



Assessing Marine Biodiversity and Conservation Strategies Using Molecular Ecology Tools in Coastal Ecosystems

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Abstract

Coastal ecosystems are among the most productive and pivotal ecosystems on the planet. Their biological productivity is unparalleled in value from an ecological standpoint. Still, these ecosystems face increasing challenges from climatic shifts, habitat fragmentation, human anthropogenic pressure, and anthropogenic habitat destruction. Despite their biodiversity assessment methods providing some utility, they still fall short regarding marine life, especially cryptic, rare, or microscopic life forms. Today, eDNA analysis, DNA barcoding, and next-generation sequencing (NGS) are rapidly changing this scenario by enhancing precision and efficiency in biodiversity assessment. Species identification at low concentrations using water samples and monitoring biodiversity becomes easy, inexpensive, rapid, and non-destructive to the environment. This paper analyses coastal ecosystems through the spatial patterns of biodiversity while leveraging molecular techniques and illustrating the information required to formulate effective conservation strategies. It analyses several case studies where molecular techniques were used to assess species richness, invasion biology, population biology of conservation-dependent species, and impact assessment in Marine Protected Areas (MPAs). Incorporating molecular data into biological and geospatial frameworks allows for developing more robust, holistic approaches.

Keywords:

Marine biodiversity, molecular ecology, coastal ecosystems, environmental DNA (eDNA), DNA barcoding, next-generation sequencing (NGS), conservation strategies, biodiversity monitoring, marine protected areas (MPAs), and sustainable management.

Article history:

Received: 06/03/2025, Revised: 21/05/2025, Accepted: 23/06/2025, Available online: 30/08/2025

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Introduction

All lifeforms that populate the oceanic and coastal ecosystems, including marine organisms, are part of marine biodiversity. These ecosystems are found to host microplankton as well as some large marine organisms. These ecosystems assist in climate regulation, sustaining global fisheries, balancing the economy, and providing numerous services as a global ecosystem (Hansen et al., 2018). The wise use of marine resources has protected ecosystems, but marine biodiversity is under greater threat due to human-induced overfishing and climate change. This rapidly increasing threat calls for more effective conservation strategies to be put into place. Diverse marine life forms can be physically surveyed, but traditional assessment methods lack accuracy. Surveys and visual samples over time tend to be much more valuable. Despite the gaps in approach, the survey has shown that rare and elusive species are not detectable.

Additionally, these surveys and sampling are incredibly time-consuming, which is an issue when working with complex marine habitats. The work becomes even more difficult when focusing on dynamic coastal areas requiring constant attention and monitoring. If less attention is provided, crucial information can be missed, or gaps in understanding can easily emerge. Without a correct understanding, these ecosystems can become unbalanced.

In the past few years, molecular methods such as environmental DNA (eDNA) analysis, DNA barcoding, and next-generation sequencing (NGS) have transformed the monitoring of marine biodiversity (Majdanishabestari & Soleimani, 2019). Such techniques permit unobtrusive, precise species identification using genetic material extracted from various environmental samples. For example, eDNA enables the detection of organisms through the genetic material they leave behind in water. This method captures extensive biodiversity data from organisms that are hard to study or collect using traditional observational techniques (Thomsen & Willerslev, 2016). This study is critical because it helps broaden the understanding of the leverage of molecular tools in exploring and conserving marine biodiversity in more integrated and advanced ways (Ziwei & Han, 2023).

Literature Survey

Marine biodiversity encompasses the immense life forms within the ocean and coastal ecosystems, from miniature plankton and invertebrates to massive marine mammals and apex predators. Supporting vital ecosystem services like nutrient cycling, carbon sequestration, climate control, and global food security (Bucklin et al., 2016), marine ecosystems are underpinned by biodiversity. Thus, the fundamental understanding of ecological dynamics and marine life, as well as developing effective conservation policies and strategic sustainable resource management, depends on accurately assessing comprehensive marine biodiversity. Traditional biodiversity assessment methods in marine ecology, including bottom trawling, diver-based visual censuses, net sampling, and morphological taxonomy, have played a dominant pragmatic role. These techniques, however, are slow, invasive, and lacking in resolution, especially for identifying cryptic, rare, juvenile, or diminutive species (Taberlet et al., 2018; Pearman et al., 2014). Additionally, these methods do not capture the complexity of the marine environment, especially deep or remote areas, and are subject to observer bias.

Developing sensitive, non-invasive, and scalable approaches has led to a molecular ecology revolutionizing biodiversity monitoring in recent years. The increasing availability of seawater, sediment, and biofilms as samples to be processed using eDNA analysis, as well as the ability to detect and identify organisms to a whole new level using techniques such as DNA barcoding and next generation sequencing, allows researchers to analyze genetic material without needing direct contact with the organism in question (Pržulj et

al., 2022; Miya et al., 2015). These tools have improved the efficiency and attainment of marine biodiversity studies, delivering insights into the number of organisms from various taxonomic groups across all trophic levels. For instance, eDNA analysis's ability to provide information at different depths in the water column, where flow can help transport water-suspended genetic material containing traces of organisms, has made it a valuable tool in marine environments. Research conducted in coastal and reef ecosystems showed that eDNA enabled detection of more fish species than traditional visual surveys, surpassing the detection of diurnal cryptic or elusive species that usually avoid detection (Ardura et al., 2013). With the capability of tracking and monitoring the changes in marine species biodiversity, ecosystem overfishing, and climate change, baselining is more reliable now than ever.

An informative example from the North Sea used NGS technologies to investigate plankton communities and found some novel unclassified microbial and phytoplankton taxa crucial for ocean productivity and biogeochemical cycles (Paul Thomas & Rajini, 2024; Rao & Chatterjee, 2025). The study highlighted the hidden intricacies of microbial diversity masked by traditional approaches like microscopy. In the Mediterranean Sea, DNA barcoding has been helpful in proactively managing invasive species by detecting their presence in the ecosystem at an early stage. This approach allows decision-makers and environmentalists to deploy pre-emptive control and removal measures, which could circumvent significant ecological and financial damage if invasive species proliferate unchecked (Franke et al., 2020).

These case studies demonstrate how molecular methods were instrumental in understanding marine biodiversity. Unlike traditional methods, molecular techniques provide non-destructive, quick, and high-throughput options, especially in areas with limited resources or insufficient data. Additionally, as reference databases for marine species grow, along with more accessible and affordable sequencing technologies, the hurdles for widespread adoption are rapidly declining (Xiang et al., 2017; Mächler et al., 2021). Moreover, the incorporation of molecular ecology into regular monitoring frameworks greatly enhances prospects for long-term ecological changes. It is considered a composite indicator for restoration, fisheries management, and integrated marine planning and conservation. The global shift to assessing marine systems using ecosystem-based approaches emphasizes resilience targets that fundamentally confront multi-national human-induced challenges: climate change, pollution, and habitat loss, as well as adapting marine ecosystems to withstand growing anthropogenic pressures.

Proposed Model

Coastal ecosystems, such as mangroves, coral reefs, estuaries, and seagrass beds, are among the most productive and ecologically valuable areas on Earth. They provide critical services including shoreline protection, nursery habitats for marine life, carbon sequestration, and support for coastal economies (Barbier et al., 2011). However, these environments face increasing threats from urbanization, pollution, overfishing, and climate change. Conservation in coastal ecosystems is therefore essential to preserve biodiversity, sustain fisheries, and maintain ecosystem resilience in environmental change (Lotze et al., 2006). The biodiversity loss could lead to an irreversible breakdown of ecosystems and the collapse of services essential to humanity without effective conservation tactics (Sharma & Maurya, 2024). Various strategies serve to conserve marine environments, such as creating MPAs, rehabilitating habitats, regulating fisheries, and developing management plans for particular species (Gaines et al., 2010). While these strategies are crucial, their effectiveness relies on available ecological information. In particular, the construction and execution of conservation plans are now aided greatly by molecular ecology tools (Saidova et al., 2024). For instance, eDNA monitoring within MPAs reveals whether particular endangered or invasive species are present, thereby aiding enforcement and adaptive management (Rees et al., 2014). Genetic evaluations also assist in uncovering distinct populations or

cryptic species that may need targeted conservation action (Palsbøll et al., 2007). Molecular markers also evaluate genetic diversity and the spatial connections of different populations, which is fundamental for designing networks of MPAs to sustain ecological integrity (Bernatchez et al., 2017). Integrating molecular tools in marine conservation biology enables scientists and policymakers to act effectively and optimally to maintain marine biodiversity and bolster coastal ecosystems' resiliency (Dewangan & Dewangan, 2024).

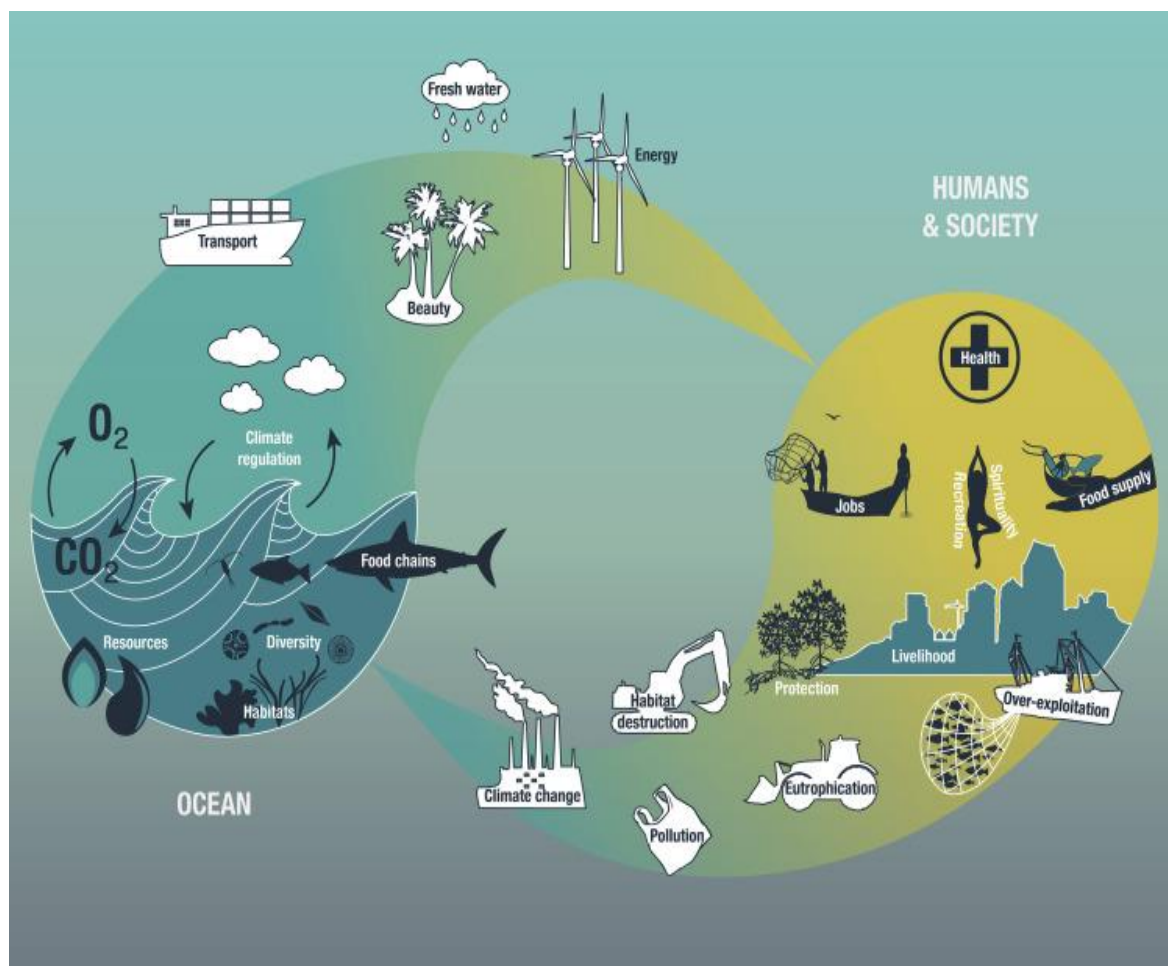


Figure 1. Proposed model flow (Raman et al., 2024a)

Figure 1 illustrates and focuses on the marine ecosystems' fundamental services, the vicious harm humanity inflicts on them, and ocean and human society interactions, which are complicated, intricate, and multilayered (Leray et al., 2019; Costello et al., 2013). The sea provides numerous services to the ecosystem, such as oxygen production, climate moderation, and hosting biological food chains, life forms, and habitats. Furthermore, the ocean aids in international transportation, energy provision, and freshwater supply, in addition to having beauty and cultural significance (Kumar & Rao, 2024). These services are fundamental to supporting the balance of the environment and all life on the planet (Vishaka & Selvi, 2017). Correspondingly, human society gains many direct ocean benefits in the form of nourishment, health care services, jobs, tourism, and general socio-economic wellbeing. Yet, the ocean's beneficent potential is increasingly undermined by human pressures like overfishing, pollution, habitat destruction, eutrophication, and the myriad impacts of climate change. This multi-faceted stress does not solely harm marine ecosystems; it also reduces the ability of the ocean to sustain life and human wellness. The figure conveys this interaction as a feedback loop, expressing that environmental degradation has consequences on human welfare, which in turn encourages further exploitative behaviors leading to more ecological damage.

To protect this sensitive equilibrium between oceanic health and societal welfare, it is indispensable to enforce robust conservation policies and incorporate sustainable methods. Such approaches entail the regulation of fisheries, pollution control, rehabilitating damaged wildlife, and tackling the fundamental drivers of climate change (Raman et al., 2024b). The inclusion of modern scientific disciplines such as molecular ecology into conservation efforts can significantly improve the comprehension of marine biodiversity, ecosystems, and their interrelationships. Environmental monitoring using eDNA and genetic barcoding enables more precise, non-invasive assessments of species and ecosystem health. This enhances comprehensive targeted conservation practices and plans alongside informed strategic considerations for environmental actions. Achieving a preferable future where nature, human society, and the economy can positively coexist requires understanding the interrelations of human health and ocean ecosystems, along with holistic considerations of social systems (Sala et al., 2020).

Results and Discussion

The implementation of molecular tools in the coastal ecosystem of Australia has greatly advanced the understanding of the distribution of biodiversity and how well it is being conserved. Using DNA analysis of water, sediment, and marine organisms' samples, species that were previously undetected, or cryptic ones, were found. The genetic data also revealed hotspots and strong indicators of ecological value. Furthermore, myriad marine biological data revealed species richness, community composition, invasive species, and potential threats to native biodiversity. These findings demonstrate more strongly than ever the complementary value of molecular techniques of traditional ecological surveys, which enable proper evaluation and monitoring. The spatial analysis aids in determining more precise conservation measures, like establishing marine protected areas, alongside management tailored to specific habitats. Furthermore, the unregulated practices, such as pollution and overfishing, that alter vital species' genetic diversity signal the need for immediate policies and sustainable action strategies. It enables well-informed conservative choices while improving the sustained health of coastal ecosystems.

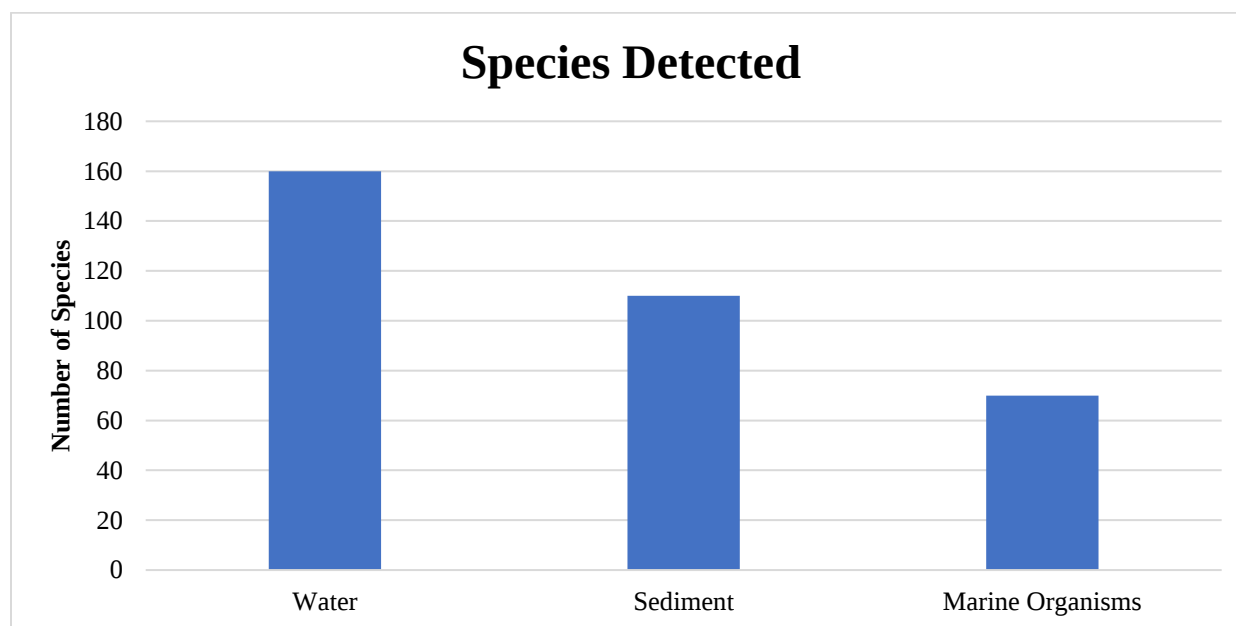


Figure 2. Species detection

Figure 2 illustrates the comparison of species detected through molecular ecology tools in water, sediment, and marine organism samples. Most species were detected in water samples, which shows that eDNA

in water is an effective medium for ascertaining marine biodiversity. Sediment samples showed a moderate level of species, indicative of the presence of some benthic organisms and sediment-dwelling microbial communities. Conversely, marine organism samples had the lowest species count as a result of focusing on host-specific biodiversity, not ecosystem-wide diversity. The data emphasize the effectiveness of non-invasive sampling techniques such as water eDNA in assessing biological diversity. These approaches facilitate quick and extensive biodiversity monitoring efforts with minimal ecological impact. The variation in species detection across sample types also indicates that multiple sample types used in conjunction can portray a more comprehensive representation of the ecosystem's biological diversity. This knowledge is crucial to setting conservation priorities and monitoring environmental shifts in coastal ecosystems.

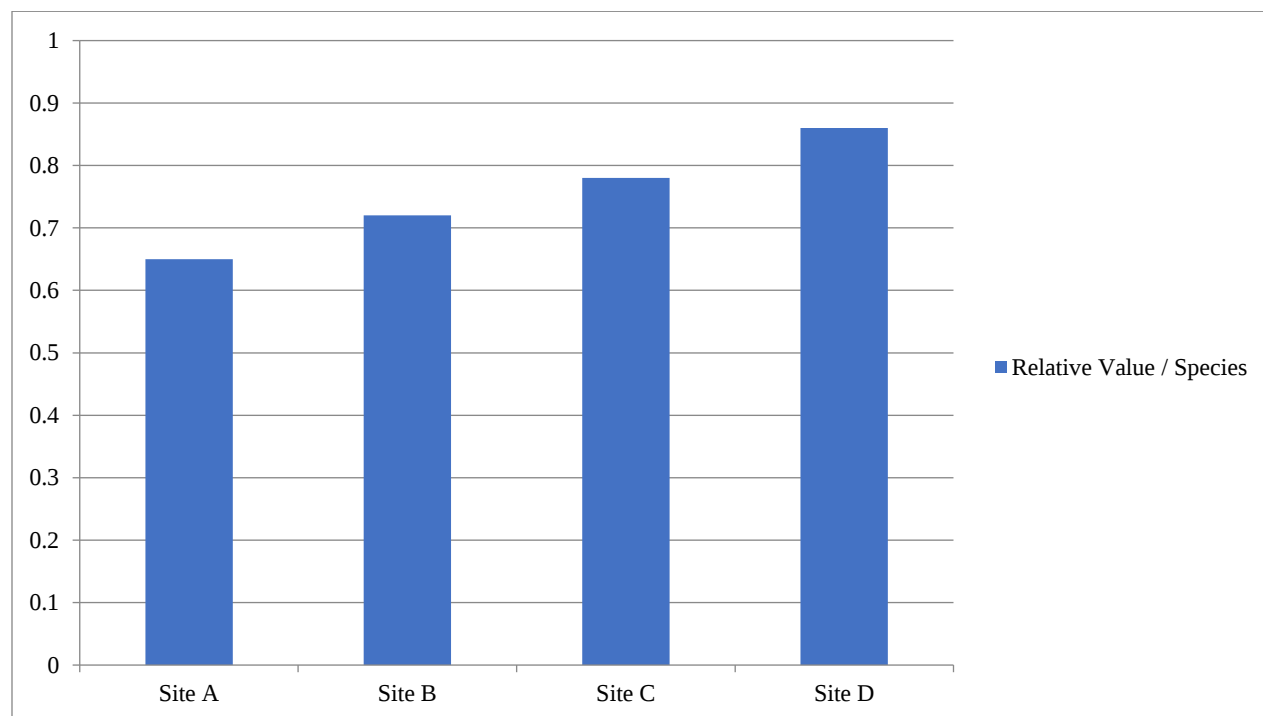


Figure 3. Relative species richness across selected coastal sites

Figure 3 shows the relative species richness recorded from four coastal sites, Site A through Site D, with their corresponding molecular ecological assessments. The relative measure or count of species found is positioned on the y-axis, whilst the different locations sampled are identified on the x-axis. A distinct upward trend in biodiversity was observed moving from Site A (0.65) to Site D (0.87), where Site D displayed the highest relative species richness within the sites considered. This suggests that some coastal regions could be important for biodiversity, perhaps because the environment is more suitable or there is less human impact. Applying molecular methods like environmental DNA (eDNA) analysis enables the identification of greater numbers of species, including those that are rare, difficult to sample conventionally, or cryptic. These findings emphasize the need for targeted conservation approaches for specific locations and maintaining areas with high biological diversity.

Conclusion

The study elucidates the sophisticated molecular ecology tools that advance our understanding of biodiversity and formulate refined conservation strategies in coastal ecosystems. Advanced techniques such as environmental DNA (eDNA) analysis and genetic barcoding revealed many species of marine life and complex patterns of species diversity within coastal habitats. These molecular methods revealed additional common and

elusive taxa, better understanding coastal biodiversity. The differences in biodiversity in various coastal localities strengthen the case for geo-specific conservation strategies. Some areas appeared to have drastically higher species richness, classifying those regions as biodiversity hotspots which require immediate and concentrated protection. eDNA and barcoding not only improved the accuracy of species identification but also rendered them ideal for long-term monitoring due to their cost-effectiveness and low-impact nature. Overall, our results point towards the increased need for molecular data integrated into management frameworks, increasing the ability to detect early stress indicators and shifts in community composition resulting from human activity or climate change. In particular, conserving high-diversity areas and human impacts like pollution, coastal development, and habitat fragmentation require further concerted action. This is the case because molecular ecology is a strong approach to conservation—entirely rational and provably so, requiring no tools for research beyond policy. Adapting these technologies helps promote proactive and adaptive management of ecosystems, increases their resilience to changes, protects marine biodiversity, and guarantees the provision of crucial services in the face of accelerated environmental change.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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