Dynamics of Seagrass Conservation Research in Indonesia: A Bibliometric Analysis and Ecological Challenges in the Era of Climate Change

ABSTRACT

Seagrass ecosystems in Indonesia provide essential ecological services, including carbon sequestration, marine biodiversity support, and coastal protection. However, these ecosystems face significant threats from human activities, climate change, and pollution. This study utilizes bibliometric analysis to examine research trends in seagrass conservation in Indonesia from 2007 to 2024, identifying 118 publications with an annual growth rate of 18.53%. Key research topics include biodiversity conservation, seagrass roles in climate change mitigation, and the management of protected areas. The findings indicate a growing awareness of seagrass functions, such as carbon storage and support for fisheries, but highlight ongoing challenges related to limited financial resources and public awareness. Community perceptions and participation, especially through community-based conservation initiatives, are crucial for the success of seagrass conservation efforts. The study emphasizes the need for adaptive management strategies and collaboration among stakeholders to overcome the challenges of seagrass conservation in Indonesia.

Keywords: seagrass conservation Indonesia; carbon sequestration; biodiversity; community-based conservation; climate change adaptation

1. INTRODUCTION

Provide a factual background, clearly defined problem, proposed solution, a brief literature survey and the scope and justification of the work done.] Seagrass meadows in the tropical Indo-Pacific bioregion support abundant fisheries (1) due to the presence of complex habitats. The presence of seagrasses delivers essential ecosystem services, including ecological, socio-economic, and cultural benefits to communities (2). Seagrasses cover only 0.1% of the ocean's surface, yet they play a crucial role in the global carbon cycle. It is estimated that these ecosystems capture between 27 and 44 Tg of organic carbon annually, representing 10% to 18% of total carbon burial in the oceans (3). Seagrass meadows significantly contribute to climate change mitigation through carbon sequestration (4) while also providing crucial support for the economic sustainability of small-scale fishers, particularly in providing fish and other economically valuable marine species. The estimated economic value of fish and marine species harvested from seagrass ecosystems is USD 40,669.00 and USD 21,105.00 per hectare per year, respectively, totaling USD 61,774.00 per hectare per year (5). The importance of seagrasses to ecosystems makes their conservation crucial for maintaining marine balance and the welfare of coastal communities.

Seagrass conservation efforts face significant challenges caused by human activities, climate change, and pollution. Activities such as coastal development and destructive fishing practices have led to the substantial loss of seagrass habitats (6). Climate change exacerbates these conditions by increasing sea temperatures and the frequency of storms, resulting in erosion and degradation of seagrass ecosystems (7). Pollution from agricultural and industrial waste, including microplastics and heavy metals, further worsens seagrass health through eutrophication and oxygen depletion in the waters (8). These challenges have a significant impact on the success of conservation efforts and the sustainability of seagrass ecosystems. Habitat degradation reduces the extent and quality of seagrass needed to support biodiversity and essential ecosystem services such as coastal protection and carbon sequestration. When seagrass habitats are damaged, conservation efforts become more difficult and expensive, requiring extensive restoration. Addressing these challenges requires comprehensive and coordinated conservation strategies at various levels.

Community perceptions play a crucial role in enhancing conservation policies and environmental management, as well as supporting the success of conservation efforts through local engagement (9). Community support is essential because many conservation initiatives depend on local participation in resource management, monitoring, and long-term protection. Negative perceptions can lead to non-compliance with conservation rules, sabotage, or conflicts with those implementing the projects. Research by Quevedo et al. (2020) shows that when communities understand the benefits of seagrasses, such as supporting local fisheries, they are more likely to support conservation efforts. For example, in a seagrass conservation project in Eastern Samar, Philippines, although community awareness of the importance of seagrass ecosystems was high, its utilization remained low. However, their understanding of the direct benefits provided by seagrasses increased support for conservation efforts.

Research on seagrass conservation shows a growing trend, although it remains limited compared to other coastal habitats (11–14). Despite the rapid growth of this research, the number of researchers involved is still relatively small and tends to focus on a few specific species, such as *Zostera sp.*, *Thalassia sp.*, and *Posidonia sp.* (15–17). The current scientific literature provides a comprehensive overview and supports evidence-based decision-making through bibliometric analysis, which identifies trends, key topics, and gaps in seagrass conservation research (18). These knowledge gaps hinder effective management and conservation, especially in developing countries with limited funding and scientific capacity. By analyzing the existing literature, this research aims to uncover knowledge gaps and offer research opportunities that can support future conservation efforts. Understanding the socio-economic value of seagrasses and raising public awareness is also crucial for designing more effective and evidence-based conservation interventions (15).

2. METHODOLOGY

Bibliometric analysis is a rigorous method for exploring and analyzing large amounts of scientific data. This method allows researchers to uncover the evolutionary dynamics of a specific field while highlighting emerging areas within that field (18). Through the analysis of bibliometric data, such as citations, publications, and collaborations, bibliometrics provides quantitative measures and insights into the impact, visibility, and influence of scientific work (19). This research first identifies databases and selects those most suited to the research needs. The study utilizes the Scopus database, which is one of the most renowned scientific citation index databases worldwide. This database provides academics with access to articles from scientific journals, books, and other academic documents across all scientific fields.

The search was conducted using the keyword 'seagrass conservation'. We further performed data extraction to filter the data based on unique search keywords determined using TITLE-ABS-KEY (seagrass AND conservation) AND (LIMIT-TO(DOCTYPE, "cp") OR LIMIT-TO(DOCTYPE, "re") OR LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(AFFILCOUNTRY, "Indonesia")), which must contain articles related to seagrass conservation in Indonesia. We searched based on title, abstract, author's keywords, and year. We also limited our data search to Scopus' "pre-review" published articles, primarily focusing on seagrass conservation in Indonesia to capture a smaller part of the larger context. We intentionally restricted this advanced extraction to more accurately observe trends.

It is important to note that, to capture the latest developments in this field, papers published in 2024 were included, reflecting the most recent advances, as the data collection was conducted in September 2024. To enhance the accuracy of our dataset, articles written in languages other than English were excluded, and only articles published in scientific journals and conference proceedings were included, excluding books or unpublished research reports. This resulted in a curated dataset of 118 documents. These articles were saved in Research Information Systems (RIS) format.

Each article title, author, journal, publication year, volume, issue, article pages, abstract, and keywords were checked for completeness using Mendeley version 1.19. The following criteria were used to discard articles with incomplete attributes, such as missing author names, abstracts, or keywords; and articles without accessible websites. To unravel intricate patterns within this extensive dataset, the capabilities of R software version 4.2.2 (20), the Biblioshiny package (21), and VOSviewer software (22) were utilized for bibliometric mapping and visualizations. A minimum frequency of five keywords per year was used to analyze the development of topics over time. Multiple correspondence analysis was applied in factorial analysis to create conceptual keyword structure maps.

3. RESULTS AND DISCUSSION

3.1 Result

Table 1 presents a detailed summary of bibliometric statistics related to seagrass conservation in Indonesia, shedding light on the research landscape in this field. Covering the period from 2007 to 2024, a total of 118 publications were identified, demonstrating substantial academic engagement. The field has seen an annual growth rate of 18.53%, signifying a significant increase in research output. Each document has been cited an average of 19.23 times, indicating the importance and influence of research in this area. With the participation of 624 authors and an average of 6.88 co-authors per publication, the collaborative nature of the field is evident. Furthermore, 44.07% of the publications involve international collaboration, highlighting the global interest and cooperation in seagrass conservation research in Indonesia. The document types include primarily articles (77), reflecting a strong emphasis on original research. There are also 39 conference papers, pointing to active academic dialogue, and 2 reviews, indicating some level of synthesis in this body of work. This bibliometric analysis offers a solid basis for understanding the scholarly activity and collaborative dynamics within seagrass conservation in Indonesia over the analyzed timeframe.

Table 1. Overview of bibliographic statistics for seagrass conservation in indonesia

Description	Results
Main information about data	

Period	2007:2024
Documents	118
Annual Growth Rate %	18.53
Average citations per doc	19.23
Authors	624
Single-authored docs	1
Co-Authors per Doc	6.88
International co-authorships %	44.07
Document types	
Article	77
Conference paper	39
Review	2

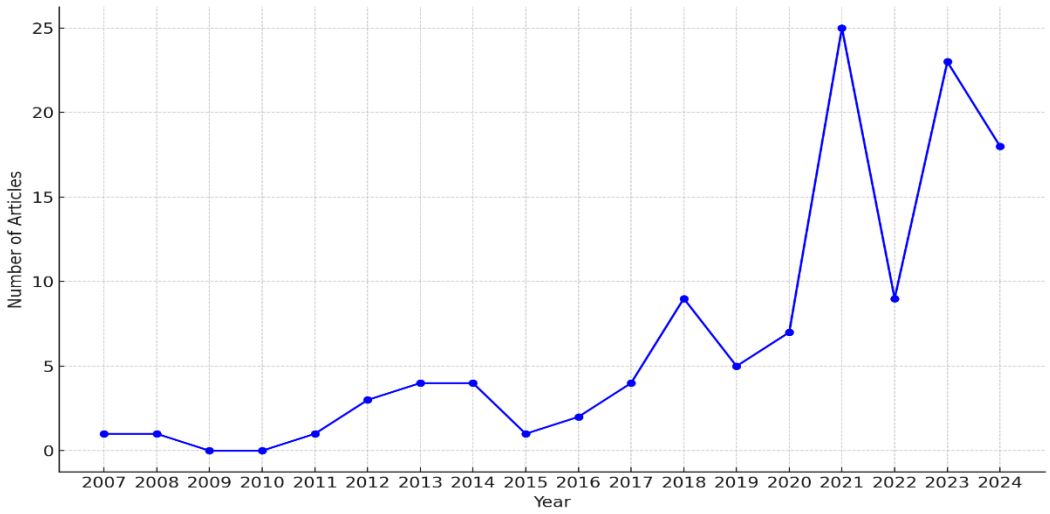

Fig. 1. Yearly Output of Scholarly Publications Related to Seagrass Conservation in Indonesia

Fig. 1. illustrates the annual output of scientific publications related to seagrass conservation in Indonesia over a specified period. The graph shows annual research output trends, providing insights into the increasing interest and activity among researchers. The peaks and dips reflect periods of heightened research activity or shifts in focus. Overall, the graph serves as a tool to understand the temporal distribution and development of research in this field. The data shows a significant increase in 2021 with 25 publications, followed by 23 and 18 publications in 2023 and 2024. In the early period, the number of publications per year was relatively low, with only 1 publication in 2007, 2008, and 2011, and no publications recorded in 2009-2010. After 2012, a more consistent increase in research output is observed. The significant rise in 2021-2024 indicates that the field has matured, driven by technological advancements and a growing commitment to sustainability. Factors such as environmental awareness and the recognition of the importance of seagrass ecosystems likely contributed to this surge in research activity.

There is a dynamic development in research topics related to seagrass conservation in Indonesia, as shown in **Fig. 2.** In its early emergence around 2012, topics such as 'turtle' and 'endangered species' were the main focus of coastal ecosystem research. These early

studies concentrated on the protection of vulnerable marine species, including turtles and other endemic species, closely associated with coastal ecosystems such as coral reefs (23). During the period from 2014 to 2018, research focus began to shift towards topics related to 'coral reef', 'marine environment', and 'coastal zone', highlighting the importance of conserving broader marine ecosystems. 'Marine park' also became a frequently discussed topic in the context of conservation area management involving local communities (24,25).

From 2018 to 2020, there was an increased focus on issues such as 'biodiversity', 'ecosystems', and 'conservation'. This indicates a growing awareness of the importance of preserving biodiversity within broader coastal and marine ecosystems. 'Fisheries' also garnered attention, reflecting an increased awareness of the importance of overall ecosystem sustainability and its link to global challenges like climate change (26–28). During the period from 2021 to 2023, research topics began to focus on issues such as 'climate change', 'carbon', 'biomass', and 'organic carbon'. Recent studies have also covered topics like carbon and biomass, highlighting the growing attention toward the role of seagrasses in climate change mitigation and carbon storage. Additionally, the concept of the blue economy, which links conservation to sustainable resource management, has increasingly been featured in these studies (29,30). Moreover, topics related to 'protected area' and Indonesia have continued to receive attention, reflecting the importance of sustainable conservation area management at the national level. These recent studies demonstrate that coastal ecosystems like seagrass meadows are not only ecologically significant but also play a crucial role in addressing global challenges such as climate change.

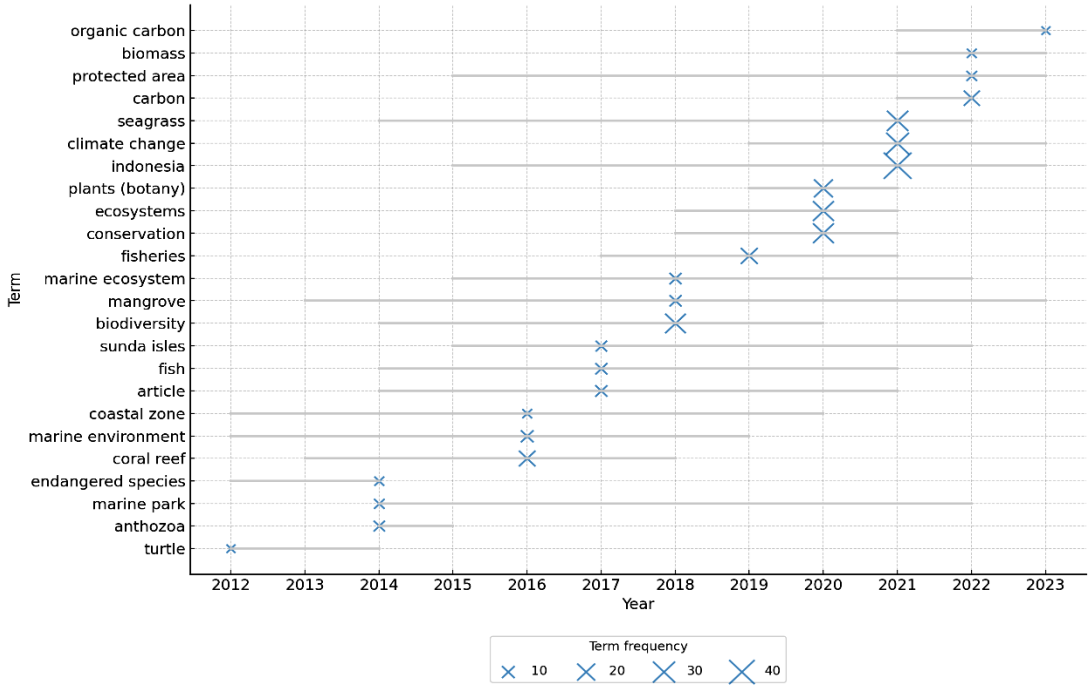

Fig. 2. Trends in Seagrass Conservation Topics in Indonesia Based on Year

The co-keyword visualization (**Fig. 3.**) for seagrass conservation research in Indonesia shows that the keyword 'Indonesia' dominates the network, indicating that most research is focused on this region. Other keywords such as 'seagrass ecosystem', 'conservation', and 'biodiversity' suggest that research in this field is centered on seagrass ecosystems and the importance of their conservation and biodiversity. The network consists of several color clusters. The red cluster focuses on seagrass ecosystems, 'restoration', and 'utilization',

reflecting attention on habitat restoration and its potential uses, both ecologically and economically. The green cluster centers on 'biodiversity' and 'coastal ecosystem', highlighting the close relationship between seagrass meadows and biodiversity in coastal areas. The blue cluster is associated with 'conservation', 'assessment', and 'marine' ecosystems, indicating that much research is focused on evaluating and conserving marine ecosystems. Additionally, a smaller cluster with keywords such as 'coral reef' suggests an intersection of research between seagrass ecosystems and coral reefs.

The strong connection between 'Indonesia', 'seagrass ecosystem', and 'biodiversity' indicates that research in Indonesia is highly focused on studying seagrass ecosystems and their crucial role in supporting biodiversity. Furthermore, the link between the keywords 'conservation' and 'assessment' reflects the prevalence of studies centered on evaluating the condition of seagrass ecosystems and conservation efforts. Research focusing on 'restoration' and 'utilization' is also emerging, indicating increasing attention towards ecosystem restoration and the sustainable use of seagrass meadows.

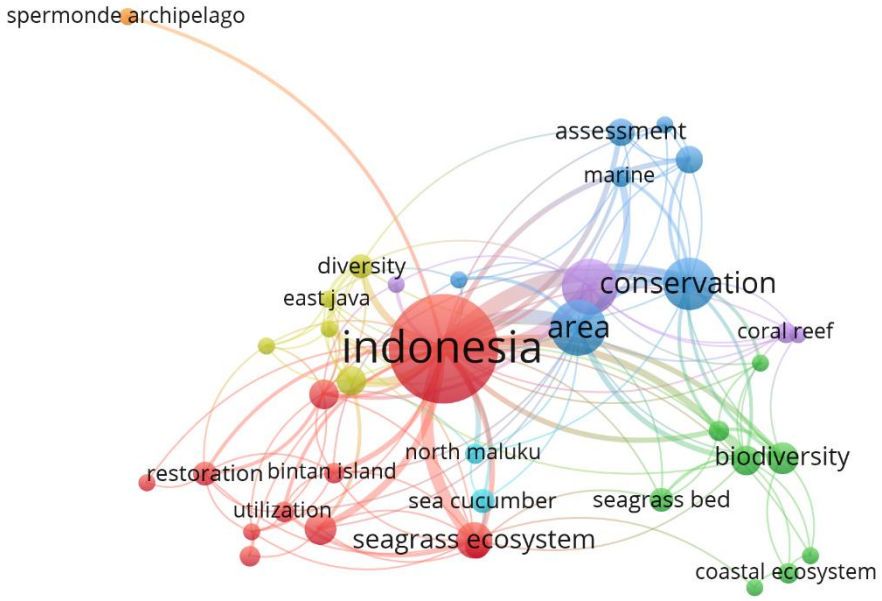

Fig. 3. Co-Keyword Network Visualization on Seagrass Conservation in Indonesia Research

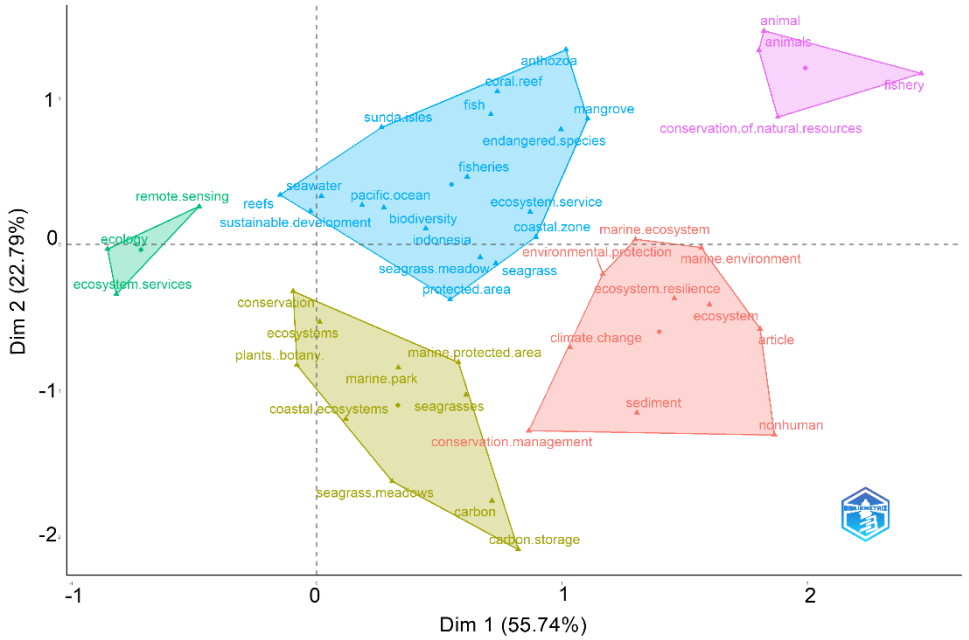

Fig. 4. Conceptual Structure Map of Seagrass Conservation Research in Indonesia Using the Multiple Correspondence Analysis (MCA) Method

The conceptual structure map of seagrass conservation research in Indonesia using the Multiple Correspondence Analysis (MCA) method (**Fig. 4.**) reveals several key clusters that depict the research focus in this field. In the first dimension, which explains 55.74% of the data variation, seagrass conservation research in Indonesia is primarily influenced by topics related to marine ecosystems, environmental protection, and biodiversity conservation. The second dimension, which accounts for 22.79% of the variation, highlights an additional focus on ecosystem services and biodiversity in coastal ecosystems.

Seagrass conservation research is divided into several clusters. The green cluster focuses on ecosystem services, remote sensing technology, and sustainable development, emphasizing the importance of protecting coastal ecosystems through technology-based approaches. The blue cluster highlights issues of biodiversity, seagrass meadows, and protected areas, indicating a focus on protecting critical habitats and endangered species. The yellow cluster centers on carbon storage, marine parks, and seagrass meadows, underscoring the role of seagrass ecosystems in climate change mitigation through carbon sequestration. Meanwhile, the red cluster encompasses topics such as climate change, environmental protection, and ecosystem resilience, suggesting that this research also seeks to understand how seagrass ecosystems can adapt and provide benefits in the face of environmental change. The purple cluster places more emphasis on natural resource management related to fisheries and natural resource conservation.

The relationships between topics show a strong connection between seagrass meadows, ecosystem services, and biodiversity. This research emphasizes the importance of seagrass meadows in supporting biodiversity and providing vital ecosystem services, such as carbon storage and coastal protection. Additionally, climate change is also receiving considerable

attention, with research focusing on how seagrass ecosystems can contribute to climate change mitigation.

3.2 Discussion

3.2.1 Ecological Services Provided by Seagrasses

Seagrass ecosystems provide various ecological services that are critical to the health of the marine environment. One of the primary benefits of seagrass meadows is their ability to store carbon, making them essential in climate change mitigation (31,32). Seagrass ecosystems act as carbon sinks, storing carbon in their biomass and sediments, which helps reduce atmospheric carbon dioxide levels. Additionally, seagrass meadows serve as nurseries for a variety of marine species, including commercially valuable fish and invertebrates, contributing to fisheries productivity and supporting food security for coastal communities (33,34).

Based on bibliometric research, the keywords 'carbon', 'biomass', and 'carbon sequestration' have become an important focus in research related to seagrass ecosystems since 2018, indicating growing scientific awareness of the critical role seagrasses play in carbon storage and climate change mitigation. Publications linking seagrass ecosystem services to climate change mitigation have steadily increased, particularly in Indonesia, which has one of the largest seagrass areas in the world. As global efforts to combat climate change intensify, the capacity of seagrass meadows to store carbon is recognized as a valuable asset in reducing greenhouse gas emissions (26,31,32). Indonesia, as one of the countries with the largest seagrass meadows globally, has significant potential to contribute to global climate goals by protecting and restoring these ecosystems (35). By preserving these natural carbon sinks, Indonesia can enhance its efforts to meet international climate commitments while protecting its marine biodiversity and supporting the livelihoods of coastal communities.

In addition to their role in climate change mitigation, seagrass ecosystems offer a range of additional benefits, making their conservation a priority for sustainable development. Seagrass meadows help maintain water quality by trapping sediments and absorbing nutrients, preventing harmful algal blooms and ensuring water clarity (36,37). They also function as natural buffers, protecting shorelines from erosion and storm surges, which is vital for small island communities vulnerable to rising sea levels and extreme weather events (38–40). Moreover, seagrass ecosystems support tourism activities such as snorkeling and diving, which contribute to local economies and raise awareness of the importance of marine conservation (13,41,42).

3.2.2 Community Perceptions of Seagrass Ecosystem Conservation

Community perceptions of seagrass ecosystem conservation play a crucial role in determining the success of conservation efforts in Indonesia. Generally, coastal communities that directly depend on marine resources often have a high awareness of the importance of seagrass ecosystem sustainability. However, public knowledge of the ecological functions of seagrass, such as carbon storage, habitat provision for various marine species, and coastal protection, remains limited to a few communities (43). Many people are more familiar with the direct benefits of seagrass ecosystems, such as fisheries and tourism, compared to the less visible long-term ecological functions. Positive attitudes toward conservation are typically higher among communities that have been involved in community-based conservation initiatives or have received education and outreach on the importance of seagrass ecosystems.

Education about the role of seagrasses in climate change mitigation and other ecological benefits can enhance community support for conservation programs. In areas where strong environmental awareness campaigns are in place, communities often take an active role in maintaining and restoring seagrass meadows. For example, in some regions, programs such as the establishment of Marine Protected Areas (MPAs) involving community participation have increased awareness of the importance of protecting seagrasses for their own livelihoods (44,45). Bibliometric analysis also shows an increasing trend of international collaboration in seagrass conservation research in Indonesia, as evidenced by the frequent appearance of the keywords 'marine park' and 'protected area'. This indicates that community-based approaches are increasingly recognized as an effective strategy for managing and protecting seagrass ecosystems in Indonesia.

3.2.3 Challenges in Seagrass Conservation in Indonesia

Despite these efforts, there are still significant barriers to effective seagrass conservation in Indonesia. Limited financial resources, lack of public awareness, and weak enforcement of environmental regulations are challenges that hinder the progress of conservation initiatives (11,46). Additionally, the impacts of climate change, such as rising sea temperatures and ocean acidification, pose new threats to the health and resilience of seagrass ecosystems. Therefore, it is essential to develop adaptive management strategies that take into account the dynamics of marine ecosystems and the uncertainties associated with climate change. Collaboration between government, non-governmental organizations, academics, and local communities is crucial to overcoming these challenges and ensuring the long-term conservation of seagrass ecosystems in Indonesia. In terms of scientific research, bibliometric results show that studies focusing on the impacts of climate change on seagrass ecosystems have been increasing since 2020, with keywords such as 'climate change' and 'carbon' dominating recent publications. However, more research is needed on the adaptation of seagrass ecosystems to changing environmental conditions, particularly regarding ocean acidification and rising water temperatures.

4. CONCLUSION

The conservation of seagrass ecosystems in Indonesia is vital for maintaining marine biodiversity, supporting coastal livelihoods, and mitigating the impacts of climate change. Bibliometric analysis reveals a significant increase in research output from 2007 to 2024, highlighting the growing scientific interest in seagrass conservation. Key themes that have emerged over time include biodiversity conservation, the role of seagrass in carbon storage, and the broader ecological services provided by seagrass ecosystems, such as water quality improvement and coastal protection. Despite these positive trends, the research also identifies persistent challenges in seagrass conservation, such as the degradation of ecosystems due to coastal development, pollution, and destructive fishing practices. These issues are further compounded by the emerging threats of climate change, including rising sea temperatures and ocean acidification, which pose new risks to the health and resilience of seagrass ecosystems. Community-based conservation efforts, the establishment of Marine Protected Areas (MPAs), and restoration projects have shown promise in mitigating these challenges. However, their success depends heavily on active community participation, government support, and long-term monitoring. Additionally, enhancing public awareness of the ecological and climate-related benefits of seagrass ecosystems is crucial to gaining broader societal support for conservation initiatives.

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