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REVIEW ARTICLE

A Bibliometric and Scientometric Analysis of the Marine Biotechnology Research Using CiteSpace: A Web of Science Based Study (1980-2023)

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Abstract: A growing interest in marine biotechnology has spurred the exploitation of oceanic resources for novel products. However, a comprehensive, data-driven mapping of this evolving landscape remains limited. This study presents a systematic scientometric analysis using CiteSpace to map global research trends and structural knowledge domains in marine biotechnology. Utilizing metadata extracted from the Web of Science Core Collection (WoSCC) database, we applied targeted search strings and strict inclusion criteria, focusing exclusively on original English-language research articles published between 1980 and 2023. After systematic screening and data cleaning, a final dataset of 3,092 documents was analyzed. Analytical measures, including publication trajectories, country co-authorship networks, reference co-citations, and keyword clustering, were evaluated to determine node centrality and network density. The results reveal an exponential publication surge after 2018, peaking in 2022. While the USA leads in total publication volume, European nations (such as France) exhibit the highest structural network centrality. Co-citation and keyword clustering identified "bacterial diversity," "deep-sea sponge," and "valuable pigment" as dominant, high-growth research fronts. Dynamically, these findings move beyond a descriptive summary to provide a foundational roadmap for researchers, industrial stakeholders, and policymakers to optimize funding allocation and target under-explored high-potential domains in the global blue economy.

Keywords: Marine Biotechnology, Scientometric Analysis, Bibliometrics, Cite Space, Knowledge Mapping

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Introduction

Marine ecosystems are estimated to host 2.2 million species, yet only 183,441 to 242,626 have been formally described across taxa such as bacteria, fungi, micro-algae, macro-algae, invertebrates, and vertebrates [1, 2]. This vast, uncharacterized biodiversity represents an exceptional frontier for marine biotechnology (or "blue technology") to deliver novel products, pharmaceuticals, and sustainable goods [3, 4]. Recent technological advancements have accelerated bioprospecting, concurrently optimized resource exploitation, and promoted ecological sustainability [5].

To date, marine biotechnology research has successfully spanned several functional domains. In food production and aquaculture, biotechnological interventions enhance the valorization of seafood processing side streams such as Atlantic cod frames and Tuna heads, thereby minimizing industrial waste and maximizing value-added product recovery [6, 7]. In the pharmaceutical and nutraceutical sectors, marine organisms serve as rich repositories of high-value bioactive compounds (e.g., peptides, fatty acids, pigments, and polysaccharides) with potent antioxidant, antiviral, anti-inflammatory, and wound-healing properties [8, 9]. Furthermore, the discipline offers critical environmental and industrial solutions, ranging from microalgae-mediated wastewater bioremediation to clean energy generation via algal biofuel hydrocarbon extraction [10, 11].

Despite this extensive, multi-disciplinary literature base, the global research trajectory of marine biotechnology remains highly fragmented. While specific narrative reviews summarize isolated sub-fields such as marine food systems or environmental bioremediation, a holistic, data-driven synthesis that systematically charts the intellectual structure, collaborative networks, and evolutionary trends of the overall domain is noticeably absent. Consequently, a clear gap exists in mapping marine ecosystems to biotechnological frameworks. Existing bibliometric and scientometric analyses in biotechnology have historically operated under narrow geographic or thematic constraints. Prior efforts remain bound to specific national contexts [12, 13] or isolated sub-themes [14, 15]. This study directly addresses this deficit by executing a systematic, macro-level scientometric analysis of marine biotechnology literature indexed in the Web of Science Core Collection over the past four decades.

By delineating publication trajectories, institutional co-authorship networks, and keyword co-occurrence clusters, this manuscript provides an empirical roadmap of historical milestones, current hotspots, and under-explored areas. Ultimately, this comprehensive structural mapping provides actionable, high-utility insights for researchers, industrial stakeholders, and policymakers, demonstrating how bibliometric techniques serve as a vital tool for strategic research planning, funding optimization, and macro-level bioeconomy policymaking.

Methodology

Database Source and Search Strategy

The bibliographic metadata for this study were retrieved from the Clarivate Analytics Web of Science Core Collection (WoSCC) database. WoSCC was selected as the sole data source due to its stringent indexing standards, high-quality citation data, and long-standing reputation as one of the most authoritative databases for comprehensive scientometric analysis. The search query was conducted on January 30, 2024, spanning a four-decade publication window from 1980 to 2023. The search architecture utilized a combination of topic keywords (`TS=Topic`), Boolean operators (`AND`/`OR`), and wildcards (`*`). The "marine" search terms were adapted and modified from [16]. The "biotechnology" search terms were integrated based on established scientometric literature in the biotechnology domain [12, 14, 15, 17, 18]. The exact, finalized search string applied in the WoSCC advanced search interface was as follows: *TS = ("marine" OR "ocean" OR "sea" OR "salinit*" OR "seawater" OR "saline water") AND TS = ("biotechnolog*"* OR "bio-technolog*" OR "biotech*" OR "biolog* and technolog*" OR "biolog* & technolog*" OR "technolog* appl* of biolog* system*").

Inclusion and Exclusion Criteria (Screening Process)

The initial database search yielded 4,963 literature records. To ensure a highly refined and relevant dataset for macro-analysis, formal inclusion and exclusion criteria were rigorously applied. Inclusion Criteria:

(1) Peer-reviewed, original research articles

(2) Literature published between January 1, 1980, and December 31, 2023

(3) Publications written exclusively in the English language

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Exclusion Criteria

(1) Document types classified as reviews, editorial material, book chapters, conference proceedings, letters, corrections, or news items

(2) Non-English publications

(3) Articles published in or after 2024

A secondary search update was executed on February 12, 2024, to capture late-indexed entries from the 2023 publishing year that had not been finalized during the initial January extraction, which added 15 valid records. Duplicate records were systematically evaluated and removed using the automated data-cleaning function within Cite Space software (Version 6.3.R3). Following screening, 3,092 research articles with 135,388 total citations were selected for analysis. The complete workflow, adhering to a modified PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) structure, is illustrated in Fig. 1.

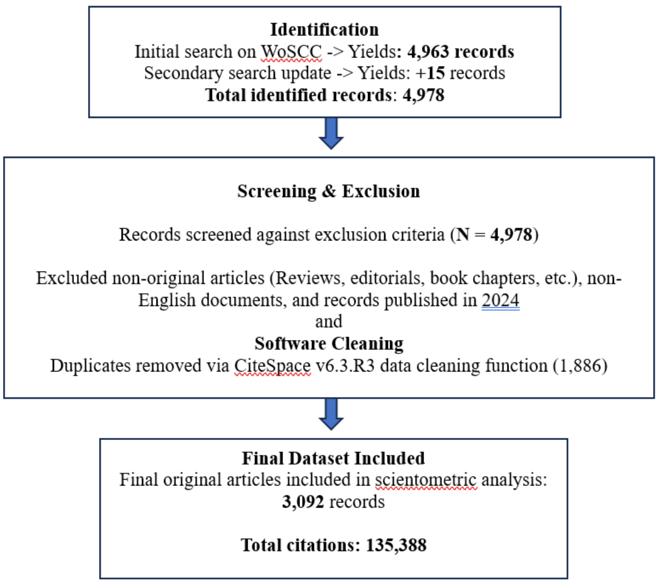

Fig. 1: PRISMA flow diagram outlining the literature screening and selection protocol

Scientometric Analysis and Software Configuration

Quantitative visualization and structural knowledge mapping were performed using CiteSpace (Version 6.3.R3), an advanced Java-based application optimized for detecting and visualizing emerging trends and critical transitions in scientific literature [19]. To ensure strict study reproducibility, the following standardized configuration parameters were established in CiteSpace: Time Slicing: From 1980 to 2023, with a slice length of 1 year (# Years per Slice = 1). Text Processing: Selection of Title, Abstract, Author Keywords, and Keywords Plus (ID). Node Types: Selected dynamically based on the analytical objective (e.g., Country, Institution, Author, Keyword, Cited Reference, Cited Journal). For selection criteria, the Top *N* method was applied with *N* = 50. This extracts the top 50 most frequently cited or occurring items within each 1-year time slice to construct the local networks. Pruning Methods: PathFinder and Pruning Sliced Networks were active simultaneously to streamline the structural network visualizations, eliminate redundant links, and enhance clarity without compromising the core topological properties.

Results

Publication Evolution and Trends

The chronological distribution of marine biotechnology publications from 1980 to 2023 shows an overall upward trajectory divided into three distinct phases (Fig. 2). Phase I (1980–2006) represents an initial foundational period characterized by

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baseline publication volumes. Subsequently, Phase II (2007–2017) reflects a period of steady growth, followed by a rapid surge in publication volume during Phase III (2018–2023), with research output peaking significantly within the last five years.

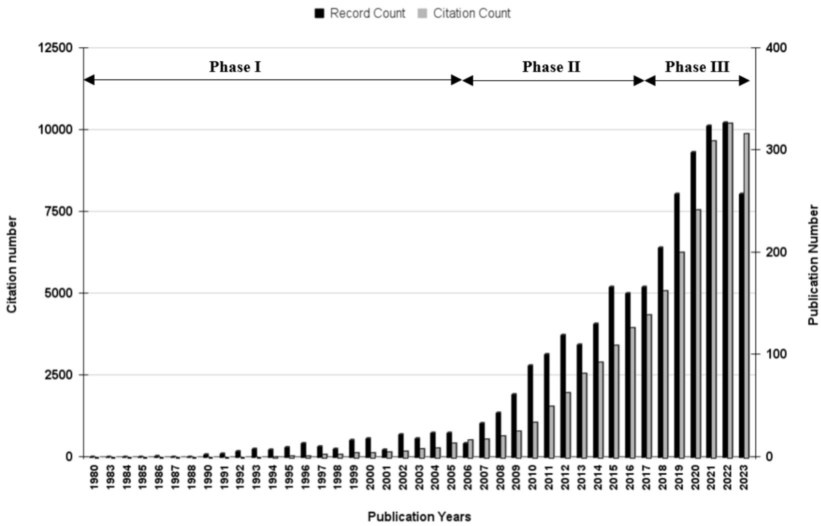

Fig. 2: Annual publication trajectory and growth phases of marine biotechnology research (1980–2023)

Country Level Research Activity

The global research landscape is highly collaborative yet unevenly distributed a total of 116 countries or regions have actively contributed to marine biotechnology literature, accounting for approximately 60% of global sovereign states Quantitative volume tracking indicates that the USA, China, India, Italy, and Brazil represent the top five most prolific nations in terms of total publication counts (Fig. 3A). However, network centrality mapping reveals a divergence between publication volume and structural network influence (Fig. 3B) In network analysis, betweenness centrality serves as a metric for an entity's 'connectedness' or structural 'influence,' indicating how effectively a country or institution functions as an intellectual bridge linking disparate research groups across the global network. Using a threshold value of 4, European nations, specifically France, Germany, and Spain, alongside the USA, emerge as the primary topological bridges in the global co-authorship network, yielding high centrality scores between 0.14 and 0.19.

Institutional Productivity and Author Collaboration Networks

The institutional landscape involves 3,326 organizations. The Chinese Academy of Sciences (China) stands as the most prolific institution by publication volume, followed by the National Research Council (Italy) and the Russian Academy of Sciences (Russia). In contrast, network analysis identifies Aix-Marseille University (France) as the node with the highest structural centrality in the institutional collaboration framework (Fig. 4). The analysis mapped 14,372 authors at the individual researcher level. Co-author analysis identifies Chiara Lauritano (Stazione Zoologica Anton Dohrn Napoli, Italy) and Lara D. Sette (São Paulo State University, Brazil) as the most prolific authors within the Web of Science Core Collection (WoSCC) dataset. Crucially, CiteSpace network metrics revealed that no authors achieved high centrality scores, with all scores remaining below 0.10.

Keyword Frequencies and Citation Burst Trajectories

Keyword co-occurrence metrics identified 12 terms appearing more than 100 times: "growth," "diversity," "identification," "purification," "expression," "sp nov," "bacteria," "biotechnology," "biosynthesis," "marine," "microalgae," and "protein." High centrality scores (>0.06) were generated for "biotechnology," "bacteria," "growth," "expression," *Escherichia coli*, "enzymes," "culture," "biomass," "bacterium," "adaptation," "cells," and "DNA." Temporal network tracing (Fig. 5) highlights a shifting focus toward modern terms such as "antimicrobial activity," "abiotic stress," "expression tool," and "rare earth elements." The top 25 citation burst analysis (Table 1) reveals that "phytoplankton" and "metabolism" maintained the longest active burst duration, spanning 26 years. Conversely, the technical terms displaying the highest absolute burst strength values are "system," "biotechnology," and "culture."

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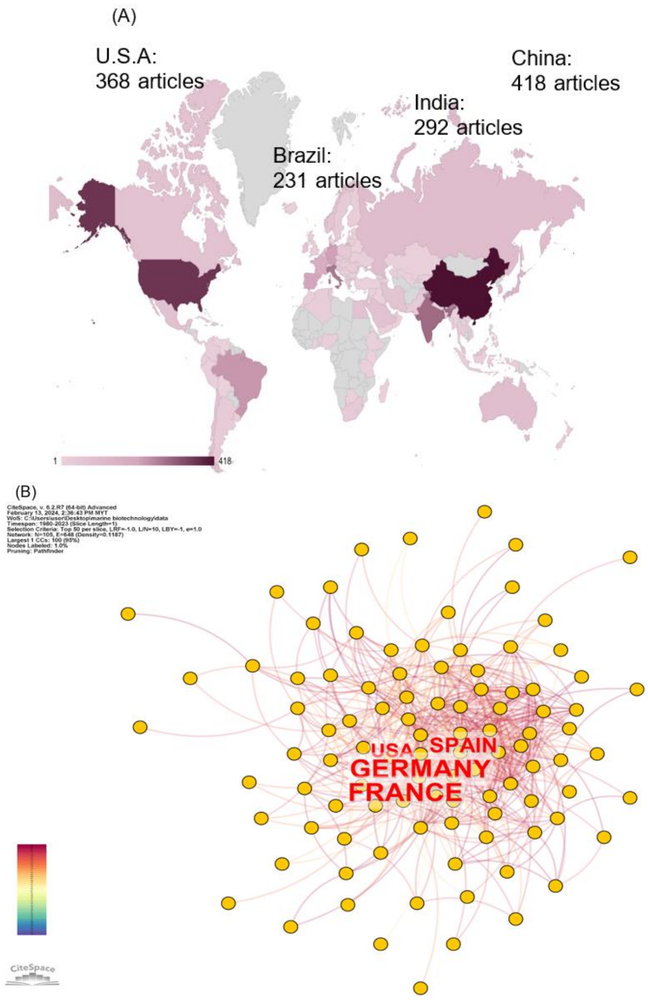

Fig. 3: (A) Global distribution and (B) structural network centrality of country-level research outputs

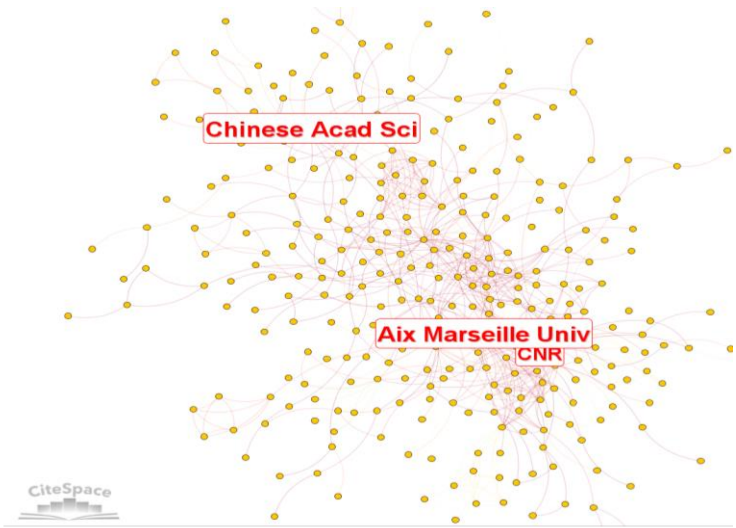

Fig. 4: Institutional collaboration network showing the primary high-volume and high-centrality nodes with the highest centrality score of 0.07 and above

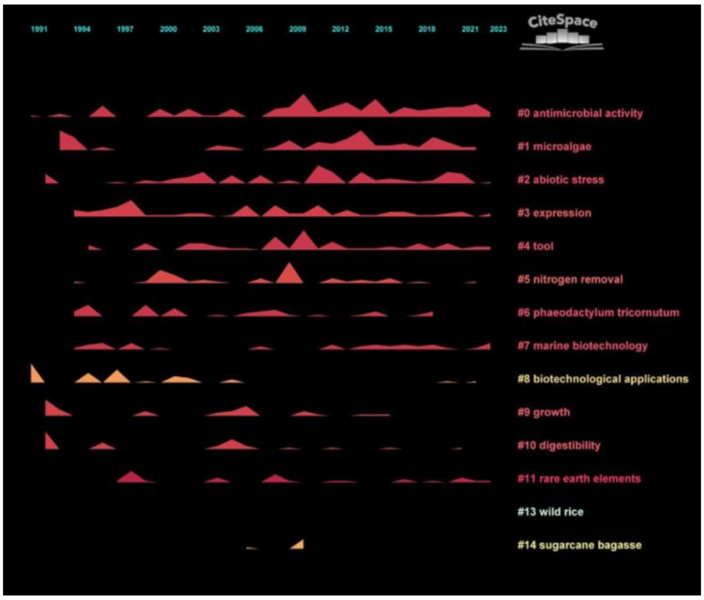

Fig. 5: Co-occurrence network visualization of the keywords used in the research published on marine biotechnology, based on the analysis using CiteSpace software through data generated from Web of Science Core Collection database

Reference Co-Citation Clusters

The reference co-citation network, generated via the clustering function in CiteSpace, yielded 16 major structural clusters mapping the global research fronts of marine biotechnology from 1980 to 2023 (Fig. 6). The network architecture exhibits a high and statistically significant Modularity (Q) score, confirming that the domain is divided into highly distinct, well-structured sub-specialties. Furthermore, these 16 clusters are characterized by high individual silhouette scores that closely approach the maximum value of 1.0 (Table 2). The silhouette score serves as a direct indicator of a cluster's internal consistency and thematic reliability, where a score approaching 1.0 mathematically demonstrates that the publications grouped within that specific cluster share highly consistent, tightly focused research content, effectively isolating them from neighbouring clusters. A temporal analysis reveals a clear evolutionary transition within the dataset. The analysis identifies 'nature-based biotechnological tool' and 'transgenic tomato' as highly consistent, long-standing historical clusters that supported the field's early development. Chronologically, the most recent and rapidly growing active research frontiers are tightly concentrated around three specific nodes: "valuable pigment" (exhibiting a modern mean publication year of 2019), followed closely by "environmental plastic degradation" (mean publication year of 2018), and "Mediterranean Sea" (mean publication year of 2018).

Cluster Analysis

The cluster analysis in CiteSpace software identifies the crucial theme within the knowledge area of “marine biotechnology”, and the present analysis will discuss the top eight (8) research clusters in the field, which are: “Cluster #0: Biotechnological Application”, “Cluster #1: Deep Sea Sponge”, “Cluster #2: Mediterranean Sea”, “Cluster #3: Bacterial Diversity”, “Cluster #6: Valuable Pigment”, “Cluster #7: Marine microorganism”, “Cluster #8: Exceptional Diversity” and “Cluster #9: Lipid Productivity”.

Cluster #0: Biotechnological Application: Based on the study by [20], biotechnological applications require the precise coordination of diverse experimental components to achieve cost-effective, high-value production. The largest cluster in the field of marine biotechnology is named “Biotechnological Application”, with a total of 151 articles related to the theme or cluster. Four papers drive this research cluster: [21, 22] lead in global citation impact, while [23] (44,032 citations) and [24] (32,097 citations) serve as the primary internal citation hubs within the cluster network. These publications focus heavily on bioinformatics frameworks, specifically utilizing the Molecular Evolutionary Genetics Analysis (MEGA) software for evolutionary modeling. In parallel, [21] leveraged genome-resolved analytics to survey marine microbial genomes capable of synthesizing novel, high value biotechnological compounds. Meanwhile, [22] showed that a specific Nannochloropsis sp. enzyme increases polyunsaturated fatty acid (EPA) production for industrial applications.

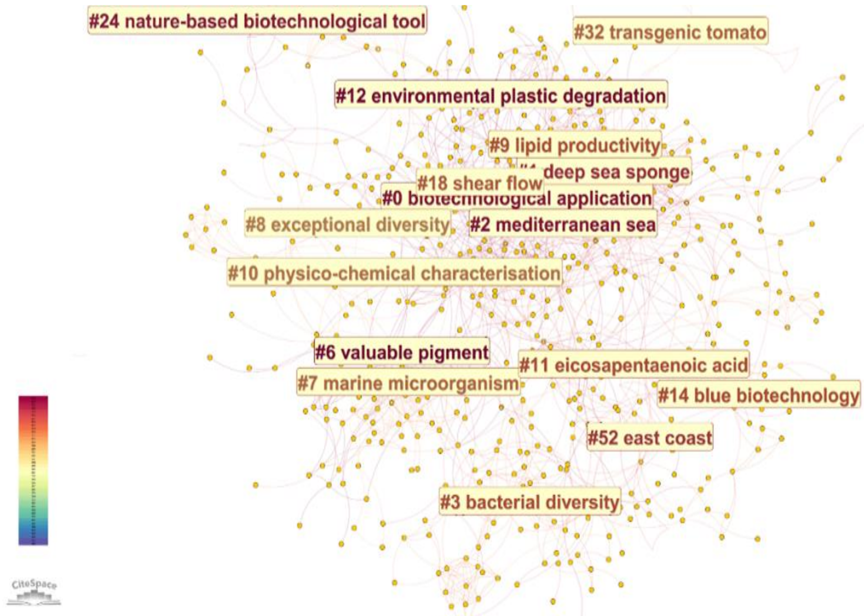

Fig. 6: Reference co-citation network clusters mapping the modern research frontiers

Cluster #1: Deep Sea Sponge: The second largest cluster in the marine biotechnology field is among the most similar or consistent studies, with an almost 0.977 silhouette value, called “deep sea sponges”. Marine sponges span from intertidal zones to deep-sea habitats. In this cluster, [25, 26] are the most cited publications. [25] focused on deep-sea sponge microbiomes, confirming the technological utility of their symbiotic bacteria. The landmark publication on MEGA5 by [26] has achieved major citation impact, recording nearly 48,000 citations. This research was followed by [27, 28] both studies mostly referred to the deep-sea sponge species and their biotechnological potential and evolution.

Cluster #2 ('Mediterranean Sea') reflects a geographically distinct research frontier characterized by high marine biodiversity and exceptional species endemism. Connected to the Atlantic Ocean and separating Europe, Africa, and Western Asia, this basin offers a unique environment for bioprospecting. Within this network, specific regional studies like [29] focus on the Adriatic Sea, while [30] serves as a primary citation hub for the cluster. Bibliometrically, the highest citation density in this group belongs to the Food and Agriculture Organization’s SOFIA flagship report [31], underscoring the impact of macroeconomic data on this research cluster and the integration of macroeconomic fisheries data with regional biotechnology research.

Cluster #3: Bacterial Diversity: The fourth-largest cluster, 'Bacterial Diversity,' contains 76 articles and has a silhouette score of 0.932. [26, 32] are the most cited publications and central members within this cluster. Esteves and the team explained the significance of bacterial diversity associated with the Arminidae sponges and their future potential for sustainable technological advancements.

Cluster #6 ('Valuable Pigment') represents a rapidly emerging domain in marine biotechnology. The Food and Agriculture Organization (FAO) defines a pigment as a compound colored by the light it absorbs. In this context, valuable pigments include bioactive substances with high industrial and economic utility. CiteSpace chronological metrics indicate that marine biotechnology research has recently shifted focus toward this thematic area. Within this cluster, [33, 34] emerge as the primary internal citation hubs. [33] evaluated the biotechnological potential of microalgal pigments, focusing on carotenoids, phycobiliproteins, and fucoxanthin. Conversely, [34] highlighted the utility of antiSMASH (Antibiotics and Secondary Metabolite Analysis Shell) in identifying and comparing biosynthetic gene clusters.

Cluster #7: Marine microorganism: Marine microorganisms, such as bacteria, fungi, or algae, hold significant biotechnological potential, such as bioremediation components, biocatalysis, industrial enzymes and processes, as well as biofuels. Within the 'marine microorganisms' network, the foundational analyses by [35, 36] represent the core defining literature. Both studies identified the bioprospecting potential and attraction of marine microorganisms for any significant industrial relevance.

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Table 1: Top 25 keywords with the strongest citation bursts sorted by chronological appearance

Keywords	Year	Strength	Start	End	1980 - 2023
Biotechnology	1992	9.74	1999	2013	
Escherichia-Coli	2000	5.82	2000	2013	
Expression	1997	4.8	2003	2012	
Marine algae	2004	4.56	2004	2012	
Cloning	2008	5.93	2008	2016	
Marine bacterium	1994	4.33	2008	2012	
Culture	2009	6.8	2009	2014	
Escherichia coli	1996	5.6	2009	2014	
Gene-Expression	2010	5.44	2010	2015	
Fatty-acids	2012	4.16	2012	2013	
Phytoplankton	1993	6.73	2014	2018	
Fermentation	2012	4.5	2014	2016	
Induction	2014	4.19	2014	2015	
Aquaculture	1996	4.23	2015	2018	
System	2016	9.02	2016	2019	
Lipid production	2016	5.45	2016	2019	
Sp-nov	2016	5.03	2016	2019	
Metabolism	1993	4.38	2016	2018	
Phylogeny	2017	4.46	2017	2021	
Synthetic biology	2019	4.47	2019	2020	
Stress tolerance	2020	6.22	2020	2023	
Salinity stress	2012	4.18	2020	2023	
Secondary metabolites	2015	4.45	2021	2023	
Oil	2013	4.28	2021	2023	
Ph	2021	4.2	2021	2023	

The seventh-largest cluster, Cluster #8 ('Exceptional Diversity'), includes 40 members and has a silhouette value of 0.931. This cluster holds the oldest references, with most articles published between 2007 and 2014. [37] investigated marine sponge microbe interactions and explored their ecological and biotechnological implications, such as nutrient cycling, novel bioactive compounds, pharmaceuticals, and natural products research. Serving as the primary internal citation hub for this cluster, [38]

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detail how the MEGA software package facilitates comparative genomics, molecular sequence alignment, and phylogenetic tree reconstruction.

Table 2: Quantitative summary profiles and silhouette scores of the 16 major co-citation clusters

Cluster-ID	Size	Silhouette	Label (LSI)*	Label (LLR)*	Label (MI)*	Average Year
0	151	0.878	Biotechnological potential	Biotechnological application (301.84, 1.0e-4)	Mangrove habitat (5.22)	2017
1	99	0.977	Biotechnological potential	Deep sea sponge (350.13, 1.0e-4)	Kolumbo submarine volcano (1.38)	2014
2	76	0.964	Biotechnological application	Mediterranean Sea (289.69, 1.0e-4)	Nitrogen source (0.62)	2018
3	76	0.932	Bacterial diversity	Bacterial diversity (322.17, 1.0e-4)	Cdp-13 augment (0.3)	2010
6	45	0.972	Valuable pigment	Valuable pigment (145.08, 1.0e-4)	Blue economy (0.27)	2019
7	43	0.948	Biotechnological application	Marine microorganism (104.74, 1.0e-4)	Sp ls-a18 (0.02)	2009
8	40	0.931	Marine sponge	Exceptional diversity (120.38, 1.0e-4)	Yucatan aquifer (0.09)	2007
9	36	0.972	Lipid productivity	Lipid productivity (108.18, 1.0e-4)	Model diatom (0.03)	2011
10	23	1	Physico- chemical characterization	Physico- chemical characterization (58.42, 1.0E-4)	Biotechnological potential (0.02)	2007
11	23	0.988	Plastidial monogalactosyldiacylglycerol level	Eicosapentaenoic acid (89.91, 1.0e-4)	Microalga nannochloropsis salina (0.01)	2012
12	21	0.991	Extreme environment	Environmental plastic degradation (76.33, 1.0e-4)	Biotechnological potential (0.02)	2018
14	17	0.987	Marine-derived fungi	Blue biotechnology (68.76, 1.0e-4)	Biotechnological potential (0.02)	2011
18	14	0.997	Shear flow	Shear flow (69.47, 1.0e-4)	Biotechnological potential (0.02)	2008
24	11	1	Restoring salt-affected soil	Nature-based biotechnological tool (75.21, 1.0e-4)	Biotechnological potential (0.02)	2016
32	9	1	Transgenic tomato	Transgenic tomato (44.4, 1.0e-4)	Biotechnological potential (0.02)	2008
52	6	0.998	Marine actinobacteria	East coast (30.36, 1.0e-4)	Biotechnological potential (0.02)	2013

*Log-Likelihood Ratio (LLR), latent Semantic Indexing (LSI), and Mutual Information (MI)

Cluster #9 ('Lipid Productivity') is the eighth-largest cluster in marine biotechnology, comprising 36 articles with a silhouette value of 0.972. Lipid productivity is defined as the rate at which an organism generates lipids per unit of biomass and time [39, 40]. Three key publications drive this cluster: [41-43]. Among these, [41] represents the primary citation hub, accumulating nearly 10,000 citations to date. This study introduced the web-based computational tool Signal P 4.0, which utilizes machine learning to accurately predict signal peptides and differentiate them from transmembrane protein regions. In contrast, [42, 43] explored the biotechnological potential of hydrogenase activities, focusing on biohydrogen production and bioremediation.

Discussion

Geopolitical Power Dynamics and Global Knowledge Asymmetries

The distinct three-phase publication trajectory identified in the results indicates that marine biotechnology has successfully transitioned from an isolated academic interest into a highly prioritized global research framework. The exponential surge observed during the "Rapid Phase" from 2018 onward indicates that the discipline is tightly synchronized with both shifting international environmental policies and revolutionary molecular breakthroughs. Politically, this post-2018 acceleration reflects a major global response to the implementation of the United Nations Sustainable Development Goals (SDGs) and the formal preparation and launching of the UN Decade of Ocean Science for Sustainable Development (2021–2030). These international policy shifts effectively redirected vast channels of public and private research capital toward oceanic bio-resource security, blue carbon tracking, and marine sustainability. Mechanistically, this rapid expansion phase was simultaneously accelerated by critical technological leaps, most notably the commercial scaling of high-throughput Next Generation Sequencing (NGS), meta-omics, and CRISPR-Cas9 gene editing systems. These molecular tools lower the cost and time required to engineer unculturable marine organisms, turning extreme oceanic environments into rapid bioprospecting frontiers.

The country and institutional network metrics reveal a clear structural divide between sheer publication volume and structural network centrality. Prolific volume dominance remains concentrated within macroeconomic powerhouses like the USA and China, confirming that advanced marine biotechnology correlates strongly with substantial national infrastructure investments, such as deep-sea research vessels and state-funded laboratories [44, 45]. However, adding a critical layer of geographical nuance, the network metrics show that France exhibits the highest structural betweenness centrality in the global landscape, outranking higher volume nations. This structural phenomenon is directly driven by France's deep integration within high impact European collaborative networks. Transnational funding frameworks, such as the European Union's Horizon 2020 and Horizon Europe programmes, legally mandate multinational consortiums for grant eligibility. Furthermore, France hosts key hubs for centralized regional infrastructure, such as the European Marine Biological Resource Centre (EMBRC). These integrated European frameworks position French institutions as vital central conduits through which global marine biotechnology collaboration and data flow.

Conversely, the minimal publication footprint from the African continent reveals a stark global knowledge asymmetry. Despite possessing expansive marine biodiversity across vast exclusive economic zones, African nations face acute infrastructural and funding barriers that limit independent bioprospecting. This highlights a critical need for international scientific diplomacy and technology transfer frameworks. These systems help prevent monopolistic resource exploitation and bridge the global innovation investment gap.

Analytical Interpretation of Keyword Shifts and Technical Bursts

The transition of keywords from baseline biological terminology to applied technical frameworks represents a clear paradigm shift in the field. The long-standing 26-year burst of "phytoplankton" and "metabolism" captures the historical era focused on fundamental marine biology and primary productivity. In contrast, the modern clustering of "stress tolerance," "salinity stress," "secondary metabolites," and "pH" reflects how climate change shapes modern research fronts.

In the keyword co-occurrence network, foundational terms including *Escherichia coli*, enzymes, biomass, and DNA exhibited high betweenness centrality scores above 0.06. Conceptually, keywords exhibiting high betweenness centrality represent critical intellectual conduits or structural bridges that connect disparate knowledge areas across the wider scientific landscape. In this network, the high centrality of these terms indicates that while marine biotechnology focuses on bioprospecting wild marine organisms, its operational and commercial framework relies heavily on established terrestrial industrial biotechnology models. Highly central nodes, such as *E. coli*, bridge marine genetic resources and terrestrial expression systems for downstream enzyme and biomass cultivation. Furthermore, the high burst strength of the technical terms "system," "biotechnology," and "culture" identifies the core operational bottleneck of the discipline. Moving from laboratory-scale discovery to commercial viability is a major hurdle. Bioprocess literature and citation bursts confirm that research has evolved from strain identification to scalable bioreactor engineering for industrial-scale production [46-48].

High Level Thematic Pillars of the Research Frontiers

Rather than evaluating the 16 co-citation clusters as fragmented collections of papers, they can be synthesized into three macro-thematic pillars that define the modern research front and map its temporal evolution: The Molecular Bioprospecting Pillar (Clusters #0, #1, #3, #7, #8); This core domain targets extreme or unique niches (such as deep-sea sponges and hydrothermal vent bacterial diversity) to screen for novel metabolites. Chronologically, this represents the foundational layer of the field. The thematic focus has shifted from descriptive taxonomy (*"sp nov."*) to uncovering the genetic mechanisms behind metabolite synthesis, allowing researchers to unearth novel antimicrobial and therapeutic strains. The High-Value Industrial Bioprocessing Pillar (Clusters #6, #9): Representing the newest active frontiers ("Valuable Pigment" with a mean year of 2019 and "Lipid Productivity"), this pillar targets metabolic engineering to optimize microalgal culture conditions. Its direct applicability lies in maximizing carotenoid and lipid extraction efficiencies to feed the commercial cosmetic, nutraceutical, and biofuel markets, grounding the field's utility in the global Blue Economy. The

Environmental and Climate Resilience Pillar (Clusters #2, #5): Emerging prominently around 2018 (e.g., "Mediterranean Sea" and "Environmental Plastic Degradation"), this active frontier focuses on ecological problem-solving. This includes using marine microbial consortia to degrade marine plastic or transferring marine stress-tolerance genes into terrestrial crops ("transgenic tomato") to mitigate climate induced soil salinization.

Methodological Disconnects and Study Limitations

A key structural insight derived from the author co-authorship network analysis is that all individual centrality scores fall strictly below 0.10. This empirical finding reveals a critical architectural characteristic of the discipline: the human collaboration network in marine biotechnology is highly fragmented and relies heavily on distributed collaboration. Rather than a lack of impactful research, this low betweenness centrality signifies that the field is confined within isolated regional clusters or localized "invisible colleges." There is a distinct absence of globally connected principal investigators capable of acting as primary topological bridges across continents. This fragmentation implies that research teams globally are likely operating in parallel, disconnected spaces, underscoring the urgent need for international consortiums to bridge these structural gaps and unify global bioprospecting tracks. Furthermore, several inherent limitations of this scientometric study must be acknowledged: Database Selection: Relying solely on the WoSCC database ensures high citation reliability but omits alternative metadata structures present in Scopus, PubMed, or Google Scholar. Linguistic and Document Restrictions: Restricting the search to English-language original research articles introduces a language bias, omitting key localized discoveries published in native-language journals (e.g., in China or Japan) and missing early-stage industrial data from patents and conference proceedings. Search String Constraints: Boolean configurations ("marine" AND "biotechnology") are vulnerable to term omission. Studies focusing on specific marine genera were omitted if they lacked these broad umbrella keywords in their titles or abstracts.

Conclusion

This study provides a comprehensive scientometric mapping of marine biotechnology from 1980 to 2023, identifying structural knowledge domains, emerging frontiers, and future research directions. Empirical evidence indicates that the discipline has evolved from a niche academic interest into a rapidly growing scientific domain aligned with international sustainability frameworks. While publication volume remains concentrated within macroeconomic powerhouses across the Americas and Asia, structural network centrality is predominantly driven by integrated European research consortia. The thematic mapping indicates that the current cutting-edge frontier has converged on the "Blue Economy" through the lens of high-value marine bioproducts, specifically highlighted by the recent emergence of the "Valuable Pigment" research cluster. Based on the macro-trends and structural gaps identified in this analysis, several targeted practical implications are proposed to guide future research tracks for key stakeholders: For Academic Researchers: The profound fragmentation and low centrality scores within the author collaboration network indicate an urgent need to bridge localized "invisible colleges." Researchers should actively form cross-continental networks to standardize global bioprospecting protocols and minimize parallel, redundant investigations. Furthermore, research should transition from descriptive strain isolation toward multi-omics and metabolic engineering frameworks. This shift is critical to understanding how climate-driven abiotic stressors (such as ocean acidification and salinity shifts) can be leveraged to upregulate cryptic secondary metabolites.

Policy Makers and Funding Bodies: The stark global knowledge asymmetry characterized by the severe underrepresentation of African nations despite their expansive marine biodiversity demands a restructuring of international scientific diplomacy. Capital-intensive infrastructure such as research vessels and molecular platforms must be accessible through equitable North-South technology transfer frameworks. This accessibility helps prevent asymmetrical genetic resource appropriation. Additionally, public funding agencies should strategically allocate resources toward high-growth thematic pillars, shifting funds from baseline taxonomic screening to targeted environmental remediation (e.g., microplastic degradation) and climate-resilient crop engineering. For Industrial Stakeholders: The intense citation bursts for technical terms like "culture" and "system" indicate that the primary commercial bottleneck has shifted from strain discovery to bioprocess scale-up. Industrial investors and bioengineers should prioritize funding for advanced photobioreactor design, process optimization, advanced metabolic flux modeling, and scalable microbial fermentation systems. Translating laboratory-scale discoveries into economically viable industrial applications (such as high-value cosmetic carotenoids, clinical antimicrobials, and third-generation biofuels) will require aggressive public-private partnerships focused on maximizing yield efficiency and downstream purification technologies.

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Author's Contributions

Jasnizat Saidin: Funding acquisition, Validation, Visualization, Write original draft. Read and approved the final manuscript.
Idham Sumarto Pratama: Data curation, Investigation, Validation, Write original draft. Read and approved the final manuscript.
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Thirukanthan Chandra Segaran: Methodology, Resources, Visualization, Validation. Read and approved the final manuscript.
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Ethics

Authors should address any ethical issues that may arise after the publication of this manuscript.

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