

Bacterial associations in seagrass ecosystems: a systematic review of microbial diversity and ecological roles

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Abstract. Seagrasses are important marine plants that support coastal ecosystems, yet their bacterial associations remain insufficiently explored. This bibliometric study and meta-analysis examine bacterial communities associated with seagrass species, focusing on their roles in plant health, nutrient cycling, and ecosystem functioning. A comprehensive search was conducted using Scopus and Web of Science databases, applying the Boolean keywords: ("bacteria*" OR "bacterial*" OR "microbe*" OR "microbial*") AND ("seagrass*" OR "*Phyllospadix**" OR "*Zostera**" OR "*Enhalus**" OR "*Halophila**" OR "*Thalassia**" OR "*Posidonia**" OR "*Amphibolis**" OR "*Cymodocea**" OR "*Halodule**" OR "*Syringodium**" OR "*Thalassodendron**"). The review reveals a wide diversity of bacterial groups, including endophytic, epiphytic, and rhizosphere bacteria, with significant functions in nutrient cycling, disease resistance, and plant-microbe interactions. However, research gaps persist, particularly in understanding the functional roles of these microbial communities under varying environmental conditions. This study provides a comprehensive synthesis that highlights the importance of bacterial diversity associations in seagrass ecosystem. Crucially, this review presents a profound new perspective on critical new insight into their ecological roles, solidifying the foundation for future microbe-based conservation and management strategies.

1 Introduction

Seagrass is a flowering plant that thrives entirely underwater forming extensive meadows in shallow coastal waters across the globe [1]. As one of the most productive coastal ecosystems, seagrass meadows play a vital role in sustaining the ecological balance of marine environments by providing a range of critical ecosystem services. These include substantial blue carbon storage, which contributes to climate change mitigation; nutrient regulation and recycling; shoreline stabilization and protection against erosion; as well as offering structurally complex and biodiverse habitats for numerous marine species [2, 3]. Furthermore, seagrass serves as a crucial nursery ground for a range of economically valuable

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fish species, while also contributing to the reduction of greenhouse gas emissions through its remarkable ability to absorb and sequester substantial amounts of carbon [3]. Despite their exceptionally high ecological and socioeconomic value, seagrass meadows worldwide are currently under severe threat. The global rate of decline is estimated at about 7% annually, driven predominantly by anthropogenic pressures, including pollution from land-based activities, coastal infrastructure development, and the impacts of global warming, which contribute to rising sea surface temperatures [4, 5]. This degradation not only poses a significant risk to the long-term sustainability of marine biodiversity but also undermines the capacity of these ecosystems to deliver essential environmental services.

Within seagrass ecosystems, bacteria play a crucial role in maintaining ecological stability and functionality. These microorganisms participate in a range of critical biogeochemical processes, including nitrogen fixation to enhance ecosystem fertility, the decomposition of organic matter that contributes to nutrient cycling, and sediment stabilization, which supports the integrity of habitat structure. Additionally, specific bacterial communities serve as bioprotective agents by suppressing the proliferation of harmful pathogens [6, 7]. Symbiotic associations between bacteria and seagrasses have been shown to enhance host resilience against various environmental stressors, including eutrophication and elevated sea surface temperatures [8]. A prominent example is the occurrence of symbiotic bacteria in *Zostera marina*, which have been shown to inhibit the onset of vibriosis in nearby marine organisms, thereby playing a vital role in maintaining the health and stability of coastal ecosystem communities [6].

While the ecological significance of bacteria-seagrass interactions is well-recognized, the body of literature exploring them is still scarce. This gap is especially evident in the lack of bibliometric analyses, which are needed to map the evolution of the research field and highlight future directions[3]. Bibliometric approaches offer a systematic framework for this purpose by enabling researchers to evaluate literature, detect trends, and map collaboration networks[9]. Applying such an analysis to bacterial-seagrass associations can provide valuable insights into the fields progression and uncover new opportunities for investigation. Accordingly, this study employs a bibliometric approach to identify patterns and trends in publications on this topic. The result are expected to deepen our understanding of microbe–seagrass interactions and guide future research toward the effective management and conservation of seagrass ecosystems.

2 Material and methods

This study utilizes a meta-analysis study that aims to analyze bacterial communities associated with seagrass species. The literature search was conducted using two major academic databases, Scopus and Web of Science, covering articles published between 1982 and 2024. The search was designed to identify peer-reviewed English-language articles focusing on the bacterial communities associated with seagrass species. The following keywords were used to guide the search: ("bacteria*" OR "bacterial*" OR "microbe*" OR "microbial*") AND ("seagrass*" OR "*Phyllospadix**" OR "*Zostera**" OR "*Enhalus**" OR "*Halophila**" OR "*Thalassia**" OR "*Posidonia**" OR "*Amphibolis**" OR "*Cymodocea**" OR "*Halodule**" OR "*Syringodium**" OR "*Thalassodendron**")

From the initial search, the dataset was filtered to remove inaccessible literature and studies that did not meet the inclusion criteria, resulting in 201 articles on seagrass-associated bacteria ready for analysis. In this study, a bibliometric analysis was performed using Microsoft Excel and the Biblioshiny package in R, providing a comprehensive overview of research areas, author distribution, and overall productivity within the field. Results are presented both quantitatively and qualitatively, as well as visually, to identify emerging trends, dominant keywords, and critical gaps in the literature. These findings not only

pinpoint the key bacterial species associated with seagrasses but also highlight thematic areas such as bioprospecting, nutrient cycling, disease resistance, and plant–microbe interactions, as well as the most prolific research collaborations. Together, they provide a solid foundation for future research recommendations. The complete research framework is depicted in Figure 1.

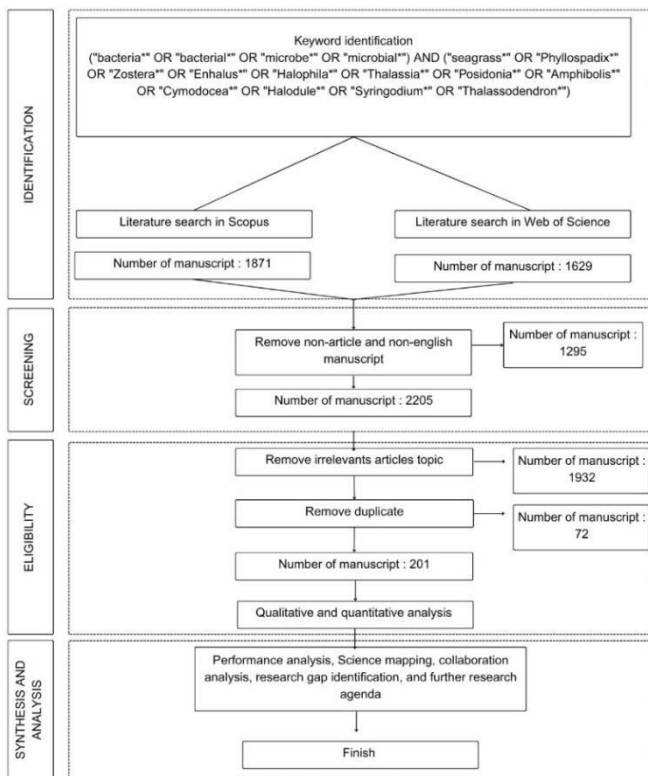


Fig. 1. Research framework shows literature search criteria.

3 Results and discussion

3.1 Performance analysis

Based on the bibliometric dataset collected, this section presents a performance analysis to evaluate research productivity, publication trends, and collaboration patterns in studies on seagrass-associated bacteria. The analysis covers the period from 1982 to 2024, representing more than four decades of scientific activity. A total of 201 documents were identified, reflecting a specialized thematic focus within the broader field of marine microbiology. The annual publication growth rate of 5.64% indicates a steady increase in research interest over time. The average document age of 9.84 years suggests that the dataset includes both foundational studies and recent advancements, providing a balanced overview of the field’s evolution. In terms of research productivity and publication sources, studies on bacterial communities associated with seagrass species were distributed across 81 journals. This indicates that the topic spans multiple disciplines within marine and microbial ecology rather than being confined to a single specialized outlet. The literature is dominated by journal articles, accounting for 200 papers, with only one proceedings paper recorded. This suggests

that most research outputs are disseminated through peer-reviewed journals rather than conference publications. The average citation rate of 31.01 citations per document reflects a moderate level of scholarly impact, showing that while the field attracts consistent academic attention, it has not yet reached the high citation influence observed in more established research areas. The authorship and collaboration aspects reveal a strong collective character, with a total of 922 authors contributing to the body of work. The high number of authors, relative to the modest number of documents, indicates a prevalent practice of collaborative research. Only three documents were single-authored, underscoring the inherently collaborative nature of this literature. The average number of co-authors per document is 5.78, a figure that reflects the involvement of large research teams and suggests the likelihood of multi-institutional or cross-disciplinary collaboration. The proportion of international collaboration stands at 27.86%, indicating that a substantial portion of this research involves cross-country partnerships, which can enhance both the visibility and the impact of the work. A summary of research performance in these areas is presented in Table 1 and Figure 2.

Table 1. The descriptive summary.

Component	Description	Result
Publication	Total number of research publications	201
Publication Period	Period Active period of research publications	1982:2024
Productivity	Annual Growth Rate %	5.64
Source	Total number of journal sources in related fields	81
Total citation	Total citation in all publication	6233
Average Citations per Document	Total citation/publication	31.01
Total Author	Total research authors contributing to the field	922
Single Author Publication	Individual research publications	3
Author's Keywords	Total publication keywords	610

3.2 Annual scientific production

Figure 2 depicts the growth in yearly publications related to bacteria associated with seagrass (leaf, sediment, or rhizomes) from 1982 to 2024. The dashed line represents the linear regression analysis conducted on the total number of publications. The R-square (coefficient of determination) is calculated to be 0.47, indicating that the linear trend line may account for around 47% of the increase in publications. The trend line also demonstrates a significant increase in publications since the early 2000s, with a notable surge after 2017. This indicates that the academic and scientific community has increasingly focused on research related to bacteria associated with seagrass in recent years.

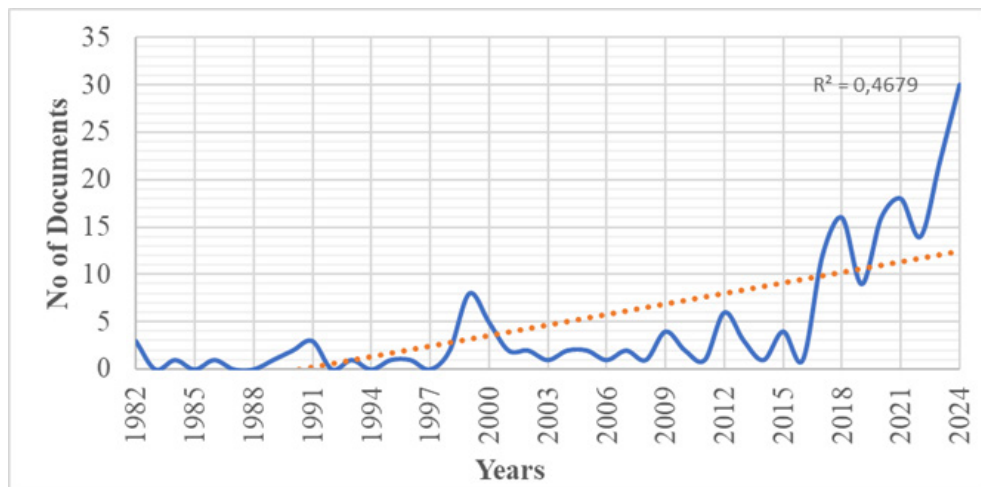


Fig. 2. Annual publication trend from 1982 to 2024.

3.3 Analysis of journals

Bibliometric data reveal that a total of 81 journals contain at least one article on bacteria associated with seagrass. Among these journals, a significant majority, 56.79% (46 journals), have published only a single article on the subject. This suggests that these journals do not have a specialized focus on bacteria associated with seagrass, possibly indicating that the topic is a cross-cutting theme relevant across various fields of knowledge. Furthermore, 20.98% of journals have published two articles, 11.11% have published three articles, and 3.7% have published four articles. Additionally, 7.4% of journals have published five or more articles, reflecting a comparatively higher level of engagement with the topic.

Table 2 presents the rankings, citations, and H-index of the ten most productive journals. These top-tier journals collectively account for 97 articles, constituting 49.25% of the total articles included in the study. Among them, the journal “Marine Ecology Progress Series” emerges as the most prolific contributor, with an impressive 28 articles. Notably, this journal also boasts the highest citation count, with a total of 1,846 citations, and the highest H-index, at 25. Following closely behind, the journal “Frontiers in Microbiology” ranks second with 18 articles, while the journal “Aquatic Microbial Ecology” holds the third position with 11 articles. The journal “Frontiers in Marine Science” ranks fourth, having published 13 articles. Notably, this journal also boasts an impressively high citation count of 144 and an H-index of 8.

Table 2. Top ten most productive journals and their citations and H-Index.

No	Source	Articles	Total Citation	H-Index
1	Marine Ecology Progress Series	28	1846	25
2	Frontiers in Microbiology	18	545	12
3	Aquatic Microbial Ecology	11	490	8
4	Frontiers in Marine Science	13	144	8
5	Applied and Environmental Microbiology	7	647	7
6	International Journal of Systematic and Evolutionary Microbiology	5	156	5

7	FEMS Microbiology Ecology	4	223	4
8	Scientific Reports	4	99	4
9	ISME Journal	3	175	3
10	Microbes and Environments	4	56	3

Figure 3 illustrates the prominent journals renowned for their high citation counts in the field of bacteria associated with seagrass. Notably, the journal “Marine Ecology Progress Series” emerges as the most cited journal, accumulating a substantial total of 1,846 citations. This exceptional citation count is primarily attributed to a single article by [10], which investigates the influence of marine plants on carbon decomposition, nutrient fluxes, and denitrification in Australian lagoons. Following closely, the journal “Applied and Environmental Microbiology” secures the second position, amassing a noteworthy 647 citations. Additionally, the journal “Frontiers in Microbiology” ranks third in terms of citations, with a respectable total of 545 citations.

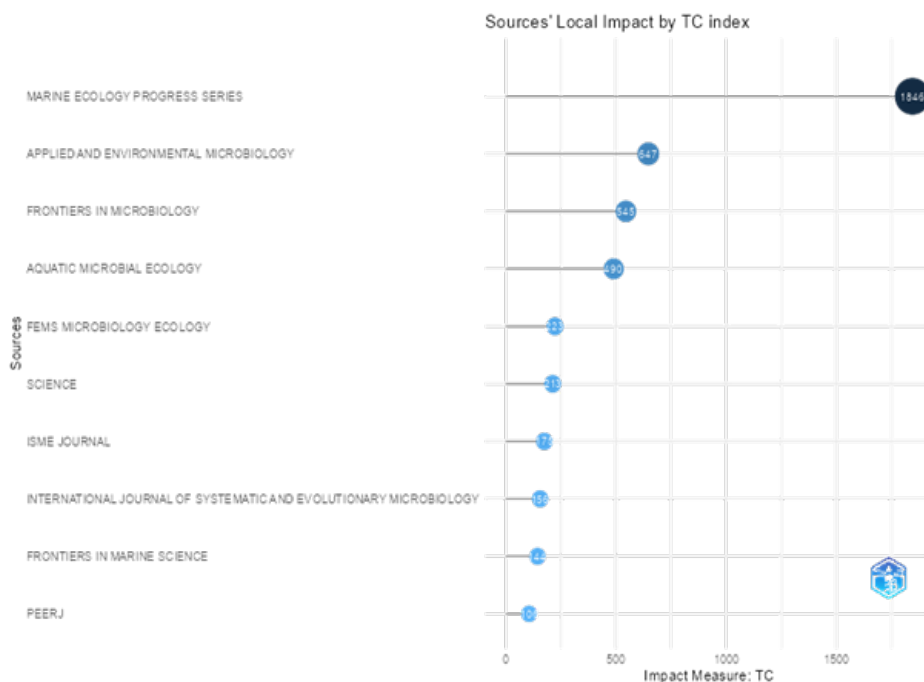


Fig. 3. Top 10 most cited journals.

3.4 Most relevant countries

Following the analysis of journal distribution and publication trends, it is equally important to investigate geographical distribution of research productivity to better understand global contribution disparities. Therefore, a country-level analysis was performed, focusing on author affiliations to determine which nations have contributed most to the study. Following the analysis of journal distribution and publication trends, it is equally important to investigate geographical distribution of research productivity to better understand global contribution disparities. Therefore, a country-level analysis was performed, focusing on author affiliations to determine which nations have contributed most to the study. This analysis indicates that the global research landscape on seagrass-associated bacteria is still in its early stages of development, exhibiting an uneven distribution of contributions. Although

there is cumulative participation from 32 countries, the data reveal a high concentration of research productivity within a limited number of nations. Specifically, publications are overwhelmingly dominated by a small group, with only four countries having published more than ten articles, and only three surpassing the twenty-five article mark. This limited international engagement clearly affirms that the research niche of bacteria-seagrass interactions has not yet become a primary focus, leaving the field wide open for further exploration and cross-border investigation across the globe.

Table 3 lists the 10 nations with the highest academic production and citations in the field of research on bacteria associated with seagrass. These countries collectively account for 79.6% of the total articles and 92.22% of the total citations. Notably, the United States stands out as the most productive nation, having published 39 articles and received the most citations (1,760). Australia ranks second in both productivity and citations, with 26 articles and 996 citations. China ranks third in productivity, with 26 articles, and fifth in terms of citations (314). This discrepancy highlights the significant impact and influence of India's limited contributions, suggesting that the articles it has published may have attracted substantial attention or addressed highly relevant research questions in the field of bacteria associated with seagrass.

Table 3. Highest producing and cited nation.

Highest Producing Nations			Highest Cited Nations		
Country	Articles	Citations	Country	Citations	Articles
USA	39	1760	USA	1760	39
Australia	26	996	Australia	996	26
China	26	314	Denmark	722	14
Denmark	14	722	Netherlands	409	6
Japan	13	249	Italy	316	12
Italy	12	316	China	314	26
Spain	11	309	Spain	309	11
Germany	7	208	Japan	249	13
Netherlands	6	409	India	239	2
Saudi Arabia	6	130	Germany	208	7

Fig. 4 illustrates the involvement of multiple-country (MCP) and single-country (SCP) collaborations among corresponding authors in publications related to research on bacteria associated with seagrass. The analysis reveals that the United States exhibits the highest productivity in SCP with 29 articles, while ranking second in MCP with 10 articles, indicating a significant focus on this research area. Australia appears as the nation that collaborates the most, providing the most MCP (11 articles) and ranking third in SCP with 15 articles. China follows closely behind, ranking second in SCP with 24 articles and ninth in MCP with only 2 articles. Notably, among the top ten countries, the majority are more engaged in single-country publications (SCP) compared to multi-country collaborations (MCP). This trend suggests that while there is substantial individual research output from these nations, there is still room for increased international cooperation in this field. The United States, Australia, and China, despite their leadership roles, exhibit varying levels of involvement in MCP, suggesting differences in research strategies or international partnerships.

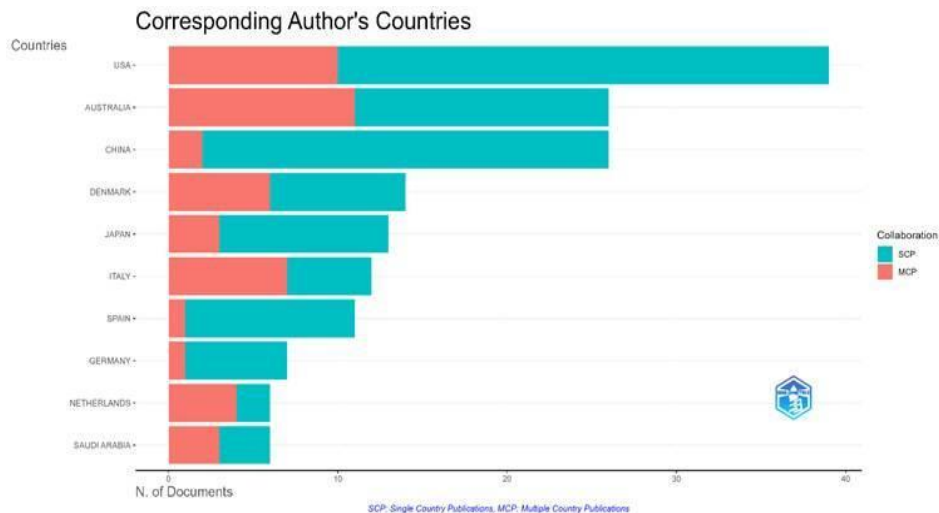


Fig. 4. Multiple-country (MCP) and single-country (SCP) collaboration.

3.5 Topmost relevant documents

The bibliometric analysis reveals a markedly skewed citation landscape in the literature on bacterial communities associated with seagrass species: of the 201 documents included, only 2 ($\approx 0.99\%$) have surpassed 200 citations and 13 (6.47%) have more than 100 citations, showing that a tiny subset of publications accounts for the field's most significant citation influence. This concentration suggests the presence of a few obvious, potentially foundational studies that shape subsequent work. At the same time, the majority of papers receive relatively modest attention, an outcome that can reflect the field's niche size, varied methodologies, uneven journal visibility, or the long-time lags often required for ecological papers to accumulate citations. Practically, such a distribution has two important implications: first, reliance on a handful of high-impact studies may skew theoretical framing and methodological norms if those few papers are not broadly representative; second, many valuable but less-cited contributions may be under-recognized despite their potential to refine understanding. As research activity in this area continues to expand and open access, data sharing, and interdisciplinary collaborations increase, aggregate citation counts and the diversity of influential works are likely to grow. However, addressing current imbalances will also require deliberate efforts to improve visibility and reproducibility across the corpus. For a focused view of the most influential contributions, the ten most-frequently cited documents and brief summaries of their principal contributions are compiled in Table 4.

Table 4. Top ten most relevant documents on

No	Reference	Key Highlight	Total Citations
1	Van D H T et al. (2012), Science	This study reveals a three-way symbiotic relationship among seagrasses, lucinid bivalves, and sulfide-oxidizing bacteria, which functions as a key mechanism for mitigating sulfide stress in seagrass ecosystems. Through the release of oxygen from seagrass roots, the symbiosis not only promotes seagrass growth but also supports the metabolic needs of the bivalves and their bacterial partners. This interaction regulates sulfide levels in sediments, thereby preventing toxicity, maintaining sediment health, and facilitating favorable conditions for benthic communities. Such microbial–faunal–plant partnerships demonstrate how biological interactions underpin critical biogeochemical processes in coastal environments.	213
2	Eyre and Ferguson (2002), Marine Ecology Progress Series	Denitrification efficiency in shallow coastal lagoons is strongly linked to carbon decomposition rates, with higher decomposition rates reducing nitrogen removal and increasing nitrogen recycling, which may drive eutrophication. Dissolved organic nitrogen is a significant component of nitrogen fluxes, while seagrass habitats, especially <i>Zostera capricorni</i> and seagrass epiphyte assemblages, maintain high nitrogen removal efficiency by limiting ammonium release. The productivity-to-respiration ratio predicts whether sediments act as nutrient sinks or sources, and benthic microalgae contribute to sediment oxygenation, thereby enhancing coupled nitrification and denitrification.	205
3	Weidner et al. (1996), Applied and Environmental Microbiology	A culture-independent approach using PCR–ARDRA revealed a wide range of uncultured bacterial phylotypes inhabiting the leaf surfaces of <i>Halophila stipulacea</i> . The community included biofilm-forming bacteria such as Hyphomonas and plastid-like sequences likely originating from epiphytic algae. These findings highlight the complex and multi-origin nature of microbial assemblages on seagrass leaves.	170
4	Kristensen et al. (2000), Aquatic Microbial Ecology	Microbial processes along the mangrove and seagrass gradient exhibited a clear shift from iron-reducing dominance in mangrove sediments to increased aerobic respiration in bioturbated mudflats and oxygen-based pathways in seagrass meadows. Nitrogen was largely retained through rapid bacterial assimilation, influenced by the high C:N ratio of organic matter from plant litter. These patterns highlight the roles of sediment type, iron availability, plant roots, and infaunal activity in regulating carbon and nitrogen cycling, aligning with the literature on microbial diversity and ecological functions in seagrass-linked ecosystems.	130

5	Welsh et al. (2000), Marine Ecology Progress Series	The intertidal <i>Zostera noltii</i> meadow functions as a highly autotrophic system where nitrogen uptake is driven mainly by seagrass and epiphyte assimilation, independent of ambient nutrient levels. Rhizosphere-associated bacteria play a central role through active nitrogen fixation that surpasses denitrification, resulting in a net gain of nitrogen and supporting sustained primary productivity. Biomass export and sediment burial, rather than microbial nitrogen loss, dominate nutrient removal, highlighting how plant–microbe interactions shape nutrient cycling and contribute to ecosystem stability in seagrass habitats.	122
6	Fahimipour et al. (2017), Applied and Environmental Microbiology	Leaves host microbiomes resembling the surrounding seawater with high variability, while roots maintain stable, distinct communities enriched in sulfur-metabolizing bacteria, indicating roles in sulfide detoxification. Aboveground communities are environmentally driven, whereas belowground microbiomes are shaped by host selection for functional traits, highlighting compartment-specific bacterial diversity and ecological roles in seagrass resilience.	119
7	Caffrey and Kemp (1990), Marine Ecology Progress Series	The presence of <i>Potamogeton perfoliatus</i> and <i>Zostera marina</i> enhances sediment microbial activity, particularly in the processes of ammonification, nitrification, and denitrification. Root oxygen release supports nitrification, while organic inputs from plant material stimulate ammonification. Nitrate is often reduced back to ammonium, conserving nitrogen within the system. Seasonal growth cycles influence the magnitude and coupling of these processes.	119
8	Ziegler and Benner (1999), Marine Ecology Progress Series	Nutrient dynamics in subtropical seagrass ecosystems are strongly mediated by interactions between the water column and benthos, with dissolved organic matter (DOM) released from vegetated sediments serving as a major driver of bacterioplankton activity and nitrogen regeneration. Bacterioplankton rely heavily on seasonally variable dissolved organic nitrogen (DON), which influences their growth efficiency and nutrient cycling. These results highlight the critical ecological role of bacteria–seagrass associations in maintaining nutrient availability, ecosystem productivity, and resilience, providing empirical evidence directly relevant to understanding microbial diversity and functions in seagrass ecosystems.	115
9	Holmer et al. (2004), Aquatic Microbial Ecology	Bacterial carbon sources in seagrass sediments shift from seagrass detritus in pristine meadows to seston and macroalgae in nutrient-enriched environments, reflecting high metabolic flexibility and influencing primary productivity and sediment biogeochemistry.	112
10	Küsei et al. (1999), Applied and Environmental Microbiology	The rhizosphere of <i>Halodule wrightii</i> hosts a diverse array of anaerobic bacteria, particularly sulfate-reducing bacteria and acetogens, which colonize both the root surface and the deep cortex layers, indicating adaptation to fluctuating oxygen conditions and involvement in key biogeochemical processes,	105

		such as sulfur and carbon cycling, as well as potential nitrogen fixation.	
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3.6 Frequent trending keyword

This section examines the main keywords used by authors, their interrelationships, and the keywords currently trending within the field of Marine Biodiversity. The analysis is based on a comprehensive dataset comprising a total of 201 published documents, from which 1,732 keywords were identified and retrieved in total. Among all identified keywords, only a small proportion appeared with high frequency: one keyword (0.1%) occurred more than 50 times, 36 keywords (2.1%) occurred more than ten times, 82 keywords (4.7%) occurred more than five times, while the vast majority, 1,613 keywords (93.1%) appeared only once. Figure 5 presents a visual representation of the fifty most frequently used keywords. The analysis reveals that “seagrass” is the most dominant keyword, occurring 94 times, followed by “bacteria” (49 occurrences), “diversity” (30 occurrences), and “microbial community,” “nitrogen-fixation,” and “zostera marina,” each with 27 occurrences.

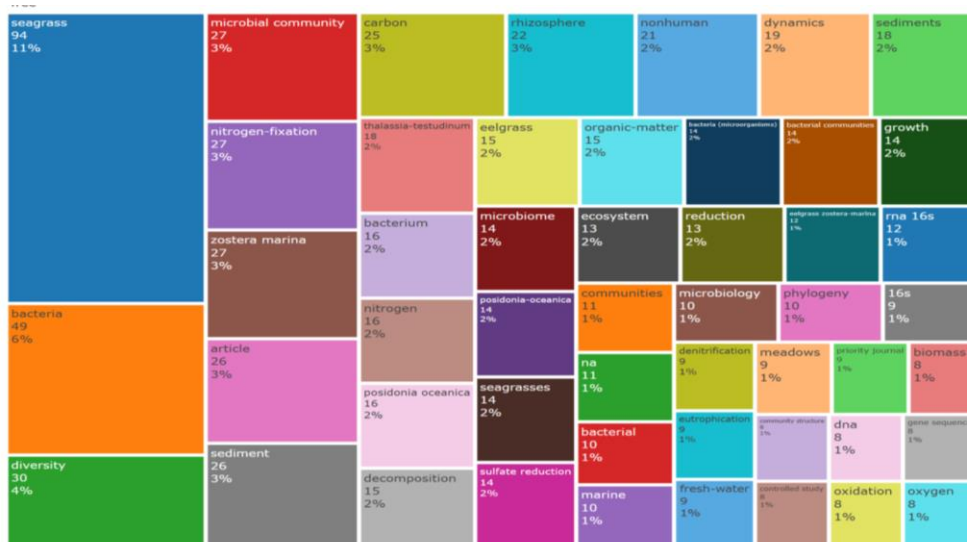


Fig. 5. Most frequent keywords.

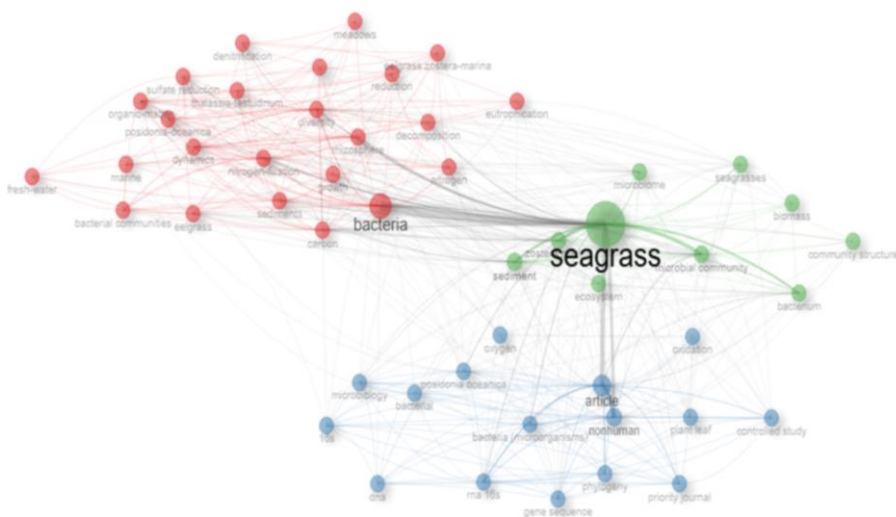


Fig. 6. Co-occurrence network of author’s keywords.

In Figure 6, the visual network mapping, each circle represents a specific author keyword, with its size corresponding to the frequency of occurrence. The larger the circle, the more frequently the keyword appears in the literature. Connecting lines between circles indicate keywords that frequently co-occur, with thicker lines representing stronger associations. Circles sharing the same color denote keywords belonging to the same cluster of closely related topics. The analysis identified three main clusters, each assigned a distinct color.

The first cluster, represented in red, is characterized by the combination of “bacteria” and related terms such as “diversity,” “nitrogen,” and “organic-matter,” which show more frequent co-occurrences. The second cluster, shown in green, is predominantly defined by the recurring keyword “seagrass,” closely associated with topics such as “microbial communities,” “sediment,” and “biomass.” The third cluster, represented in blue, highlights significant keywords including “article,” “microbiology,” and “controlled study.” This clustering analysis reveals the thematic structure and co-occurrence patterns of the most dominant author keywords in the literature.

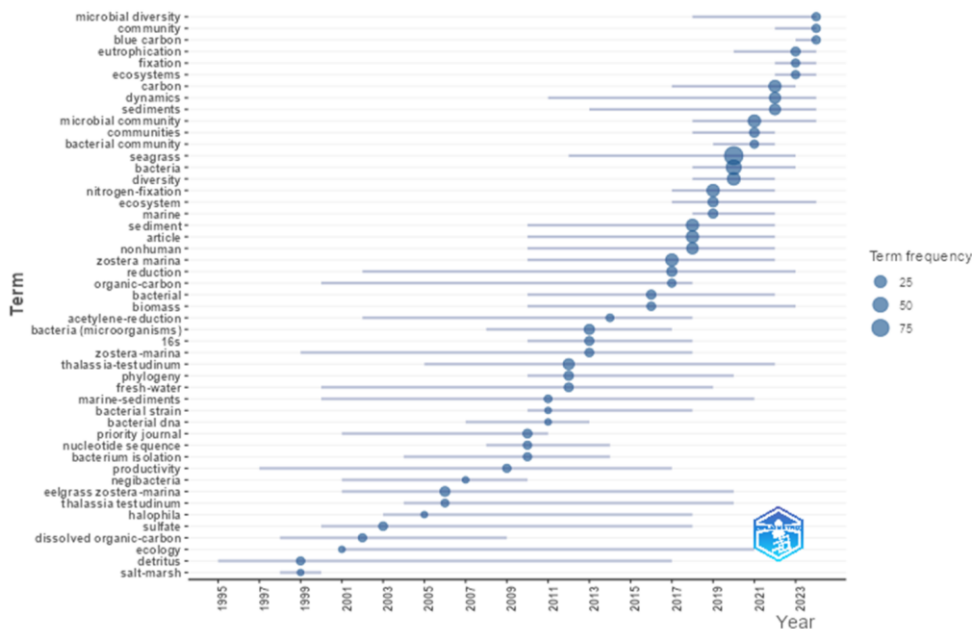


Fig. 7. Trending keywords of last ten year (1995–2024).

Figure 7 illustrates the twenty leading research topics, along with the most dominant author keywords used during the study period (1995–2024). The results show that “seagrass” (94 occurrences) is the most frequently used keyword, first appearing in 2012 and continuing through 2024. It is followed by “bacteria” (49 occurrences) and “diversity” (30 occurrences), both of which first appeared in 2018. In the most recent period, specifically in 2024, emerging trending terms include “microbial diversity,” “community,” and “blue carbon,” reflecting the growing research interest in microbial associations and their ecological roles within seagrass ecosystems.

4 Discussion

4.1.1 Microbial diversity and ecological roles

Seagrass ecosystems support a broad taxonomic diversity of bacteria, including *Bacillus* spp., Pseudomonadaceae, Shewanellaceae, Rhodobacteraceae [11], Firmicutes, Actinobacteria, and various classes of Proteobacteria [12], as well as specialized groups such as sulfate-reducing bacteria (SRB) and iron-reducing bacteria [13]. These bacteria play crucial roles in maintaining seagrass health by mobilizing phosphorus and iron from nutrient-poor sediments, protecting roots from sulfide toxicity, and supporting root metabolism through symbiotic interactions [13]. Specific contributions include the production of hydrolytic enzymes (amylase, cellulase, protease) and antagonistic compounds that inhibit pathogen infection.

Seagrass-associated bacteria play a crucial role in driving nutrient cycling and maintaining overall ecosystem functioning. Groups such as Desulfobacterales, Thiotrichales [2], and Chromatiales [14] regulate sulfur and nitrogen cycles, maintaining sediment fertility and biogeochemical balance. Another critical role involves pollutant detoxification: sulfur-oxidizing bacteria (SOB) neutralize toxic H₂S that threatens seagrass health, while symbiotic bacteria detoxify heavy metals and enhance salinity adaptation [11]. Collectively, these

microbial activities stabilize sediments and strengthen the resilience of tropical marine ecosystems.

Bioprospecting represents a critical aspect of seagrass-associated bacteria, particularly for pharmaceutical applications. *Streptomyces* sp. produces broad-spectrum anthraquinones effective against antibiotic-resistant bacteria [1], while *Pseudoalteromonas*, *Teredinibacter*, and members of the *Myxococcota* synthesize antibacterial, antiviral, and anticancer compounds with strong potential for drug development [2]. In aquaculture, symbiotic bacteria function as natural biocontrol agents, capable of reducing pathogenic *Vibrio* populations in less than one hour [9]. Furthermore, the production of proteolytic, amylolytic, and cellulolytic enzymes by root-associated bacteria presents promising opportunities for industrial applications and bioremediation.

4.1.2 Current Trend

Based on bibliometric data on research concerning bacterial associations in seagrass ecosystems, there has been a marked upward trend in publications from the early 1980s through 2024. Relatively few and fluctuating publications characterized the initial period (1982–1998), indicating that this research area remained sporadic and had yet to become a primary focus. From the late 1990s onward, the number of publications began to increase gradually, driven by a growing recognition of seagrasses as critical ecosystems for carbon storage, habitat provision, and biodiversity support, including the support of microbial communities. A more consistent surge has been evident since 2010, with a sharp peak occurring between 2017 and 2024. This growth is likely linked to heightened global attention to climate change, coastal habitat degradation, and advances in molecular technologies that have facilitated the analysis of bacterial communities.

In terms of journal contributions, *Marine Ecology Progress Series* ranks highest with an H-index of 25, a total of 1,846 citations, and 28 articles, reflecting its substantial influence in the field of marine ecology. Other journals such as *Frontiers in Microbiology* and *Aquatic Microbial Ecology* also make significant contributions, with total citations of 545 and 490, and article counts of 18 and 11, respectively. The presence of these journals indicates that research on seagrass-associated bacteria is inherently multidisciplinary, encompassing marine ecology, environmental microbiology, and biotechnology. The dominance of reputable international journals further underscores the global reach and high relevance of this research to marine ecosystem issues.

Country-level analysis shows that the United States and Australia lead in both publication output and citation counts, followed by China, Denmark, Italy, Spain, Japan, the Netherlands, Germany, India, and Saudi Arabia. The high contributions of these countries align with the presence of leading marine and ecological research centers in these regions, as well as adequate access to research funding. Denmark and the Netherlands, despite having relatively few publications, exhibit a high citation-per-article ratio, indicating strong research quality and significant scientific impact. This pattern is consistent with the concept of geographic concentration of innovation described by Hemminga and Duarte (2000) in *Marine Ecology Progress Series* (vol. 311, p. 233), whereby research on seagrasses and their associated organisms often clusters in locations with robust marine research infrastructure, good field access, and strong international collaboration networks.

The article by [3] in the *Journal of Experimental Marine Biology and Ecology* highlights the global distribution of seagrasses across six major bioregions, which is relevant to the distribution of countries producing publications in this field. Australia, located within the Tropical Indo-Pacific and Temperate Southern Oceans, harbors exceptionally high seagrass diversity and serves as a base for large-scale seagrass ecology research. The United States spans multiple bioregions, including the Temperate North Atlantic, Tropical Atlantic, and

Temperate North Pacific, enabling the study of seagrass-associated bacteria across a variety of ecosystem types. European countries, such as Denmark, the Netherlands, Italy, and Spain, focus on the temperate North Atlantic and Mediterranean regions, with research often utilizing *Zostera marina* as a model ecosystem for environmental microbiology studies.

Overall, the bibliometric data illustrate that research on bacterial associations within seagrass ecosystems has evolved from a limited area of study into a dynamic and strategically significant field. The notable growth in publications, contributions from reputable journals, and the dominance of countries with strong research infrastructure demonstrate that this topic is increasingly recognized as an integral component of marine ecology and conservation studies. Drawing on insights from the two reference articles, the sustainability of this research will depend heavily on international collaboration, the advancement of more sophisticated molecular methodologies, and the mapping of relationships between global seagrass distribution and their associated microbial communities.

The bibliometric data presented indicate that the United States (USA) ranks highest in both the number of publications (39 articles) and citations (1,760), followed by Australia with 26 articles and 996 citations. Other countries, including China, Denmark, Italy, Spain, Japan, the Netherlands, Germany, India, and Saudi Arabia, contribute to varying extents. However, some nations, such as Denmark and the Netherlands, display a high citation-to-article ratio, signifying substantial influence despite a relatively small publication volume. This pattern aligns with the concept of geographic concentration of innovation, as described by Feldman and Florida (1994), which posits that scientific productivity tends to cluster in regions with strong research infrastructure, extensive collaboration networks, and robust institutional support. Countries dominating in publication output generally host leading marine research centers, benefit from substantial funding, and maintain international connections that enhance the global visibility of their research.

These findings are also consistent with the study by [3] on seagrass distribution and diversity, which categorizes the world's seagrass ecosystems into six bioregions. Australia, for example, lies within the Tropical Indo-Pacific and Temperate Southern Oceans—two bioregions with the highest seagrass diversity globally—. In contrast, the USA spans several bioregions, including the Temperate North Atlantic, Tropical Atlantic, and Temperate North Pacific. European countries such as Denmark, the Netherlands, Italy, and Spain are situated mainly in the temperate North Atlantic and Mediterranean regions, with moderate diversity but a strong tradition of marine ecological research. Understanding the distribution of these bioregions is essential for interpreting variations in seagrass-associated bacterial communities, as geographic factors, the physico-chemical characteristics of the waters, and the identity of host species all influence microbial composition.

5 Conclusion

Research on bacterial associations in seagrass ecosystems has expanded rapidly since the early 2000s, with a marked increase in publications after 2017. Bacteria associated with seagrasses play vital roles in maintaining plant health, regulating nutrient cycles such as nitrogen, phosphorus, and sulfur, detoxifying pollutants, and enhancing ecosystem resilience to environmental disturbances. Several bacterial groups, including *Bacillus*, *Streptomyces*, *Pseudoalteromonas*, as well as sulfate- and iron-reducing bacteria, contribute not only to ecological functions but also hold significant potential for applications in biotechnology, bioremediation, and pharmaceuticals. Nevertheless, publication output remains concentrated in countries with advanced marine research centers, such as the United States, Australia, and Denmark, while contributions from many other regions remain limited. This highlights both geographic and thematic gaps that present opportunities for future research.

Future research should prioritize strengthening multidisciplinary approaches that integrate metagenomics, meta-transcriptomics, and metabolomics to gain a comprehensive understanding of bacterial community functions and link them to ecological parameters such as sediment quality, temperature, salinity, and pollutants. Studies should also address long-term monitoring seasonal and annual variations to assess bacterial responses to climate change and habitat degradation. Furthermore, it is essential to explore seagrass-associated bacteria for potential applications in biotechnology, bioremediation, and pharmaceuticals. Therefore, further microbial research in seagrass ecosystems is absolutely essential. This research is necessary not only to fully elucidate the bacteria's ecological functions and support ecosystem resilience, but also to develop a comprehensive global database that documents their distribution, functions, and potential applications, thereby guiding future efforts in marine conservation and management.

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