DO depletion is profound, leading to the formation of hypoxic zones, often referred to as "dead zones," where oxygen levels are insufficient to support most marine life. This phenomenon has been observed globally, with the number and severity of dead zones increasing due to anthropogenic factors such as nutrient loading and climate change (Altieri and Díaz, 2019). In the Baltic Sea, for example, the extent of anoxic and hypoxic areas has been increasing, with record high anoxic bottom areas observed in recent years (Almroth-Rosell et al., 2021).

3.2 Formation of hypoxic and anoxic zones

The formation of hypoxic (DO < 2 mg L^{-1}) and anoxic (DO < 0.5 mg L^{-1}) zones is a direct consequence of severe DO depletion. These zones are characterized by the absence of oxygen, which severely impacts marine ecosystems. In the Baltic Sea, the extent of these zones has been linked to both eutrophication and climate change, with significant regime shifts towards more anoxic conditions observed over the past decades. The stratification of water columns, particularly the presence of a halocline, plays a crucial role in maintaining these hypoxic and anoxic conditions by preventing the mixing of oxygen-rich surface waters with deeper layers (Almroth-Rosell et al., 2021).

In eutrophic estuaries, the dynamics of hypoxia are influenced by various factors, including algal blooms and community respiration (Figure 1). For example, in western Long Island Sound and Jamaica Bay, ephemeral algal blooms can cause brief periods of oxygen supersaturation, followed by prolonged hypoxia as the organic matter decomposes. Additionally, processes such as nitrification, driven by sewage discharge, further contribute to the acidification and hypoxia in these estuaries (Wallace and Gobler, 2021).

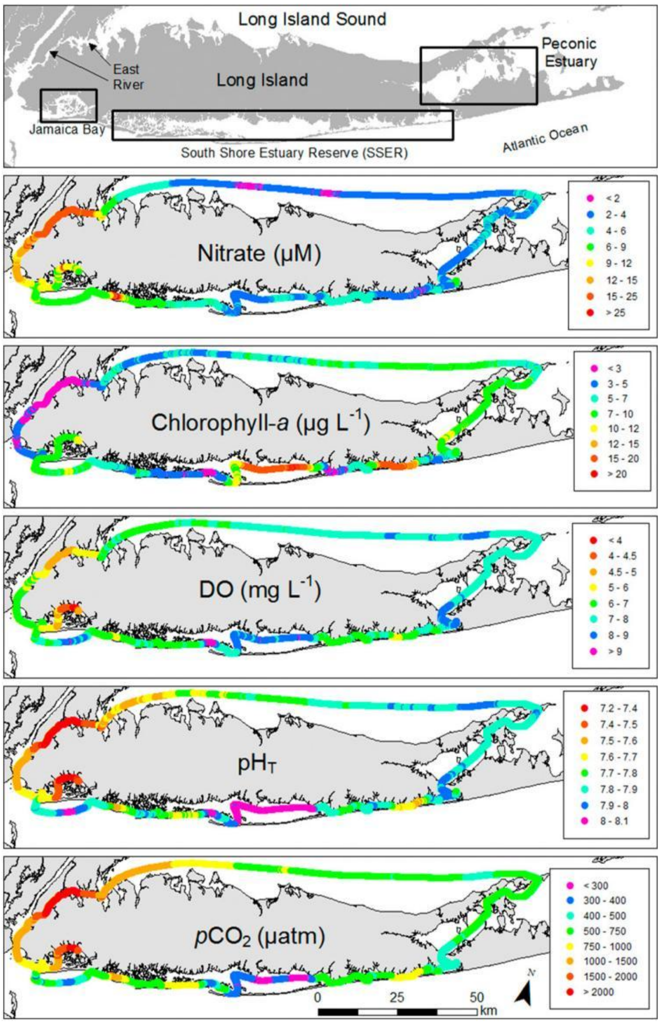

Figure 1 High-resolution continuous surface water sampling for nitrate (μM; SUNA UV nitrate sensor), normalized chlorophyll a fluorescence (μg L^{-1}), dissolved oxygen (DO; mg L^{-1}), pHT (total H+ scale), and the partial pressure of CO_2 (pCO_2; μatm) around Long Island, New York during September 2014 (Adopted from Wallace and Gobler, 2021)

The study by Wallace and Gobler (2021) demonstrated the spatial distribution of nitrate, chlorophyll a fluorescence, dissolved oxygen (DO), and pH in high-resolution continuous surface water samples. The figure shows that eutrophication-induced algal blooms significantly increased dissolved oxygen and pH levels in the surface waters. However, as algae die and decompose, oxygen is rapidly consumed, leading to hypoxia or even anoxic conditions in the bottom waters. This process illustrates that the initial increase in productivity masks the severe hypoxia that follows, highlighting the profound impact of eutrophication on oxygen distribution in water bodies.

The ecological impacts of hypoxic and anoxic zones are significant, leading to the mortality and emigration of fish, crustaceans, and other marine organisms. These zones disrupt normal biological functions and can lead to shifts in community structure and ecosystem function (Altieri and Díaz, 2019). Moreover, the interaction between hypoxia and other stressors, such as temperature, can exacerbate the impacts on marine life. For instance, low DO conditions combined with higher temperatures can increase metabolic demand and reduce the availability of thermal refuges, further stressing aquatic organisms (Roman et al., 2019).

4 Ecological Impacts on Coastal Marine Ecosystems

4.1 Effects on primary producers

Eutrophication significantly impacts primary producers in coastal marine ecosystems. Increased nutrient concentrations in seawater lead to higher phytoplankton biomass and promote the growth of opportunistic macroalgal species at the expense of canopy-forming species (Gerakaris et al., 2022). This shift is evident in the increased coverage of fast-growing, ephemeral algae over perennial macroalgae and seagrasses, causing habitat degradation (Östman et al., 2016). Additionally, climate change exacerbates these effects by promoting the growth of filamentous green algae, which are often associated with intensive algal blooms (Takolander et al., 2017).

4.2 Changes in species composition and biodiversity

4.2.1 Decline of sensitive species

Eutrophication often results in the decline of sensitive species. For instance, the structural traits of seagrass meadows, such as *Posidonia oceanica*, show negative trends with increasing levels of nutrient-related pressure indicators like ammonium, nitrate, and phosphate (Gerakaris et al., 2022). Similarly, the loss of biologically engineered habitats and the decline of marine-originating foundation species such as fucus are severe biodiversity impacts linked to eutrophication (Takolander et al., 2017).

4.2.2 Proliferation of opportunistic species

The proliferation of opportunistic species is a common consequence of eutrophication. Increased nutrient levels favor fast-growing, opportunistic macroalgae and phytoplankton, leading to shifts from perennial seagrass to these opportunistic species (Schmidt et al., 2017). This shift is further intensified by climate change, which promotes the growth of filamentous green algae (Takolander et al., 2017).

4.2.3 Shifts in community structure

Eutrophication-induced changes in primary producers lead to shifts in community structure. For example, in Atlantic Canada, eutrophication has caused distinct shifts in species composition, with increases in filter feeders, epibenthic detritivores, and some herbivores, while more hypoxia-sensitive species have declined (Schmidt et al., 2017). These changes are associated with differences in food availability and predation refuge offered by phytoplankton and opportunistic macroalgae.

4.3 Disruption of food webs and trophic interactions

Eutrophication disrupts food webs and trophic interactions by altering the distribution and flow of energy and biomass throughout the ecosystem. The introduction of invasive species, which often differ functionally from native species, generates ecological impacts that propagate along the food web, leading to changes in species abundance and interactions (Gallardo et al., 2016). Additionally, eutrophication can erode habitat gradients and behavioral mechanisms that maintain ecological separation and reproductive isolation among species, resulting in reduced ecological specialization and genetic homogenization (Alexander et al., 2017). This disruption of food webs and trophic interactions can have far-reaching consequences on the structure and functionality of aquatic ecosystems.

Overall, the ecological impacts of eutrophication on coastal marine ecosystems are profound, affecting primary producers, species composition, biodiversity, and food web dynamics. These changes highlight the need for integrated management approaches to mitigate the adverse effects of eutrophication and promote the resilience of coastal ecosystems.

5 Long-Term Consequences of Eutrophication

5.1 Alteration of habitat structure

Eutrophication significantly alters the structure of marine habitats, often leading to detrimental effects on biodiversity and ecosystem functionality. The excessive input of nutrients, primarily nitrogen and phosphorus, fosters the growth of phytoplankton and macroalgae, which can overshadow and outcompete other aquatic plants and organisms. This process can result in the loss of biologically engineered habitats such as seagrass beds and coral reefs, which are crucial for maintaining marine biodiversity (Korpinen and Bonsdorff, 2015; Wurtsbaugh et al., 2019; Malone and Newton, 2020).

Moreover, the increase in nutrient levels can lead to hypoxic or anoxic conditions, particularly in deeper waters, as the decomposition of excessive organic matter consumes oxygen. This phenomenon, often referred to as "dead zones," severely impacts the habitat suitability for many marine species, leading to shifts in species composition and reductions in biodiversity (Malone and Newton, 2020; Wåhlström et al., 2020). For instance, in the Baltic Sea, climate change combined with nutrient loads has been shown to exacerbate hypoxic conditions, further stressing marine species and altering habitat structures (Wåhlström et al., 2020).

5.2 Impacts on fisheries and marine resources

The impacts of eutrophication on fisheries and marine resources are profound and multifaceted. Initially, nutrient enrichment can lead to increased primary production, which might temporarily boost fish production. However, this is often followed by negative consequences such as hypoxia, harmful algal blooms (HABs), and shifts in competitive relationships within the fish community (Winfield, 2015; Griffith and Gobler, 2020).

Hypoxic conditions, resulting from the decomposition of excessive organic matter, can lead to fish kills and the displacement of fish populations, thereby reducing fishery yields and affecting the livelihoods of communities dependent on these resources (Winfield et al., 2015; Wurtsbaugh et al., 2019). Additionally, HABs, which are often stimulated by eutrophication, can produce toxins that are harmful to fish, shellfish, and even humans, further impacting fisheries and aquaculture (Wurtsbaugh et al., 2019; Griffith and Gobler, 2020).

The long-term recovery of fisheries from eutrophication is challenging and often incomplete. Studies have shown that even after the reduction or cessation of nutrient inputs, ecosystems may take decades to recover, and in some cases, baseline conditions may never be fully restored. This slow and partial recovery underscores the need for sustained and integrated management efforts to mitigate the impacts of eutrophication on marine resources (McCrackin et al., 2017; Wilkinson, 2017).

The long-term consequences of eutrophication on coastal marine ecosystems are severe, leading to significant alterations in habitat structure and substantial impacts on fisheries and marine resources. Effective management and mitigation strategies are essential to address these challenges and protect the health and productivity of marine ecosystems.

6 Mitigation and Management Strategies

6.1 Nutrient load reduction techniques

Effective nutrient load reduction is critical for mitigating eutrophication in coastal marine ecosystems. Various strategies have been implemented globally with varying degrees of success. One of the primary methods involves the reduction of point source inputs, such as those from sewage treatment plants, which has shown increasing success in many regions (Malone and Newton, 2020). However, controlling inputs from diffuse sources, such as agricultural runoff, remains a significant challenge (Boesch, 2019; Malone and Newton, 2020).

Advanced wastewater treatment technologies have been pivotal in reducing nutrient loads from urban areas, but agricultural sources require more complex solutions. Best management practices (BMPs) targeting nonpoint source (NPS) pollution have been implemented in various regions, with mixed results. For instance, BMPs in Roberts Bay, Florida, and Newport Bay, California, significantly reduced nutrient concentrations and harmful algal blooms over approximately 20 years, despite concurrent human population growth (Green et al., 2021). Conversely, in the Peconic Estuary, New York, the dominance of nitrogen inputs from groundwater and atmospheric sources posed greater technical and financial challenges, highlighting the need for targeted approaches based on the dominant nutrient sources (Green et al., 2021).

6.2 Restoration of affected areas

Restoration of ecosystems affected by eutrophication involves both immediate and long-term strategies. Immediate actions often include eco-remediation techniques, such as the reduction of phosphorus followed by nitrogen, which has been effective in regions like Shenzhen Bay, China (Zhou et al., 2019). The recovery period for such interventions can be substantial, often taking at least five years to observe significant improvements (Zhou et al., 2019).

Long-term restoration requires sustained efforts and monitoring. A global meta-analysis of recovery from eutrophication indicated that lakes and coastal marine areas achieved only 24%~34% of baseline conditions decades after nutrient reduction efforts, suggesting that full recovery may not always be possible (McCrackin et al., 2017; Wang, 2024). This underscores the importance of long-term monitoring and adaptive management to understand recovery trajectories and adjust strategies accordingly (McCrackin et al., 2017).

6.3 Policy and regulatory approaches

Policy and regulatory frameworks play a crucial role in managing eutrophication. Effective governance requires the engagement of high-level officials, clear communication of risks and benefits to the public, and binding requirements for nutrient load reductions (Boesch, 2019). Voluntary actions alone are often insufficient; thus, regulations must be enforceable and accompanied by public subsidies based on performance (Boesch, 2019).

In Europe, the Marine Strategy Framework Directive (MSFD) has been instrumental in guiding nutrient management. However, projections suggest that proposed nutrient reduction measures may not significantly impact the structure and function of marine ecosystems, indicating the need for more rigorous policies (Piroddi et al., 2021). The Baltic Sea Action Plan is an example of a policy that addresses both nutrient load reductions and climate change impacts, emphasizing the necessity of integrated approaches (Wåhlström et al., 2020).

7 Case Studies of Eutrophication in Coastal Regions

7.1 Examples from developed countries

In developed countries, eutrophication has been extensively studied and managed with varying degrees of success. For instance, the Chesapeake Bay in the United States is one of the most impacted coastal ecosystems due to anthropogenic nutrient inputs, leading to severe eutrophication and the development of "dead zones" (Malone and Newton, 2020). Through comparative analysis of seven coastal regions including the Chesapeake Bay, the Baltic Sea, and the Northern Adriatic Sea, the study revealed how nutrient inputs driven by human activities have exacerbated ecological degradation in these areas, particularly the formation of hypoxic zones and the loss of biodiversity (Figure 2). Similarly, the Baltic Sea and the Northern Adriatic Sea have experienced significant eutrophication, resulting in loss of biologically engineered habitats and toxic phytoplankton events (Malone and Newton, 2020). In Europe, the implementation of the Marine Strategy Framework Directive (MSFD) has led to various nutrient management scenarios aimed at reducing eutrophication. However, the impact on higher trophic levels has been minimal, with only slight improvements observed in the Baltic Sea (Piroddi et al., 2021). Additionally, the Mar Menor lagoon in Spain demonstrated a sudden eutrophication break followed by a relatively rapid recovery, highlighting the resilience of some coastal ecosystems (Pérez-Ruzafa et al., 2019).

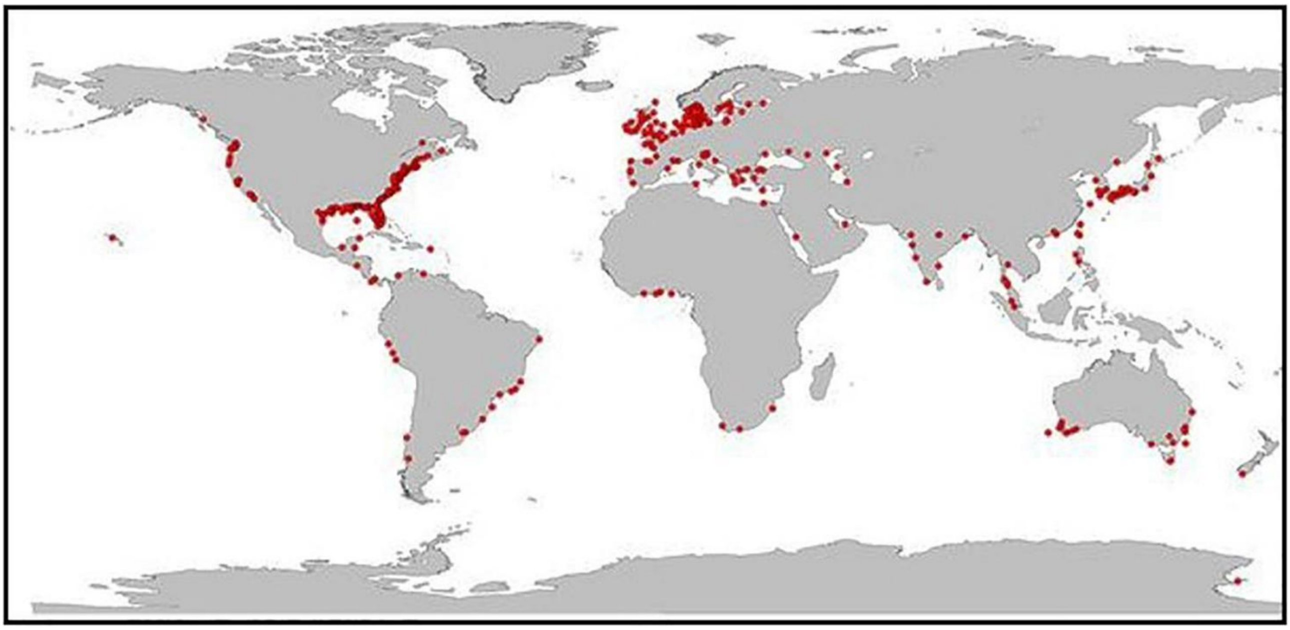

Figure 2 Global distribution of eutrophic coastal marine ecosystems (Adapted from Breitburg et al., 2018)
Image caption: Recent coastal surveys by the United States and the European Union found that 78% of U.S. coastal waters and 65% of Europe's Atlantic coastal waters exhibit symptoms of eutrophication (Adapted from Breitburg et al., 2018)

7.2 Examples from developing countries

In developing countries, rapid economic development and urbanization have exacerbated eutrophication issues. Shenzhen Bay in China, for example, has been heavily influenced by anthropogenic activities, leading to severe eutrophication. However, intensive management actions implemented since 2000 have shown improvements in water quality and a reduction in nutrient loads (Zhou et al., 2019). The East China Sea is another example where increased nutrient loading has led to significant eutrophication, exacerbated by synergies with other pressures such as overfishing and coastal development (Malone and Newton, 2020). These cases highlight the challenges faced by developing countries in managing eutrophication, often due to limited resources and infrastructure for effective nutrient management.

7.3 Lessons learned and best practices

Several lessons can be drawn from these case studies. First, the importance of integrated and sustained management of both point and diffuse sources of nutrients is evident. In developed countries, reductions in point source inputs from sewage treatment plants have been successful, but controlling diffuse sources remains challenging (Malone and Newton, 2020). Second, the need for long-term monitoring and adaptive management is crucial, as recovery from eutrophication can take decades and may not always reach baseline conditions (McCrackin et al., 2017). Third, the role of top-down control measures, such as managing predator populations to control algal blooms, should not be underestimated (Östman et al., 2016). Finally, the inclusion of terrestrial organic matter (ter-OM) in monitoring programs can provide a more comprehensive understanding of eutrophication processes and help in developing more effective management strategies (Deininger and Frigstad, 2019).

8 Concluding Remarks

Eutrophication in coastal marine ecosystems is primarily driven by anthropogenic nutrient inputs, particularly nitrogen and phosphorus from agricultural, urban, and industrial activities. Excessive nutrient levels lead to the overgrowth of primary producers, triggering a series of ecological problems such as hypoxic "dead zones," harmful algal blooms, and the loss of biodiversity. Additionally, factors like overfishing, coastal development, and climate change further exacerbate the effects of eutrophication, placing even greater stress on marine ecosystems. Despite various efforts to reduce nutrient loading, eutrophication and hypoxia remain persistent issues, with significant regional differences in the severity of impacts and the potential for ecosystem recovery.

To mitigate the adverse effects of eutrophication, the implementation of sustainable coastal management is crucial. Management strategies should comprehensively address both point and non-point sources of nutrient pollution, adopting integrated, ecosystem-based approaches. Effective measures include reducing nutrient emissions from agriculture, enhancing wastewater treatment, and restoring natural habitats such as wetlands to bolster ecosystem resilience. Additionally, managing predator populations to control algal growth can complement nutrient reduction efforts and support the restoration of vital habitats like seagrass and seaweed beds. Coastal management should also consider the impact of terrestrial organic matter on eutrophication, incorporating it into monitoring and policy frameworks to ensure the long-term health of ecosystems.

Future research should focus on understanding the complex interactions between nutrient inputs, climate change, and other anthropogenic pressures to develop more effective management strategies. There is a need for advanced modeling frameworks that integrate human activities and environmental variables to predict and mitigate the impacts of eutrophication under changing climate conditions. Furthermore, innovative remediation techniques, such as geo-engineering methods to bind phosphorus in anoxic sediments, may offer rapid recovery solutions for eutrophicated marine ecosystems. Collaboration among scientists, policymakers, and stakeholders is essential to ensure the long-term sustainability of coastal marine ecosystems.

Acknowledgments
The author sincerely appreciates the efforts of the two anonymous peer reviewers in providing their suggestions on this manuscript.

Conflict of Interest Disclosure
The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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