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A Bibliometric Analysis of the Seagrass Meadow Ecosystem Functions and Services

Noor Hidayah Abu[1,*], *Mohd Fitri Mansor*[2], *Nor Hasni Osman*[1], *Rahimi Abidin*[1], *Hashibah Hamid*[3], *Alminnourliza Noordin*[1] *and Haryati Abd. Wahab*[4]

[1]School of Technology Management and Logistics, Universiti Utara Malaysia, Kedah, Malaysia
[2]Faculty of Business and Communication, Universiti Malaysia Perlis, Perlis, Malaysia
[3]Institute of Strategic Industrial Decision Modelling, School of Quantitative Sciences, Universiti Utara Malaysia, Kedah, Malaysia
[4]Bahagian Sumber Perikanan Tangkapan, Jabatan Perikanan Malaysia, Pusat Pentadbiran Kerajaan Persekutuan, Putrajaya, Malaysia

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Abstract: This paper provides a thorough review article via bibliometric analysis of the global research landscape on seagrass meadow ecosystem functions and services. Seagrass meadows play a crucial role in supporting marine biodiversity, stabilizing coastlines, enhancing water quality, and mitigating climate change through carbon sequestration. However, these vital ecosystems face increasing threats from coastal development, climate change, and pollution. Using data retrieved from the Scopus and Web of Science (WoS) databases, 265 relevant publications were analysed with ScientoPy and VOSviewer to explore research trends, prolific authors, countries, institutions, and commonly used keywords. The findings reveal a significant increase in research output post-2015, with the United States, Australia, and Spain leading in publication volume. *Marine Pollution Bulletin* and *Science of the Total Environment* emerged as the most productive journals. The most frequently cited topics include blue carbon, ecosystem services, fisheries, and coastal protection, highlighting the growing focus on seagrass ecosystems' ecological and economic value. Despite growing academic attention, the article emphasises the need for more research, especially in underrepresented regions. The results provide a valuable reference for researchers, conservationists, and policymakers to guide future work and sustainable management strategies for seagrass ecosystems.

Keywords: Seagrass, bibliometric, ecosystem function, services, total economic value

1 Introduction

Seagrasses are marine angiosperm plants that grow in shallow coastal areas, generally at depths of up to 30 meters where sufficient sunlight allows photosynthesis. They are commonly found along coastal shorelines and in patches associated with coral reef ecosystems around islands. The distribution and extent of seagrass habitats are influenced by seabed topography, current strength, and water clarity. Similar to terrestrial flowering plants, seagrasses possess roots, stems, and leaves that enable them to survive in saline environments. Their ecological functions include carbon storage, habitat provision for marine organisms, and coastal protection through wave attenuation and sediment stabilisation.

Seagrass meadows are among the most productive coastal ecosystems, providing essential ecosystem functions and services, including carbon sequestration, biodiversity conservation, shoreline protection, nutrient cycling, fisheries support, and climate change mitigation. Over the last two decades, research interest in seagrass ecosystems has increased significantly due to growing concerns regarding climate change, blue carbon, biodiversity conservation, ecosystem restoration, and sustainable coastal management.

Despite the increasing number of studies on seagrass ecosystems, existing reviews remain fragmented, focusing mainly on specific ecological functions such as habitat provision, carbon sequestration, coastal protection, biodiversity conservation, or restoration [1], [2], [3], [4]. Furthermore, previous studies have generally examined ecosystem functions and ecosystem services separately, despite their interconnected roles in supporting sustainable marine ecosystem

* Corresponding author e-mail: dayah@uum.edu.my

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management. Therefore, an integrated bibliometric assessment combining ecosystem functions and services using multiple bibliographic databases remains limited.

Previous reviews have examined selected aspects of seagrass ecosystems, including ecological interactions and restoration [5], [6], ecosystem services [7], [8], blue carbon assessments [9], ecosystem dynamics and future research prospects [2] and seagrass distribution and status [10]. However, comprehensive bibliometric studies examining the overall intellectual structure, research evolution, collaboration patterns, emerging themes, and future research directions concerning seagrass ecosystem functions and services remain limited.

Seagrass ecosystems have also gained increasing recognition in supporting global sustainability initiatives, including Sustainable Development Goal (SDG) 14, Blue Economy strategies, and climate change mitigation efforts. Nevertheless, limited evidence exists regarding how global research themes have evolved in supporting these sustainability agendas. Therefore, this paper conducts a comprehensive bibliometric analysis of global research on seagrass ecosystem functions and ecosystem services using Scopus and Web of Science databases. The paper identifies publication trends, influential authors, institutions, countries, collaboration networks, thematic evolution, and emerging research hotspots to support future sustainable seagrass management.

The contributions of this paper to the existing body of literature can be highlighted in four aspects. First, it provides a comprehensive bibliometric synthesis integrating ecosystem functions and ecosystem services of seagrass meadows using two major bibliographic databases. Second, it reveals the intellectual structure and knowledge development of global seagrass research through citation analysis, collaboration networks, keyword co-occurrence, and thematic analysis. Third, it identifies emerging research areas that can guide future scientific investigations and interdisciplinary collaboration. Finally, the findings provide evidence-based insights for policymakers, conservation agencies, and researchers to strengthen sustainable coastal ecosystem management.

1.1 The Role of Seagrass Ecosystem Services

Seagrass meadows are recognised as important marine ecosystems that support biodiversity, ecological stability, and coastal productivity. They provide essential habitats and nursery grounds for various marine organisms, including fish, shrimp, shellfish, squid, seahorses, dugongs, and turtles [11], [12]. The presence of seagrass habitats contributes to maintaining marine populations while indirectly supporting the livelihoods of coastal communities, particularly fisheries-dependent communities.

Seagrass ecosystems also provide important coastal protection functions. Their rhizome roots stabilise seabed sediments by preventing erosion and reducing sediment movement, while their flexible leaves reduce wave energy and current velocity [13], [14]. These physical characteristics enable seagrass meadows to act as natural coastal barriers and support the stability of adjacent ecosystems such as coral reefs and mangroves.

Furthermore, seagrass meadows play an important role in global climate regulation through blue carbon storage. Through photosynthesis, seagrasses capture carbon dioxide and store carbon within plant biomass and surrounding sediments, creating long-term carbon sinks [15]. They also contribute to water quality improvement by absorbing excess nutrients such as nitrogen and phosphorus, reducing eutrophication risks and maintaining suitable conditions for marine biodiversity and fisheries.

1.2 Threats to Seagrass Ecosystems and Degradation

Although seagrass ecosystems provide significant ecological and economic benefits, they are increasingly threatened by anthropogenic activities and climate change. Coastal development, land-use change, pollution, and infrastructure expansion have contributed to habitat degradation and loss [16]. [17] reported that seagrass habitats have experienced global declines estimated at approximately 7% annually, making them among the most vulnerable marine ecosystems.

Climate change further intensifies these pressures through rising sea temperatures, sea-level changes, and altered salinity conditions. Increased freshwater inputs from heavy rainfall and flooding may also accelerate sediment deposition, reducing water clarity and affecting seagrass photosynthesis [14]. The decline of seagrass ecosystems threatens biodiversity, fisheries productivity, carbon sequestration capacity, and coastal resilience.

1.3 Total Economic Value of Seagrass Ecosystem Services

The assessment of Total Economic Value (TEV) provides an important approach for quantifying the direct and indirect benefits generated by seagrass ecosystems. These benefits include fisheries production, coastal protection, carbon

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sequestration, tourism, research, and cultural services. Understanding the economic value of seagrass ecosystems can support better decision-making and strengthen conservation strategies.

Previous studies indicate that seagrass ecosystems provide substantial economic benefits compared with many terrestrial ecosystems. Costanza et al. [18] estimated the annual ecosystem service value of seagrass at approximately US$28,916 per hectare, substantially higher than the estimated value of tropical forests at US$5,382 per hectare. This highlights the significant economic contribution of seagrass-associated ecosystems and their importance in supporting human well-being.

Seagrass habitats also support fisheries production, with reported economic values ranging from $3,500 per hectare per year to more than $60,000 per hectare per year in some regions [19], [20].

In Malaysia, seagrass ecosystems contribute economic benefits through fisheries, tourism, research activities, and ecosystem conservation. [6] highlighted the importance of seagrass ecosystems in supporting fisheries-related income, tourism activities, research opportunities, and educational programmes. In addition, carbon sequestration values demonstrate the important role of seagrass ecosystems in climate change mitigation [21].

Despite their ecological and economic importance, research synthesis focusing specifically on the combined ecosystem functions and services of seagrass meadows remains limited. Bibliometric approaches have been widely applied to examine research development in related ecological fields, including mangrove ecosystems [22], coral reefs [23], blue carbon research [24], and climate change studies [25]. However, a comprehensive bibliometric assessment of seagrass ecosystem functions and services remains insufficient.

Thus, this paper is designed to examine and summarise the global trends and developments in research related to seagrass ecosystem functions and services. Specifically, the paper identifies publication trends, leading journals, productive countries and institutions, major research themes, collaboration patterns, and highly cited articles to enhance understanding of knowledge evolution and support sustainable seagrass ecosystem management.

2 Materials and Methods

This section provides an overview of the research methodology employed for data collection, preprocessing, and bibliometric analysis. This paper primarily aimed to assess the current evidence base on seagrass meadow ecosystem functions and services. In this regard, the following research questions have been proposed to guide this paper.

(i) How has research on seagrass meadow ecosystem functions and services evolved over time?
(ii) Which journals contribute the most publications in this research field?
(iii) Which countries lead global research on seagrass ecosystem functions and services?
(iv) Which institutions are the most productive in seagrass ecosystem functions and services research based on their publication output?
(v) What are the most frequently used author keywords in publications on seagrass ecosystem functions and services?
(vi) Which articles have received the highest citations?

2.1 Data Collection and Search Strategy

The data collection process was conducted from September 8, 2024, to October 8, 2024, using two major bibliographic databases: Scopus and Web of Science (WoS). The search strategy was developed to identify publications related to seagrass ecosystem functions and services. The search string applied in both databases was: (“seagrass” OR “seagrass bed” OR “meadows” OR “seagrass meadows” OR “seagrasses”) AND (“blue carbon” OR “sediment” OR “carbon sequestration”) AND (“fisheries” OR “coastal protection”).

For Scopus, the search was conducted using article title, abstract, and keyword fields to retrieve relevant publications. Scopus was selected because it provides comprehensive scientometric information and extensive coverage of scientific publications, making it suitable for mapping emerging research areas [26], [27], [28]. The search was limited to journal sources and included articles, conference papers, reviews, book chapters, and books at the final publication stage. The analysis was restricted to English-language publications to maintain consistency across the study. The search criteria applied in Scopus are presented in Table 1.

In addition to Scopus, Web of Science (WoS) was used to enhance database coverage and improve the reliability of the bibliometric analysis. WoS is widely recognised as a high-quality bibliographic database that provides extensive scientific records and reliable citation information [29], [30], [31]. Relevant publications on seagrass ecosystem functions and services were identified through a structured search strategy using consistent keywords and topic fields.

The WoS search limited to Research Articles, Review Articles, and Proceedings Papers. Only English-language publications were included to maintain consistency and ensure accurate interpretation of the retrieved data. The search criteria for WoS are presented in Table 2.

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Table 1: Search criteria for articles and reviews from Scopus

Criteria	Description
Title-Abstract-Keyword	**Limit to** ("seagrass" OR "seagrass bed" OR "meadows" OR "seagrass meadows" OR "seagrasses") AND ("blue carbon" OR "sediment" OR "carbon sequestration") AND ("fisheries" OR "coastal protection")
Source type	**Limit to** Journal
Document type	**Limit to** Article OR Conference paper OR Review OR Book chapter OR Book
Publication stage	**Limit to** Final
Language	**Limit to** English

Table 2: Search criteria for articles and reviews from WoS

Criteria	Description
Topic	**Limit to** ("seagrass" OR "seagrass bed" OR "meadows" OR "seagrass meadows" OR "seagrasses") AND ("blue carbon" OR "sediment" OR "carbon sequestration") AND ("fisheries" OR "coastal protection")
Document type	**Limit to** Article OR Review Article OR Proceeding Paper
Language	**Limit to** English

2.2 Data Preprocessing and Analysis

After data collection, the Scopus and WoS datasets were exported and processed using ScientoPy. The preprocessing stage involved cleaning, standardizing, and preparing bibliographic records for analysis. This process included removing duplicate records, correcting inconsistencies, and ensuring that the dataset was suitable for bibliometric analysis [32]. ScientoPy, a Python-based scientometric analysis tool, was used to improve data accuracy and reduce potential bias during the preparation stage.

The bibliometric analysis was conducted using ScientoPy and VOSviewer. ScientoPy was applied to evaluate publication trends, research productivity, citation performance, influential publications, leading researchers, and emerging research areas. The software also generated visual representations, including trend analysis and bibliometric indicators [33].

VOSviewer was employed to visualise and analyse bibliometric networks, including relationships among authors, institutions, countries, keywords, and publications. The software enables the identification of collaboration patterns, citation relationships, and thematic developments within a research field [27], [34].

Finally, the results were interpreted according to the research questions. The analysis focused on identifying publication evolution, leading journals, productive countries and institutions, dominant research themes, collaboration networks, and highly cited articles in the field of seagrass meadow ecosystem functions and services.

3 Results and Analysis

3.1 Preliminary Data Analysis

The downloaded data sets resulted in 354 publications utilizing both databases. Scopus contained 237 documents, whereas WoS held 105. However, a total of 77 papers has been determined duplicated and were eliminated from analysis. Table 3 demonstrates how final sample 265 was examined in this paper after duplication data was removed.

A total of 354 papers were initially loaded for analysis. This figure indicates a substantial amount of research literature available for review. Out of the loaded papers, 12 (or 3.40%) were omitted based on document type. This suggests that a small percentage of the data set was deemed irrelevant for the analysis. After omitting the irrelevant papers, 342 papers remained for further examination. This number represents the refined dataset used for subsequent analysis. Among the remaining papers, 105 were loaded from the Web of Science (WoS), accounting for 30.70% of the total. In contrast, 237 papers were sourced from Scopus, representing 69.30%. This distribution highlights a greater reliance on Scopus for research literature in this dataset. The analysis identified 77 duplicated papers, comprising 22.50% of the total papers. This indicates a notable level of redundancy within the dataset, which is common in literature reviews. Following the identification of duplicates: 5 duplicates were removed from WoS (4.80% of the original WoS papers) and 72 duplicates were removed from Scopus (30.40% of the original Scopus papers). This demonstrates a significant presence of duplicate entries, particularly from Scopus. Notably, 47 duplicated documents had different citation counts, which indicates variability in how these papers have been referenced in different contexts.

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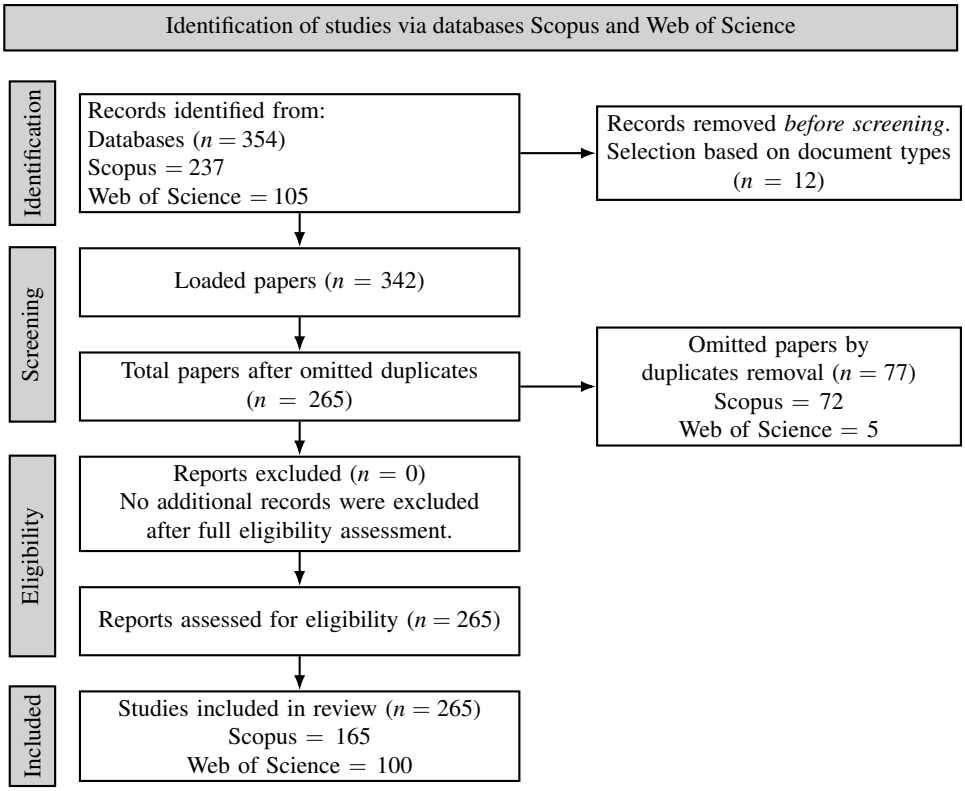


Fig. 1: Flow chart of database and register searches

Table 3: Overview of the initial data analysis results

Data retrieval	**Number**	**Percentage**
Loaded papers	354	
Omitted papers by document type	12	3.40%
Total papers after omitted papers removed	342	
WoS loaded papers	105	30.70%
Scopus loaded papers	237	69.30%
Duplicate removal results:		
Duplicated papers found	77	22.50%
WoS removed duplicated papers	5	4.80%
Scopus removed duplicated papers	72	30.40%
Duplicated documents with different cited-by counts	47	61.00%
Total papers after duplicate removal	265	
WoS papers	100	37.70%
Scopus papers	165	62.30%

This could be important to understand the impact and reach of the research. After the removal of duplicates, 265 papers remained for final analysis. This indicates a substantial reduction in the dataset, underscoring the importance of duplicate management in research reviews. The final or remaining papers were divided into: 100 papers from WoS (37.70%) and 165 papers from Scopus (62.30%). This final distribution shows that Scopus retained a larger share of the remaining relevant literature after duplicates were removed. In short, this data analysis serves a comprehensive overview in the initial data set, emphasizing the importance of effective data management practices, such as identifying and removing duplicates. The significant reliance on Scopus for relevant literature may reflect its broader coverage or relevance to the specific research focus.

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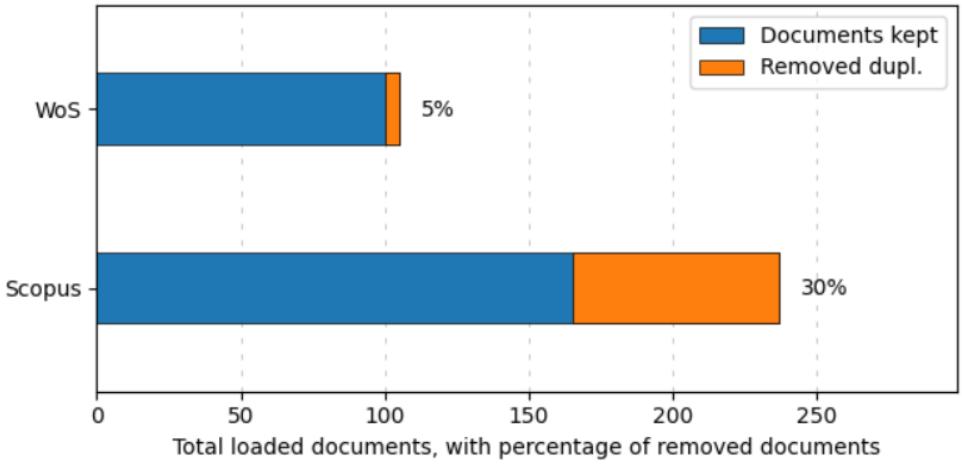


Fig. 2: Documents retained and duplicates removed by database

3.2 The Evolution of Publications

The publication trend demonstrates the evolution of research on seagrass meadow ecosystem functions and services from a relatively limited research area into a globally recognised multidisciplinary field. The overall pattern reflects increasing ecological awareness, technological advancement, research priorities, and global sustainability agendas.

During the 1980s and early 1990s, research output on seagrass ecosystems remained limited, partly due to greater research attention being directed towards more prominent coastal ecosystems such as coral reefs, mangroves, and fisheries resources. Limited funding, insufficient long-term monitoring capacity, and the lack of comprehensive ecological datasets also constrained extensive investigations into seagrass ecosystem functions and services.

From the mid-1990s to early 2000s, publication output gradually increased with several fluctuations, corresponding with growing concerns regarding coastal degradation, biodiversity conservation, and sustainable fisheries management. During this period, researchers increasingly recognised the ecological importance of seagrass meadows as nursery habitats, coastal stabilisation systems, and contributors to nutrient cycling. Improved research collaboration and accessibility to scientific databases further supported the expansion of studies in this field.

Between 2010 and 2016, Scopus-indexed publications showed a steady increasing trend, followed by a substantial acceleration between 2017 and 2023 in both Scopus and Web of Science (WoS). This rapid growth reflects rising global attention towards climate change mitigation, blue carbon ecosystems, ecosystem services, and Sustainable Development Goal 14 (Life Below Water). The recognition of seagrass meadows as efficient carbon sequestration ecosystems has further strengthened research interest among scientists, policymakers, and conservation organisations.

The comparison between databases highlights differences in indexing coverage. Scopus provides a longer historical record, with seagrass-related publications available since the 1980s, whereas WoS publications became more prominent after 2015. However, WoS demonstrated rapid growth between 2018 and 2023, indicating increasing visibility of seagrass research in high-impact environmental journals. The decline in WoS publications after 2023 should be interpreted cautiously, as it may be influenced by publication lag or database updating processes rather than reduced research interest.

Overall, the publication trajectory confirms that seagrass research has evolved from a specialised ecological field into an interdisciplinary research domain integrating marine ecology, climate science, ecosystem service assessment, socio-economic evaluation, and conservation policy. The increasing research output highlights the growing recognition of seagrass ecosystems as critical natural assets supporting biodiversity conservation, climate regulation, coastal resilience, and sustainable development.

Nevertheless, geographical disparities remain evident, particularly in developing regions where extensive seagrass habitats exist but scientific contributions remain limited. Future research should therefore strengthen international collaboration and integrate ecological, socio-economic, and governance perspectives to support effective conservation and sustainable management of seagrass ecosystems.

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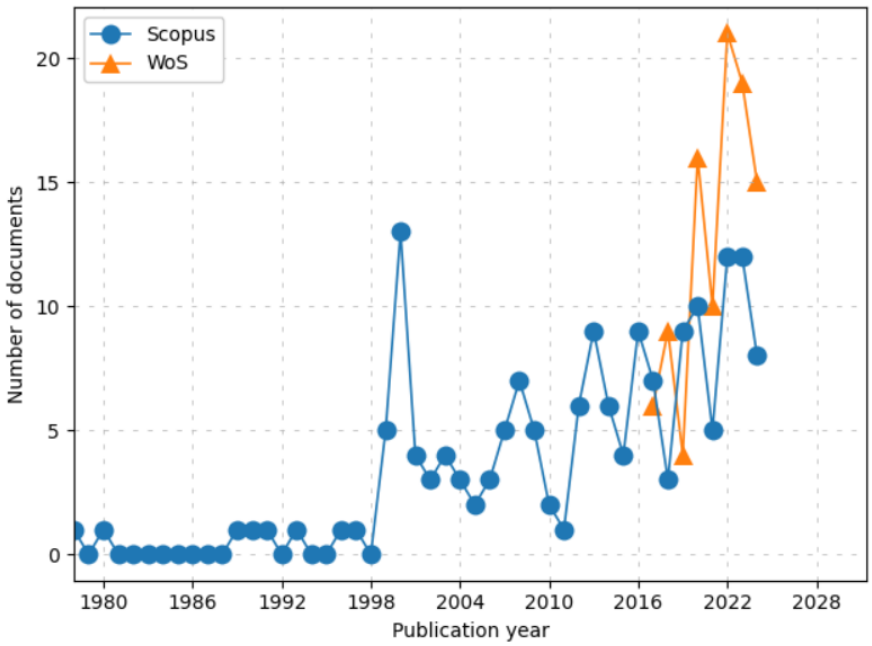


Fig. 3: Database timeline

3.3 Most Frequently Published Journals

The descriptive analysis identified the top ten source titles publishing research related to seagrass meadow ecosystem functions and services based on publication output, annual growth rate (AGR), and h-index (Table 4). Among the identified journals, *Marine Pollution Bulletin* ranked first with 16 publications, followed by *Science of the Total Environment* (12 publications) and *Frontiers in Marine Science* (11 publications).

The dominance of these journals reflects the multidisciplinary nature of seagrass research, which extends beyond marine ecology to include ecosystem conservation, climate change mitigation, pollution assessment, ecosystem services, and sustainable coastal management. Journals with broader environmental and sustainability scopes tend to attract more seagrass-related studies due to the increasing integration of ecological and socio-environmental perspectives.

In terms of publication growth, *Science of the Total Environment* recorded the highest AGR (1.5), followed by *Estuarine, Coastal and Shelf Science* (0.5), indicating increasing research interest in seagrass-related topics within environmental and coastal science communities. Although *Marine Pollution Bulletin*, *Frontiers in Marine Science*, and *Marine Ecology Progress Series* showed negative AGR values, these journals maintained strong academic influence, reflected by their relatively high h-index values. The negative AGR may represent variations in annual publication patterns rather than declining research importance.

Table 4: Top ten journals publishing research on seagrass ecosystems

Position	Source title	Total	AGR	h-index
1	Marine Pollution Bulletin	16	−0.5	12
2	Science of the Total Environment	12	1.5	6
3	Frontiers in Marine Science	11	−1.5	9
4	Marine Ecology Progress Series	8	−0.5	7
5	Marine Environmental Research	8	−1.0	6
6	Seas at the Millennium – an Environmental Evaluation – Volume 2	8	0.0	3
7	Estuarine, Coastal and Shelf Science	6	0.5	5
8	Estuaries and Coasts	5	0.0	5
9	IOP Conference Series: Earth and Environmental Science	5	−0.5	3
10	Journal of Marine Science and Engineering	4	0.0	2

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Overall, the distribution of publications across source titles suggests that research on seagrass is gaining increasing recognition in leading marine and environmental journals. The findings demonstrate the growing scientific relevance of seagrass ecosystems in discussions related to biodiversity conservation, blue carbon, climate change mitigation, and sustainable coastal management.

3.4 The Ranking of the Most Productive Country Studying Seagrass

The country-level analysis represents the second descriptive category in this paper. A total of 99 countries contributed publications related to seagrass meadow ecosystem functions and services. Figure 4 presents the top ten most productive countries based on publication output. The United States ranked first with 66 publications, followed by Australia with 57 publications and Spain with 36 publications. These countries represent the major research hubs contributing to the development of knowledge on seagrass ecosystems.

The dominance of these countries may be associated with several factors, including the extensive distribution of seagrass habitats within their coastal regions, strong marine research institutions, availability of long-term ecological monitoring programmes, and greater investment in marine conservation research. Furthermore, increasing global attention towards biodiversity conservation, blue carbon ecosystems, and climate change mitigation has further stimulated research activities in countries with established marine science capabilities.

In terms of average document output per year (ADY), Australia recorded the highest value (7.5), followed by Spain (6.0) and the United States (5.0), indicating their consistent contribution to seagrass research. However, the overall number of publications remains relatively limited compared with other established environmental research fields, suggesting that seagrass ecosystem functions and services remain an emerging research area.

The geographical distribution of publications also reveals an important research imbalance. Although seagrass habitats are widely distributed, particularly in tropical and coastal regions, many developing countries with significant seagrass resources remain underrepresented in scientific publications. This limitation may be related to insufficient research funding, limited technical expertise, inadequate monitoring infrastructure, and lower institutional research capacity.

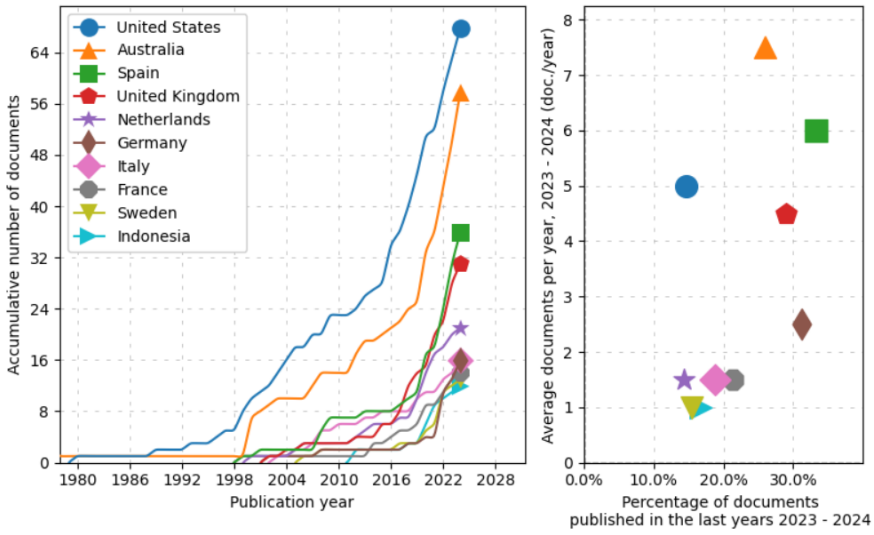


Fig. 4: Ranking of the most productive countries in research related to seagrass meadow ecosystem functions and services

Overall, the findings highlight the need to strengthen international collaboration, research capacity building, and knowledge transfer, particularly between developed and developing regions. Expanding global research participation is essential to improve understanding of seagrass ecosystems and support effective conservation strategies, sustainable coastal management, and evidence-based marine policies.

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3.4.1 Co-authorship by Country Network Visualisation

This paper examined international co-authorship patterns in research on seagrass meadow ecosystem functions and services to understand global scientific collaboration. Collaboration among researchers from different countries facilitates knowledge exchange, integrates multidisciplinary expertise, and improves research quality by combining ecological, technical, and methodological capabilities to address complex challenges in seagrass conservation and management.

Co-authorship analysis was conducted using VOSviewer. Although no standard publication threshold exists for country-level co-authorship analysis, this paper applied a minimum threshold of 10 publications per country. Of the 74 countries represented in the dataset, 12 met this criterion and formed active international collaboration networks. As illustrated in Figure 5, four collaboration clusters (red, yellow, green, and blue) were identified. Node size represents the number of publications produced by each country, while link thickness indicates the strength of collaborative relationships.

The findings reveal that the United States, Australia, and Spain occupy central positions within the collaboration network, demonstrating stronger international partnerships than other countries. Their leadership is likely driven by well-established marine research institutions, extensive seagrass resources, long-term ecological monitoring programmes, and sustained investment in marine conservation research. Active participation in international initiatives on biodiversity conservation, blue carbon, and climate change has further strengthened their collaborative networks and research productivity.

Strong collaboration among these leading countries has accelerated knowledge generation by integrating complementary expertise, geographical perspectives, and research methodologies. Such partnerships enhance research visibility, increase citation impact, and generate more comprehensive scientific evidence to support conservation planning, ecosystem restoration, and policy development.

Despite these advances, the network also reveals an imbalance in global research collaboration. Many developing countries with extensive seagrass habitats remain weakly connected within international research networks because of limited funding, technical expertise, monitoring infrastructure, and institutional research capacity. This imbalance may restrict regional ecological understanding and reduce opportunities to develop locally relevant conservation strategies.

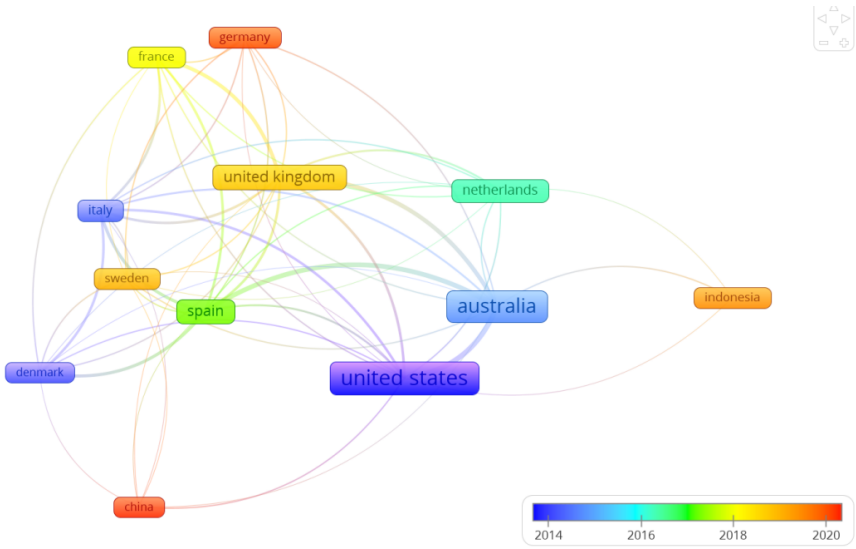


Fig. 5: Co-authorship by country network visualisation

Overall, the co-authorship network demonstrates that international collaboration has become a key driver of scientific advancement in seagrass ecosystem research. Expanding partnerships, promoting capacity-building programmes, and strengthening knowledge transfer between developed and developing countries will be essential for producing more inclusive scientific knowledge and supporting the sustainable management of seagrass ecosystems worldwide.

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3.5 Top Productive Institutions in Seagrass Ecosystem Research

Articles related to seagrass meadow ecosystem functions and services have been published by 227 institutions worldwide. Figure 6 presents the top 10 most productive institutions in this research field. Among these, five institutions are from Australia, four from the Netherlands, and one from Spain. Edith Cowan University (Australia), Radboud University Nijmegen (Netherlands), and Utrecht University (Netherlands) ranked highest, each contributing eight publications. Deakin University and the University of Groningen followed with seven publications, while the remaining institutions produced between four and six publications.

The dominance of Australian and Dutch institutions can be attributed to their strong marine research capacity, long-term ecological monitoring programmes, extensive seagrass habitats, and sustained investment in coastal ecosystem research. In addition, well-established interdisciplinary collaborations integrating marine ecology, environmental science, climate research, and ecosystem service assessment have strengthened their research productivity and international visibility.

Regarding recent publication activity (2023–2024), the Spanish National Research Council (CSIC) and Southern Cross University recorded the highest proportion of recent publications (50%), followed by Deakin University (43%) and Edith Cowan University (38%). In contrast, James Cook University and the University of Queensland recorded no publications during this period, suggesting variations in research cycles rather than declining interest in seagrass studies. Institutions actively engaged in emerging topics such as blue carbon, ecosystem restoration, and climate adaptation generally demonstrated stronger publication growth.

Overall, the findings indicate that seagrass research is concentrated within institutions possessing strong scientific infrastructure and international collaboration networks. While these institutions have advanced scientific knowledge and evidence-based conservation, the uneven institutional distribution highlights the need to strengthen research capacity and collaborative networks in regions where seagrass ecosystems are abundant but research output remains limited. This would promote more balanced global participation and improve understanding of seagrass ecosystem functions and services.

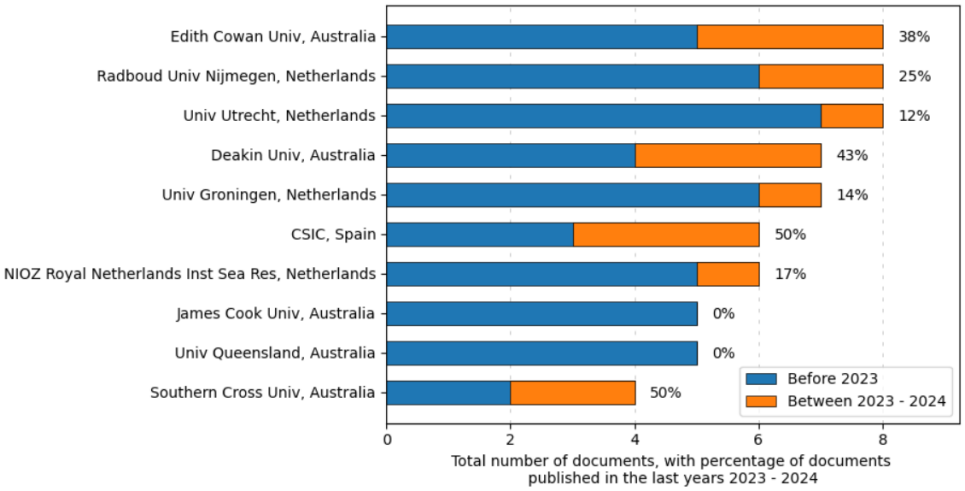


Fig. 6: Top productive institutions ranking

3.6 Most Frequent Author Keywords

Author keywords provide insights into the main research topics and conceptual structure of a research field, enabling researchers to identify prominent themes and examine their relationships through keyword analysis [35]. This analysis identified the top 10 author keywords used in publications on seagrass meadow ecosystem functions and services. Figure 7 presents the frequency of keyword occurrences and their utilisation in publications published between 2023 and 2024.

The most frequently used keywords were “blue carbon” (29 occurrences), “ecosystem services” (23), and “fisheries” (20). In recent publications, “blue carbon” appeared in 34% of studies, followed by “ecosystem services” (26%) and “fisheries” (10%). Other prominent keywords included “conservation,” “mangroves,” “climate change,” “*Posidonia*

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oceanica," "coastal protection," "sediment," and "carbon sequestration." Notably, "sediment" appeared in the highest proportion of publications during 2023–2024 (43%), followed by "blue carbon" (34%) and "carbon sequestration" (33%).

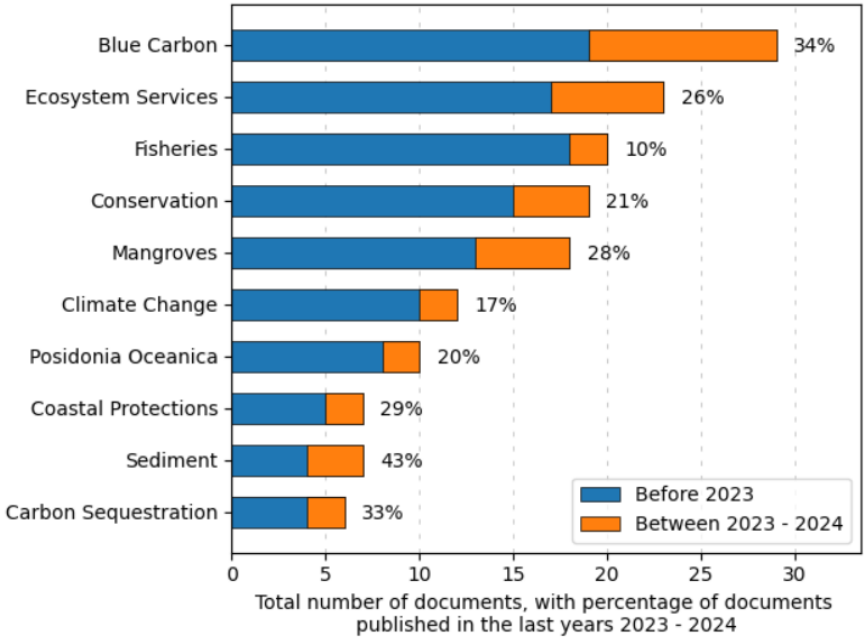


Fig. 7: Top 10 authors' keywords

The prominence of these keywords reflects a clear shift in research priorities from traditional ecological studies towards climate change mitigation, ecosystem service valuation, and sustainable coastal management. Growing international attention to blue carbon, biodiversity conservation, and nature-based solutions has accelerated research on the carbon storage capacity and ecological functions of seagrass meadows. This trend highlights the increasing recognition of seagrass ecosystems as strategic natural assets that support climate resilience, fisheries sustainability, and evidence-based coastal conservation policies.

3.6.1 Keyword Co-occurrence and Research Trend Evolution

Keyword co-occurrence analysis was conducted using VOSviewer to examine the intellectual structure and evolution of research on seagrass meadow ecosystem functions and services (Figure 8). This approach identifies how frequently keywords appear together, revealing relationships among research topics, emerging themes, and the evolution of scientific knowledge. From a total of 803 author keywords, only those with a minimum occurrence of 10 were included, resulting in eight highly connected keywords for further analysis. In the overlay visualisation, node size represents keyword frequency, link thickness indicates the strength of relationships, and colours illustrate the temporal evolution of research themes.

The findings reveal a clear shift in research priorities over time. Earlier studies, represented by blue nodes (before 2018), primarily focused on "climate change," "conservation," and the ecological roles of seagrass ecosystems, reflecting early concerns regarding habitat degradation, biodiversity conservation, and environmental protection. In contrast, more recent studies (2020-2021, shown in red) increasingly emphasised "blue carbon," "ecosystem services," "restoration," and "mangrove." These emerging themes indicate that seagrass research has evolved from describing ecological functions to evaluating ecosystem services, climate mitigation potential, and integrated coastal ecosystem management.

This transition has been driven by growing international attention to climate change mitigation, carbon sequestration, biodiversity conservation, and nature-based solutions. The recognition of seagrass meadows as efficient blue carbon ecosystems, together with advances in ecosystem service assessment, remote sensing, and restoration technologies, has broadened research beyond ecological studies towards interdisciplinary and policy-oriented investigations.

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The evolution of research themes carries important implications. It demonstrates that seagrass ecosystems are increasingly recognised not only for their ecological importance but also for their contribution to climate resilience, coastal sustainability, and socio-economic well-being. The stronger emphasis on blue carbon and ecosystem services also supports international sustainability agendas and encourages greater collaboration among marine scientists, climate researchers, economists, and policymakers. Future studies should continue integrating ecological, socio-economic, and governance perspectives to strengthen evidence-based conservation and sustainable management of seagrass ecosystems.

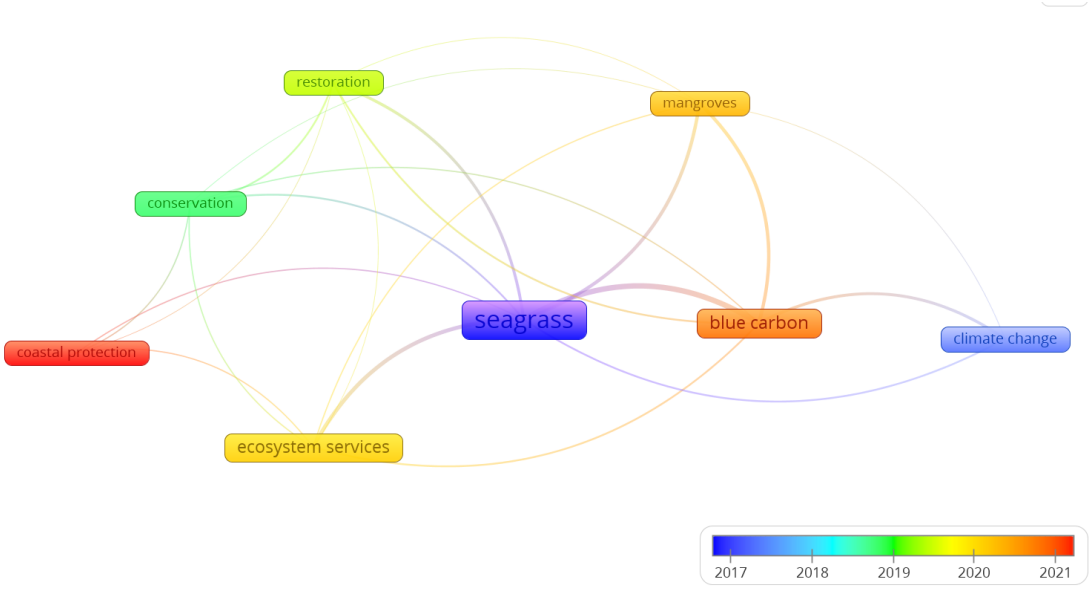


Fig. 8: Overlay visualisation of authors' keywords

3.7 The Most Frequently Cited Publications in Seagrass Research

The most frequently cited publication in the field of seagrass research is *"Developing success criteria and goals for evaluating oyster reef restoration: Ecological function or resource exploitation?"* by Coen and Luckenbach [36], with 266 citations. Although this paper focuses on oyster reef restoration, its relevance to seagrass research lies in its evaluation of ecological functions, restoration objectives, and ecosystem recovery indicators, which are also fundamental considerations in seagrass conservation and management.

The second most cited study is "Effects of fish farming on seagrass (*Posidonia oceanica*) in a Mediterranean bay: Seagrass decline after organic loading cessation" by [37], with 193 citations. This article highlights the impacts of aquaculture activities on seagrass meadows, particularly the effects of nutrient enrichment and organic waste accumulation on habitat degradation. The findings provide important evidence for understanding anthropogenic pressures affecting coastal ecosystems.

Other highly influential studies include the work of [38], which examined how tropical seagrass meadows modify seawater carbon chemistry and their implications for coral reef conservation. With 156 citations, this paper has significantly contributed to understanding the role of seagrass ecosystems in regulating ocean carbon processes and mitigating the impacts of ocean acidification.

Overall, the citation analysis demonstrates that seagrass research has evolved from a primarily ecological assessment field into a broader interdisciplinary research domain involving marine conservation, climate science, ecosystem economics, and environmental policy. The highly cited publications have provided fundamental knowledge that supports improved understanding, monitoring, and management of seagrass ecosystems.

The trend presented in Table 5 has significant implications. First, the dominance of studies related to human impacts highlights the urgent need to address coastal pressures, including pollution, aquaculture expansion, and habitat disturbance. Second, the growing influence of restoration and blue carbon studies demonstrates the increasing recognition of seagrass meadows as important nature-based solutions for climate mitigation and coastal resilience. Third,

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Table 5: The most cited publications

No.	Authors	Title	Year	Cited by
1	Coen L.D.; Luckenbach M.W.	Developing success criteria and goals for evaluating oyster reef restoration: Ecological function or resource exploitation?	2000	266
2	Delgado O.; Ruiz J.; Perez M.; Romero J.; Ballesteros E.	Effects of fish farming on seagrass (*Posidonia oceanica*) in a Mediterranean bay: Seagrass decline after organic loading cessation	1999	193
3	Unsworth R.K.F.; Collier C.J.; Henderson G.M.; McKenzie L.J.	Tropical seagrass meadows modify seawater carbon chemistry: Implications for coral reefs impacted by ocean acidification	2012	156
4	Holmer M.; Argyrou M.; Dalsgaard T.; Danovaro R.; Diaz-Almela E.; Duarte C.M.; Frederiksen M.; Grau A.; Karakassis I.; Marba N.; Mirto S.; Perez M.; Pusceddu A.; Tsapakis M.	Effects of fish farm waste on *Posidonia oceanica* meadows: Synthesis and provision of monitoring and management tools	2008	142
5	Campagne C.S.; Salles J.M.; Boissery P.; Deter J.	The seagrass *Posidonia oceanica*: Ecosystem services identification and economic evaluation of goods and benefits	2015	132
6	Rose C.D.; Sharp W.C.; Kenworthy W.J.; Hunt J.H.; Lyons W.G.; Prager E.J.; Valentine J.F.; Hall M.O.; Whitfield P.E.; Fourqurean J.W.	Overgrazing of a large seagrass bed by the sea urchin *Lytechinus variegatus* in Outer Florida Bay	1999	123
7	Pergent G.; Mendez S.; Pergent-Martini C.; Pasqualini V.	Preliminary data on the impact of fish farming facilities on *Posidonia oceanica* meadows in the Mediterranean	1999	95
8	Stoner A.W.	What constitutes essential nursery habitat for a marine species? A case study of habitat form and function for queen conch	2003	88
9	Valdez S.R.; Zhang Y.S.; van der Heide T.; Vanderklift M.A.; Tarquinio F.; Orth R.J.; Silliman B.R.	Positive ecological interactions and the success of seagrass restoration	2020	85
10	Hejnowicz A.P.; Kennedy H.; Rudd M.A.; Huxham M.R.	Harnessing the climate mitigation, conservation and poverty alleviation potential of seagrasses: Prospects for developing blue carbon initiatives and payment for ecosystem service programmes	2015	75
11	Wu J.P.; Zhang H.B.; Pan Y.W.; Krause-Jensen D.; He Z.G.; Fan W.; Xiao X.; Chung I.; Marba N.; Serrano O.; Rivkin R.B.; Zheng Y.H.; Gu J.L.; Zhang X.J.; Zhang Z.H.; Zhao P.; Qiu W.F.; Chen G.C.; Duarte C.M.	Opportunities for blue carbon strategies in China	2020	72

the integration of ecosystem service valuation provides stronger justification for conservation investments by demonstrating the ecological and socio-economic benefits of protecting seagrass habitats. Therefore, future research should continue to combine ecological knowledge, technological advancement, economic valuation, and policy approaches to support effective and sustainable seagrass ecosystem management.

4 Discussion

This bibliometric analysis provides important insights into the evolution, research development, and knowledge structure of seagrass meadow ecosystem functions and services. The findings demonstrate that seagrass research has progressively transformed from a relatively limited ecological research area into a multidisciplinary field involving marine ecology, climate science, ecosystem services, restoration, and sustainable coastal management.

Regarding research publication trends (Research Question i), the findings reveal a significant increase in scientific attention towards seagrass ecosystems over the past decades. Between 1980 and the early 1990s, publication output remained relatively low, reflecting limited recognition of seagrass ecosystems compared with other coastal habitats such as coral reefs and mangroves. This situation was influenced by limited research funding, insufficient long-term ecological monitoring, and restricted availability of comprehensive ecological datasets. However, publication growth

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gradually increased from the mid-1990s onwards, corresponding with rising global concerns regarding biodiversity conservation, coastal degradation, and sustainable fisheries management. A major transition occurred after 2015, particularly between 2017 and 2023, where publication output increased substantially in both Scopus and Web of Science databases. This growth reflects the increasing recognition of seagrass meadows as important nature-based solutions for climate change mitigation, blue carbon storage, and coastal resilience. Furthermore, improvements in ecological monitoring technologies, remote sensing applications, and international research collaboration have expanded the capacity to investigate seagrass ecosystem functions from broader ecological and socio-economic perspectives.

Regarding the most influential publication sources (Research Question ii), seagrass research is mainly published in established marine and environmental journals, with Marine Pollution Bulletin, Science of the Total Environment, and Frontiers in Marine Science representing the leading sources. The increasing contribution of journals with broader environmental scopes indicates that seagrass research has expanded beyond traditional ecological studies towards interdisciplinary themes such as climate change, ecosystem services assessment, pollution impacts, and coastal sustainability. Although some established journals recorded negative annual growth rates, their high h-index values demonstrate continued academic influence and strong citation impact. This pattern suggests that publication growth is not solely determined by the number of articles produced but also by the scientific influence and relevance of research contributions.

Concerning the most productive countries (Research Question iii), the findings indicate that the United States, Australia, and Spain represent the major contributors to seagrass research. Their research dominance may be attributed to several factors, including extensive seagrass distribution, strong marine research institutions, long-term ecological monitoring programmes, and greater investment in coastal conservation initiatives. Australia and Spain, in particular, demonstrate consistent research productivity, reflecting their strong engagement in marine ecosystem studies. However, the relatively low publication contribution from many countries highlights a geographical imbalance in global seagrass research. Although seagrass habitats are widely distributed in tropical and developing regions, many countries remain underrepresented due to limited research capacity, funding constraints, and inadequate monitoring infrastructure. Therefore, strengthening international collaboration and research capacity building is essential to improve global understanding of seagrass ecosystems.

Regarding institutional contributions (Research Question iv), the findings demonstrate that seagrass research is concentrated among universities and research institutions with established marine science capabilities, particularly in Australia and Europe. Leading institutions such as Edith Cowan University, Radboud University Nijmegen, Utrecht University, and Deakin University have contributed significantly to advancing knowledge in this field. The dominance of these institutions may be associated with their specialised expertise, access to research funding, international networks, and involvement in long-term coastal ecosystem research. However, differences in institutional productivity indicate that research capacity remains uneven globally. Expanding collaboration with emerging institutions, particularly from regions with extensive seagrass habitats, may enhance knowledge diversity and support more comprehensive conservation strategies.

Analysis of author keywords (Research Question v) demonstrates a clear transformation in research priorities. The dominance of keywords such as “blue carbon”, “ecosystem services”, and “fisheries” reflects increasing recognition of seagrass ecosystems as providers of ecological and socio-economic benefits. Earlier research primarily focused on habitat conservation and ecological functions, whereas recent studies increasingly emphasise carbon sequestration, climate mitigation, coastal protection, and ecosystem valuation. The emergence of blue carbon as a major research theme indicates a shift towards recognising seagrass meadows as strategic ecosystems within global climate and sustainability agendas. This transition has important implications because it strengthens the scientific basis for integrating seagrass conservation into climate policies, ecosystem restoration programmes, and sustainable coastal development strategies.

The keyword co-occurrence analysis further confirms this evolution by demonstrating a shift from traditional conservation-focused studies towards broader ecosystem service and climate-related research. Earlier studies were commonly associated with terms such as conservation, biodiversity, and habitat protection. However, recent research has increasingly linked seagrass with blue carbon, restoration, and ecosystem services. This change is driven by global attention towards climate change mitigation, nature-based solutions, technological advancement in ecosystem monitoring, and increasing demand for evidence-based environmental management. Consequently, seagrass research has become more interdisciplinary, involving marine scientists, climate researchers, policymakers, and conservation practitioners.

Regarding highly cited publications (Research Question vi), citation analysis highlights several dominant research themes, including ecosystem restoration, anthropogenic impacts, carbon sequestration, and ecosystem valuation. Highly cited studies have contributed fundamental knowledge regarding ecological functions, threats from human activities, and the role of seagrass ecosystems in climate regulation. The strong citation impact of these studies reflects their relevance to global environmental challenges and their contribution to developing practical approaches for ecosystem conservation and management. These influential publications have shaped current research directions by demonstrating that seagrass ecosystems provide not only ecological functions but also economic and societal benefits.

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In terms of theoretical contributions, this paper contributes to ecosystem services and sustainability research by demonstrating the transition of seagrass studies from a primarily ecological perspective towards an integrated socio-ecological framework. The findings highlight the importance of connecting ecosystem functions, ecosystem services, and human well-being to better understand the broader value of seagrass ecosystems. This integrated perspective provides opportunities for future research to incorporate ecological, economic, technological, and governance dimensions to support more effective and sustainable seagrass conservation and management.

Beyond the publication trends, the bibliometric findings provide important policy implications for the sustainable management of seagrass ecosystems. The growing emphasis on ecosystem services, blue carbon, and restoration reflects the increasing recognition of seagrass meadows as strategic natural assets for climate change mitigation, biodiversity conservation, and coastal resilience. These research priorities are closely aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) and SDG 14 (Life Below Water), as well as the UN Decade of Ocean Science for Sustainable Development (2021-2030).

The increasing focus on blue carbon also highlights the importance of integrating seagrass conservation into Blue Economy strategies, Marine Protected Area (MPA) planning, and ecosystem restoration initiatives. These findings provide scientific evidence to support more effective coastal governance and evidence-based conservation policies. However, significant geographical and thematic gaps remain, particularly in developing countries where seagrass habitats are extensive but research capacity is limited. Therefore, future policies should prioritise international collaboration, long-term ecological monitoring, and interdisciplinary research to strengthen sustainable coastal development and improve marine ecosystem governance.

The above findings could be extended toward more sophisticated research topics and interdisciplinary analytical approaches. For instance, [39] and [40] explored entropic uncertainty and entropy squeezing in nonlinear quantum systems, demonstrating the relevance of information-theoretic measures in analyzing complex system behavior. Similarly, [41] introduced a Lyapunov-based framework for finite- and fixed-time stability in discontinuous impulsive systems, providing valuable theoretical foundations for the stability analysis of dynamic models. From an environmental perspective, A Bibliometric Analysis on the Seagrass Meadow Ecosystem Functions and Services offers complementary insights into ecosystem research trends, knowledge development, and environmental assessment. Collectively, these studies highlight promising opportunities to extend the present findings through the integration of mathematical modeling, information-theoretic analysis, stability theory, and interdisciplinary environmental research.

5 Conclusion

This paper provides a comprehensive understanding of the research landscape on seagrass meadow ecosystem functions and services through a bibliometric approach. By integrating ScientoPy and VOSviewer with data obtained from Scopus and Web of Science, this paper strengthens the robustness of bibliometric analysis and provides a broader perspective on the development of seagrass research. The novelty of this paper lies in its integration of ecological and socio-economic perspectives, offering a more holistic understanding of how seagrass ecosystems are valued beyond their biological functions.

The findings highlight that future research should move towards more integrated approaches that connect ecological knowledge with economic valuation, governance, and sustainability management. Several knowledge gaps remain, particularly regarding socio-ecological interactions, policy evaluation, traditional ecological knowledge, and research representation from regions with extensive seagrass habitats. Addressing these gaps is essential to improve the effectiveness of conservation and management strategies.

This paper provides a strategic reference for researchers, conservation practitioners, and policymakers by identifying emerging research directions and potential areas for future investigation. Future studies should consider interdisciplinary approaches and combine bibliometric analysis with empirical and qualitative methods to generate deeper insights into seagrass ecosystem management. Such efforts are crucial for supporting evidence-based conservation, sustainable coastal development, and long-term protection of seagrass ecosystems.

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Author Contributions

All authors contributed equally and jointly to all aspects of the research and the writing of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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