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REVIEW

Past and Recent Trends on Navicula Research: A Comparative Systematic Literature Network Analysis

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Abstract

The *Navicula* species as a phytoplanktonic organism has attracted considerable research interest due to its simple cellular structure, remarkable photosynthetic efficiency, short life cycle, and resilience in extreme environmental conditions. This study aims to evaluate global research trends on *Navicula* using a scientometric approach to identify key applications and emerging opportunities. To understand how its roles have evolved across disciplines, we analyzed Scopus-indexed publications spanning two periods, namely 1873–2013 and 2014–2023.

Our findings reveal a marked increase in publication volume, co-authorship networks, and international collaborations in the last decade. Thematically, early studies emphasized *Navicula*'s role as a fouling organism, while more recent publications focus on antifouling strategies and material innovation. In taxonomy, early works relied on morphology-based identification with limited strain coverage, whereas current research addresses classification errors and cultivation challenges. In ecotoxicology, influential articles identify *Navicula* as a methanogen capable of accumulating methylated mercury and producing *β*-methylamino-L-alanine, raising human health concerns. Concurrently, its biochemical potential, particularly as a source of antioxidants and stigmasterol, has expanded its relevance to biomedical and nutraceutical fields. Together, these trends underscore the multidimensional importance of *Navicula* and point to promising directions for future interdisciplinary research.

Introduction

Navicula is a genus of diatoms that can be found in both benthic (bottom-dwelling) and planktonic (free-floating) environments. However, they are more commonly associated with benthic habitats. These diatoms are often found attached to surfaces in aquatic environments, such as rocks, sediments, and plants (Prasertsin et al., 2021). *Navicula* is among the most species-rich diatom genera, though its taxonomy remains contentious due to cryptic diversity and reliance on morphological traits (Kociolek & Spaulding, 2003). While ~1,200 species are formally described, high misidentification rates (Zimmermann et al., 2014) necessitate molecular validation for ecological studies. This genus has garnered extensive research attention because of its several advantages, such as possessing a straightforward cellular structure, exhibiting exceptional photosynthetic capacity, having a brief life cycle, and displaying resilience in even the most harsh environmental conditions. *Navicula* possesses numerous advantages in the field of health, for example,

serving as a natural antioxidant (Galindo et al., 2024; Zhou et al., 2023), antiviral (Lee et al., 2006), antifungal (Alallaf, 2022), antibacterial (Fabregas et al., 1986; Findlay & Patil, 1984), anticancer (Ruiz-Cruz et al., 2022), etc. Moreover, *Navicula* can be an excellent choice as the main source of new renewable energy in the development of biodiesel (Popovich *et al*., 2019) and bioethanol (Telussa et al., 2023). In controlling environmental problems, *Navicula* can also be used as a solution to reduce plastic waste by making biodegradable plastic (Telussa et al., 2023) and also as bioremediation (Ding et al., 2020) to protect polluted environments such as those affected by microplastic contamination in aquatic systems (Sridhar et al., 2024).

The utilization of *Navicula* also aligns with multiple objectives outlined in the Sustainable Development Goals (SDG) framework, including 7.1 and 7.2, which emphasize the necessity of enhancing innovative and renewable energy sources. Additionally, point 14.a in the SDGs addresses the enhancement of scientific understanding through extensive study on the utilization of marine natural resources, including *Navicula*, across many sectors. Consequently, it is essential to delineate the utilization of diverse *Navicula* species to identify trends and future opportunities. This research aims to elucidate the possibilities derived from the utilization of *Navicula*, particularly in relation to the advancement of SDG projects using a bibliometric approach.

A number of articles have emerged concerning the bibliometric study of microalgae across diverse fields. Research in the environmental sector examining trends in the utilization of microalgae for wastewater treatment, as documented in Scopus publications from 1985 to 2023, indicates a rise to 68 articles in 2022 (Santillán Ángeles et al., 2024). The utilization of microalgae as a bioremediation agent has been examined for the mitigation of phenolic pollutants resulting from chemical spills in aquatic environments (Radziff et al., 2021). Bibliometric research on microalgae has also been conducted in the health sector to examine antioxidant studies on bioactive chemicals in microalgae from 1996 to 2022 (Yang et al., 2023). Several papers also address the application of diatoms in relation to DNA metabarcoding or bioassessment for water quality monitoring (Mbao et al., 2023; Mbao et al., 2022). These studies, in contrast to the previous research article, do not limit their investigation exclusively to the genus *Navicula*.

To the best of the authors' knowledge, no research has specifically conducted bibliometric analysis for the genus *Navicula*. So, a bibliometric analysis should be done that is focused on *Navicula* alone, since the results may be different from those from general diatom studies because different genera can have different traits. To get a complete and organized picture of how the genus *Navicula* is used, we gathered and read all the publications from 1873 to 2023 that talked about how *Navicula* was used in different fields. This helped us understand how things have changed over time, keep track of recent progress in *Navicula* research applications, and also guess what might happen in the future in this area. We subsequently categorized the documents into two intervals, 1873-2013 and 2014-2023, to analyze the trends and contemporary research foci of the SDG initiative. We anticipate that this research will be beneficial for academics or scholars interested in *Navicula* or guiding future studies towards trending concentrations.

Materials and Methods

For the purpose of document collection, the online data repository Scopus was selected because of its comprehensive coverage across a variety of academic disciplines. As systematic literature network analysis (SLNA) is considered part of a systematic literature review (Canavesi & Minelli, 2022), flowcharts created based on preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines were utilized in order to report the summary of the screening process (Page et al., 2021). The process of visualization entails identifying records from databases, screening the records, evaluating reports to determine eligibility, including eligible studies, and excluding reports that do not meet the eligibility criteria (Sarantaki et al., 2022). The search query in the Scopus database is conducted using the phrase *Navicula* within the article title, abstract, and keyword to retrieve relevant article data. Based on the search query, there were a total of 2701 articles available on Scopus.

The articles were subsequently subjected to inclusion criteria, which involved selecting records published exclusively in the English language between 1873 and 2023. Records published after 2023 or in languages other than English were omitted. The records were subsequently subjected to further refinement, which involved excluding article types other than original articles. The analysis excluded records from the press that were not in their final form. A total of 2225 articles were available after the exclusion step, and articles omitted can be seen in Figure 1. All publications that were accessible were included without any additional filtering, such as screening the abstracts or full texts. The study aimed to provide a comprehensive overview of the overall trends in *Navicula* research topics, prompting this action. 2225 articles were then divided into 2 groups based on the timeframe of publication, namely 1873-2013 and 2014-2023 for further analysis. The data was extracted independently in CSV file format for analysis, and the entire extraction procedure was completed on August 31, 2024.

Extracted data in CSV format were submitted to the R-package Bibliometrix ver. 4.0.0 (Aria & Cuccurullo, 2017) and VOSviewer software ver. 1.6.20 (van Eck & Waltman, 2020) for bibliometric analysis. The two softwares was used for the analysis of the two CSV files, including performance analysis and science mapping

analysis. This study utilizes performance analysis to delineate the difference between main origins, subject areas, scholarly journals, authors, affiliations, and countries involved between the two research timestamps. In addition, scientific mapping analysis was conducted, including co-citation, bibliographic coupling, co-authorship, and co-word analysis, to reveal the changes in intellectual, conceptual, and social structures between the two time periods (Öztürk et al., 2024).

Results

Main Input

A total of 1253 articles were retrieved for the period from 1873 to 2013, while 972 items were retrieved for the period from 2014 to 2023. The similar volume of articles published between 2014 and 2023 indicates that the research conducted in the past decade is on par with that carried out in 1873-2013 (Table 1). Documents published from 1873-2013 have an annual growth rate of 3.22, which is higher than the annual growth rate (1.17) in the 2014-2023 period (Figure 2). The numbers show that there is a change in publication pattern between the two periods. Figure 2A shows that the number of publications has been increasing exponentially from 1964 to 2013, as shown by the exponential trendline ($8E\text{-}53e^{0,0618x}$), with an R^2 value of 0,8821. It is important to note that data before 1964 were not included in the trendline calculation because 0 cannot be specified as an exponent function. However, the number of articles has been fluctuating between 2014 and 2023. The low explanatory power of the linear regression line (y=3,8424x-7658,7) is evident, as indicated by the low R^2 value of 0.4472. One probable explanation is market saturation, when fundamental elements of the topic have been thoroughly examined, resulting in a stagnation of innovative contributions.

Although the average rate of document publication was higher during the period from 1873 to 2013, the citation rate was also higher than from 2014 to 2024. It suggests that the research holds a significant impact and was crucially required as a basis for subsequent studies (Douglas-Smith et al., 2020). Nevertheless, it is customary for early released publications to garner greater attention and citations, thereby making this situation appear commonplace. The number of citations utilized in publications produced over the 2014-2023 timeframe exceeds that of the preceding period. This improvement is due to the annual rise in the number of published publications, resulting in a larger pool of references to be utilized.

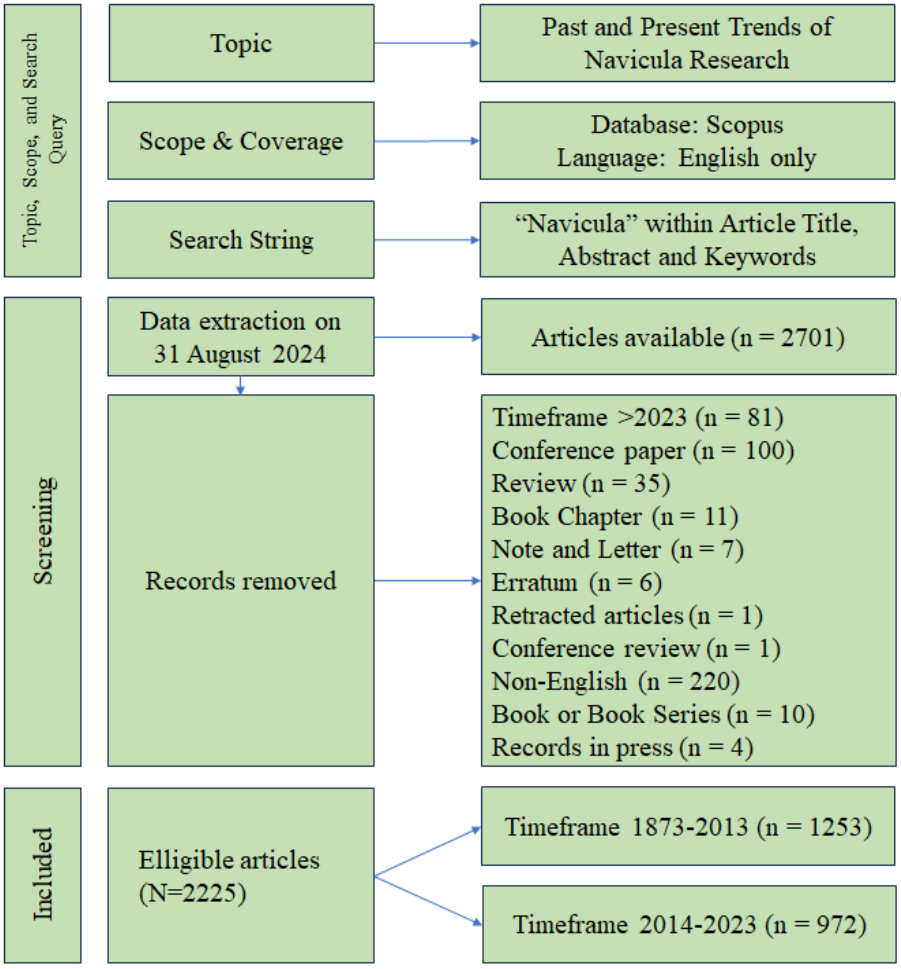

Figure 1. Article exclusion steps (n= Number of documents).

The frequency of both keyword plus and author keywords in texts written within the past decade exceeds that of the years 1872-2023. Moreover, the average annual output of articles has risen from 8.8 to a remarkable 97.2 articles each year. This suggests that the research on the Navicula issue has been more extensive in productivity than during the period from 1873 to 2013. This idea can be substantiated by the use of co-word analysis, which will be further upon in the subsequent section of this article. Furthermore, there has been a decline in the quantity of documents written by a single author and a rise in the number of co-authors per document in the past decade, indicating a greater level of collaboration compared to previous years. Remarkably, there has been a notable increase in international partnerships in recent times, as evidenced by the growing number of foreign co-authorships. From 1987 to 2013, the proportion of authors who engaged in worldwide collaboration was only 20.03%. However, in the past decade there has been a significant growth of 8%, bringing the current percentage of authors collaborating abroad to 28.5%.

Most Relevant Sources and Affiliations

Between 1873 and 2013, the Journal of Phycology published a total of 83 publications, which received a combined total of 4183 citations, followed by Diatom Research with 79 documents, accumulating a total of 1691 citations. Hydrobiologia, on the other hand, had 59 documents with a total of 1516 citations. The Biofouling journal has a greater overall number of citations in comparison to the diatom research and Hydrobiologia despite the smaller quantity of documents. This implies that the released documents may be significant and influential in the research theme. Highly influential or groundbreaking documents are typically mentioned more frequently. In order to assess the influence of a journal, a scientist, a university, or a research organization, the often used metrics are the h-index (Shah & Jawaid, 2023; Zhang, 2013), and g-index (Egghe, 2006), respectively. These indices utilize the number of citations of an article as a criterion for evaluating its influence, as these methods are regarded as valid (Wang et al., 2019).

Between 2014 and 2023, there was a change in the leading academic publications focused on the research topic. "ACS Applied Materials and Interfaces" and "Science of the Total Environment" have been identified as the two primary repositories for articles pertaining to the research topic. Despite its previous standing, the Journal of Phycology and Diatom Research failed to secure a spot among the top 10 prominent journals in 2014-2023. Biofouling's rise (18 articles, 473 citations) reflects *Navicula*'s utility in testing antifouling coatings (e.g., Rosenhahn's polymer studies). Its higher citation

Table 1. Main input of the two datasets used in the study

Description	1873-2013	2014-2023
Main Information Data		
Documents	1,253	972
Annual Growth Rate	3.22	1.75
Document Average Rate	26.1	5.17
Average Citation Per Doc	32.94	13.52
References	39,055	48,108
Document Contents		
Keyword Plus	6,197	6,404
Author's Keywords	2,604	3,050
Authors and Collaboration		
Authors	2,736	3,280
Author's of Single Authored Docs	193	41
Single-authored docs	251	45
Co-Authors per Doc	3.11	4.99
International co-authorships %	20.03	28.5

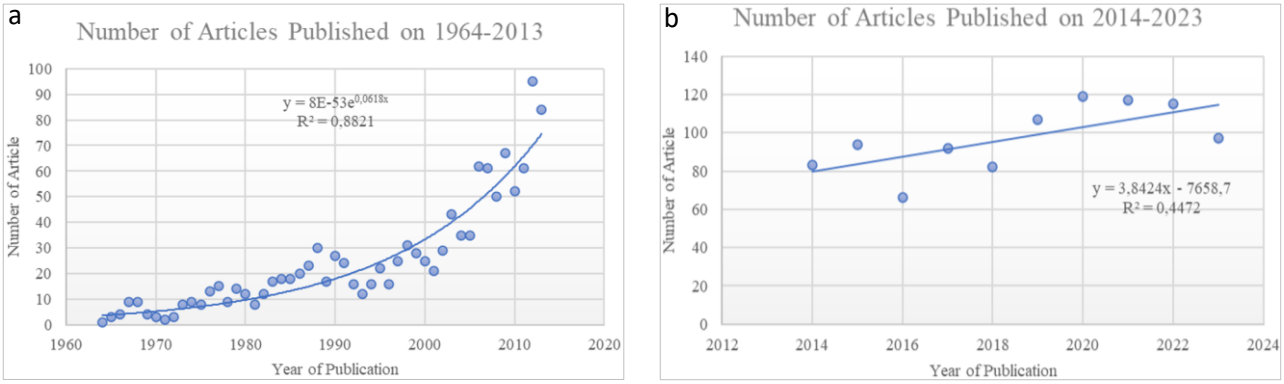

Figure 2. Number of documents published in 1873-2013 [a], and 2014-2023 [b].

impact vs. Science of the Total Environment suggests a stronger interdisciplinary appeal in marine materials science. The Biofouling journal publishes articles on specific topics, including antifouling technologies and coatings, the transmission of invasive species, antimicrobial agents, biological interfaces, biomaterials, microbiologically influenced corrosion, membrane biofouling, biofilms in the food industry, biofilm-related diseases, and indwelling biomedical devices as substrates for fouling and biofilm proliferation. Conversely, Biofouling has a niche impact by concentrating on surface colonization, adhesion processes, and biofilm management. The moderate impact factor of 2.6 and SJR of 0.518 (2023) indicate that, although it is frequently referenced, its influence is primarily limited to scholars focused on fouling and biointerface phenomena. Table 2 compiled the top 10 journals that have shown interest in the topic. The rankings are based on their h-index, which covers two different timestamps.

Individual scientists may pursue affiliations to obtain enhanced access to research resources or networks, as affiliation with an institution is intrinsically connected to resource availability, research infrastructure, and career prospects (Hottenrott & Lawson, 2017). Figure 3 shows a graph of the trending institutions (5 of the highest) who become affiliates in publications related to *Navicula* in the 2 time periods.

From 1873 to 2013, the University of Birmingham had a graph that experienced a significant increase and more than doubled the number of documents published at the end of the period, with a total of 86 documents (2013) compared to other institutions (Figure 3a). In the forthcoming era, the University of Newcastle demonstrates a consistent rise in publishing volume, culminating in a total of 402 documents by 2023, despite its absence in the preceding year. Remarkably, Ruhr University Bochum had no publications at the onset of the new era, but by 2019, the volume of publications surged significantly, securing one of the top positions (Figure 3b). This suggests that the latest trends and requisite infrastructure for *Navicula* topic research are consistently provided by emerging affiliations, which are advised to researchers contemplating this theme.

Authors and their Co-Authorship Network

According to Table 3, Maureen E. Callow from the University of Birmingham, United Kingdom, conducted research on *Navicula*. He contributed to 31 publications pertaining to the highest h-index and g-index. Significant research undertaken by Maureen and her colleague Jim A. Callow from Birmingham University examines the application of *Navicula* in anti-biofouling testing. *Navicula*, a prevalent genus of diatoms, can serve as a contaminant in synthetic materials inside aquatic

Table 2. Sources' local impact on two timestamps (1873-2013 and 2014-2023)

1873-2013					2014-2023				
Sources	h-index	g-index	N	Total Cited	Sources	h-index	g-index	N	Total Cited
Journal of Phycology	36	63	81	4183	ACS Applied Materials and Interfaces	13	15	15	600
Diatom Research	25	37	79	1691	Science of the Total Environment	12	19	19	403
Hydrobiologia	24	37	59	1516	Biofouling	11	18	18	473
Biofouling	21	25	25	1950	Phytotaxa	10	16	38	373
Aquaculture	17	21	21	855	Algal Research	9	11	11	269
Journal of Applied Phycology	17	20	20	896	Chemosphere	8	12	12	382
Marine Biology	16	21	21	933	Langmuir	8	9	9	220
Polar Biology	16	16	16	704	Progress in Organic Coatings	8	9	9	241
Botanica Marina	15	20	20	647	Environmental Science and Pollution Research	7	11	14	133
Estuarine, Coastal and Shelf Science	12	13	13	586	Environmental Toxicology and Chemistry	7	7	7	213

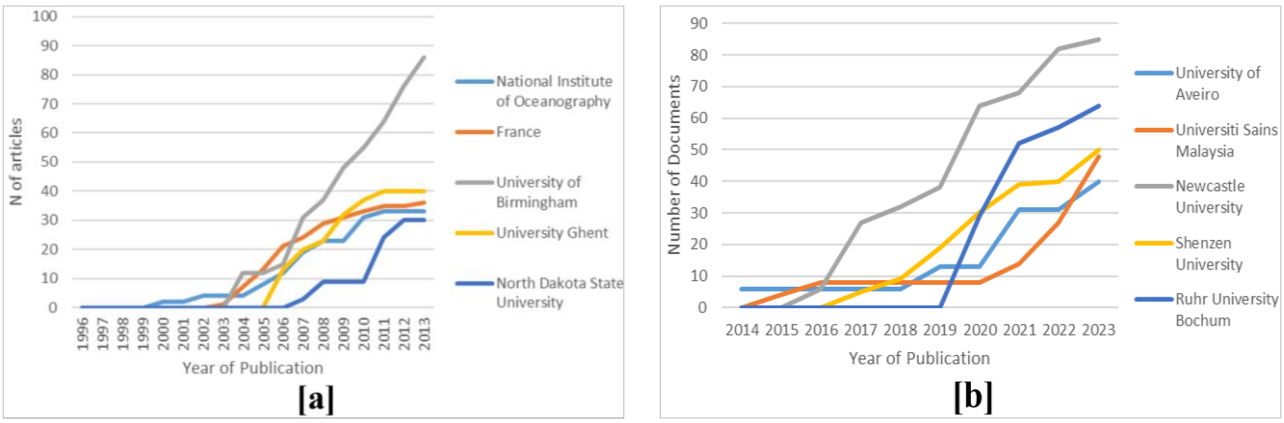

Figure 3. Affiliations Production Over Years on 1873 to 2013 [a] and 2014-2023 [b] Timestamps (Five journals based on highest number of publications were plotted).

environments (Patro et al., 2012). *Navicula* can function as a matrix for embedded biofilm organisms by secreting certain extracellular polymeric compounds (Sahan et al., 2007; Zargiel et al., 2011). This is why *Navicula* is frequently utilized as a standard in the evaluation of anti-biofouling products. (Sundaram et al., 2011; Y. Wang et al., 2011; Weinman et al., 2009).

Between 2014 and 2023, Axel Rosenhahn of Germany wrote 28 publications. Consistent with the prior time, the primary focus of the study conducted pertained to biofouling. Despite having a lower quantity of papers, he possesses a greater amount of citations than the other authors. This indicates that Axel Rosenhahn is an emerging and influential researcher in marine biofouling, employing *Navicula*, as demonstrated by his exceptional h-index, despite his absence from prior studies (1873-2013). The research he conducted was perceived as a partnership with other researchers focused on the same topic, such as Anthony S. Clare and John A. Finlay. They have collaborated in conducting much research on the topic of developing antibiofouling materials from synthetic polymers. Examples of their study included conducting biological tests on nonspecific protein adsorption, the attachment of the diatom *Navicula perminuta*, and the settlement of zoospores of the macroalga *Ulva linza* (Yu et al., 2020; 2021). When comparing the two time periods, the most frequently discussed topic is the application of *Navicula* as a biofouling-releasing agent. Although the subjects discussed remain consistent, the authors from these two eras diverge. Only John A. Finlay, present in both periods, demonstrates the author's consistency in doing related research and possesses academic influence.

To assess the authors' collaboration pattern, network analysis is done with a full counting method with a minimum of 5 documents per author on both timestamps. This limitation is due to the large number of authors who contribute to the topic of the research (2967 authors in 1873-2013 and 3588 authors in 2014-2023). Figures 4A and 4B illustrate the co-authorship network, overlaid with timeframes, for the years 1873-2013 and 2014-2023, respectively.

Despite limiting the 2014-2023 timeframe to only 10 years, the growing number of authors indicates a growing interest in the research issue. After the limitation, 52 and 65 authors meet the threshold for the 1873-2013 and 2014-2023 timeframes, respectively. Between 1873 and 2013, a total of 28 clusters were found, with the largest set comprising 11 interconnected authors, while 19 clusters had only a single author each. From 2014 to 2023, 19 clusters were identified, with the largest consisting of 25 interrelated authors, and 6 clusters had only one author each. The findings reveal that the authors exhibit a broader collaboration pattern, as evidenced by the growth in the largest connected authors, and demonstrate greater consistency in their thematic work, as reflected by the reduced presence of single authors within a cluster.

Author's Countries and Co-Countries Network

Between 1873 and 2013 (Table 4**)**, the USA was the nation that most frequently addressed this species, followed by the UK and France, based on the total citations and number of publications. In subsequent positions, however, although possessing a greater number of articles, India, China, and Turkey do not attain a spot among the top five cited countries. This may suggest that, despite a lesser quantity of articles, France, Canada, and Germany have more influential publications. The UK leads in multiple country publications among the top 10 nations, followed by the USA, according to international cooperation. Turkey is distinguished by the fact that all publications concerning *Navicula* are produced domestically.

From 2014 to 2023 (Table 5), China has emerged as the leading nation in terms of the highest number of citations, publications, and international collaborations. Notwithstanding their former prominence, the USA and UK have slipped to the second and tenth positions, respectively, in terms of total cited countries. Germany is consistently increasing in total citations and publication output, whereas India has achieved notable advancements, especially with total citations. India has attained a position in the top five, with a total of 620 citations and an average article citation of 7.80. The findings suggest that although there is a considerable volume of papers, their citation frequency is low, indicating a lack of influence compared to countries with higher average citation rates.

Table 3. Top 10 authors ranked by their h-index between the two time periods

1873-2013					2014-2023				
Author	h-index	g-index	N	Total Cited	Author	h-index	g-index	N	Total Cited
Callow M. E	30	31	31	2785	Rosenhahn A	17	23	28	573
Callow J. A	29	30	30	2830	Clare A. S	16	28	31	835
Finlay J. A	18	18	18	1728	Finlay J. A	16	28	30	817
Cox E. J	15	15	15	625	Swain G. W	10	11	11	318
Mann D. G	14	15	15	832	Ding T	9	10	10	359
Volcani B. E	14	14	14	742	Ector L	9	15	15	294
Underwood G. J. C	12	13	13	1391	Li J	9	13	13	417
Lange - Bertalot H	11	15	15	271	Wanka R	9	10	10	197
Anil A. C	10	10	10	466	Zhao W	9	12	12	300
Smol J. P	10	10	10	409	Aldred N	8	8	8	185

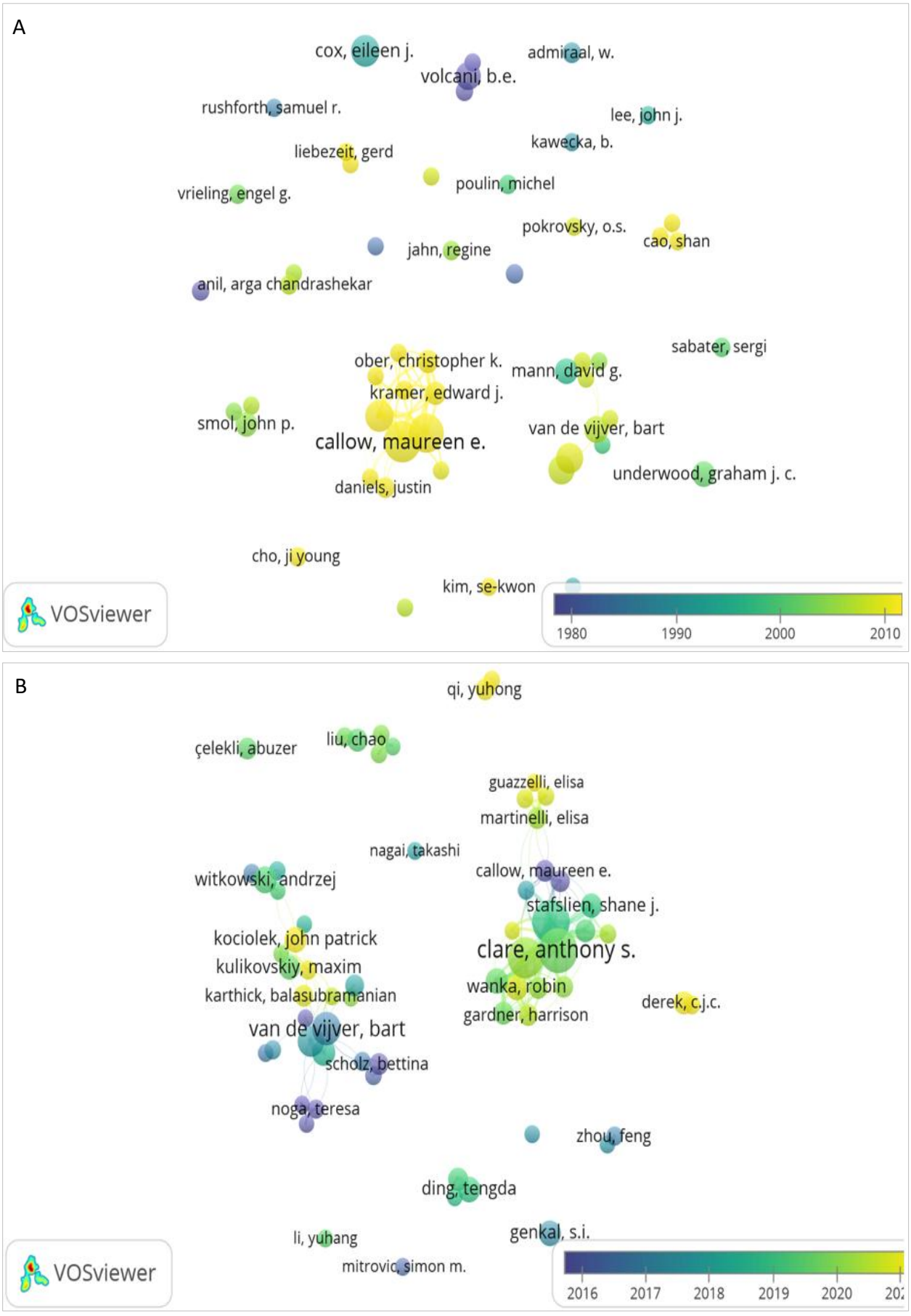

Figure 4. Co-authorship Networks on 1873 to 2013 [A] and 2014-2023 [B] Timestamps Overlay with Time (The yellow color signifies newer articles, whereas the dark blue color denotes older publications).

Network analysis is conducted using a full counting approach to evaluate the collaboration patterns of countries, requiring a minimum of five papers per country for both time periods. Subsequent to the limitation, 44 and 53 countries satisfy the criteria for the periods 1873-2013 and 2014-2023, respectively. Figures 5a and 5b depict the co-country network, annotated with periods, for the years 1873-2013 and 2014-2023, respectively.

From 1873 to 2013, eight clusters were identified, with the largest consisting of 39 related nations, and one cluster contained a single nation (Bangladesh). Between 2014 and 2023, eight clusters were detected, the largest of which comprises 51 interconnected writers, although no cluster includes a single country. Despite maintaining an identical number of clusters, a greater number of nations were interlinked, and no countries were assigned to a single cluster between 2014 and 2023. This suggests that international collaboration among countries has advanced more significantly in the previous decade than from 1873 to 2013. The USA and UK possess the most robust network line (according to both timestamps), signifying a strong link strength and a greater collaboration in published articles compared to other nations.

Most Globally Cited Documents

The ten most internationally cited articles for each time period were analyzed to identify disparities in research gaps and significant findings in prominent articles. The data derived from the publications encompasses essential findings, and the gap analysis is presented in S1 Appendix (1873-2013) and S2 Appendix (2014-2023).

The most cited work from 1873 to 2013 was authored by Van Dam et al., 1994, in the Netherlands, which examines the species of diatom genera that are both the most abundant and the most resilient to adverse environmental circumstances. *Navicula* is the most prevalent, whereas *Nitzschia* species have the greatest resilience to pollution. This article ranks first for the highest number of citations, exceeding 942 in total. Another study mentioned over 437 times is that conducted by Palmer et al. (1969), which addresses the same problem with pollution-tolerant algae. The *Navicula* genus is ranked seventh among the most pollution-tolerant genera. Both investigations had limitations regarding the information and methodologies accessible at the time of their execution (Palmer, 1969; Van Dam et al., 1994). Researchers recommend utilizing scanning electron microscopy, currently under development, with light microscopy to define various forms of *Navicula*. During this period, researchers undertook multiple studies on the development of antifouling compounds using *Navicula* as a fouling release mechanism (Holland et al., 2004; Krishnan et al., 2006).

The area of biodiesel has rapidly emerged as a promising research frontier, with subsequent studies expanding Navicula's role in biodiesel innovation through advanced formulations. For instance,

Table 4. Relevant Countries based on Total Cited and Number of Publications in 1873-2013

Based on Total Cited			Based on the Number of Publication (N)			
Countries	Total Cited	Average Article Citations	Countries	N	Single Country Publication	Multiple Country Publication
USA	2770	44.00	USA	63	41	22
United Kingdom	2691	61.20	United Kingdom	44	18	26
France	1731	64.10	India	40	38	2
Canada	1540	55.00	China	36	31	5
Germany	1423	47.40	Türkiye	31	31	0
Australia	1146	57.30	Germany	30	12	18
China	1017	28.20	Korea	29	24	5
Netherlands	901	56.30	Canada	28	20	8
Japan	847	33.90	France	27	16	11
Korea	808	27.90	Japan	25	19	6

Table 5. Relevant Countries based on Total Cited and Number of Publications in 2014-2023

Based on Total Cited			Based on Number of Publication (N)			
Countries	Total Cited	Average Article Citations	Countries	N	Single Country Publication	Multiple Country Publication
China	2678	18.60	China	144	113	31
USA	1195	25.40	India	79	69	10
Germany	722	17.60	USA	47	26	21
India	620	7.80	Germany	41	16	25
France	399	15.30	Türkiye	35	32	3
Mexico	365	19.20	Italy	29	17	12
Italy	346	11.90	France	26	10	16
Australia	345	23.00	Korea	26	20	6
Korea	323	12.40	Poland	26	15	11
United Kingdom	276	18.40	Indonesia	20	18	2

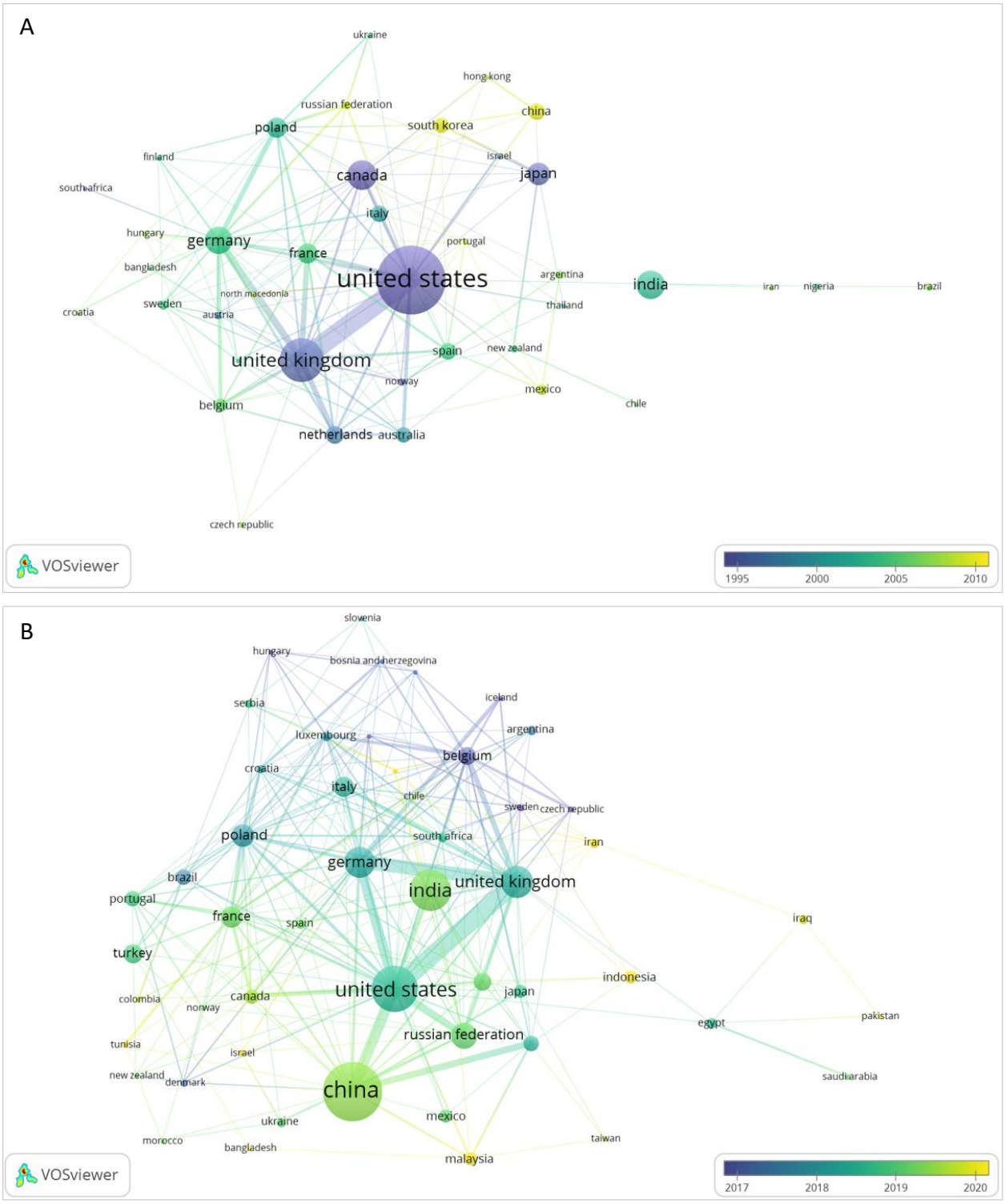

Figure 5. Co-country Networks on 1873 to 2013 [A] and 2014-2023 [B] Timestamps Overlay with Time (The yellow hue represents nations with recent articles, whereas the dark blue hue indicates nations with older publications. Lin/log modularity normalization is employed, with attraction configured to 4 and repulsion set to 0.).

Arunprasad and Elango (2020) examined the tribological properties of RuO_2-enhanced Navicula biodiesel, demonstrating less friction and wear in engine components, hence affirming its potential as a sustainable lubricant addition. The same group conducted complementary research on the performance characteristics of RuO_2 in diesel blends with Navicula biodiesel in compression ignition (CI) engines, demonstrating enhanced combustion efficiency and diminished emissions (Arunprasad & Elango, 2020b, 2020a). In addition, Bielsa et al. (2016) evaluated the concurrent synthesis of triacylglycerols (TAGs) and exopolysaccharides (EPS) in Navicula cincta, suggesting a biorefinery model that enhances the value of both lipid and polysaccharide components under non-stress settings (Bielsa et al., 2016). Furthermore, Song et

al. (2013) conducted a study to identify diatom-class microalgae with potential for biodiesel production. Despite *P. tricornutum* achieving the maximum lipid content, *Navicula* remains in the top four species with the highest total lipid content, followed by *C. vulgaris* and *S. capricornutum* (Song et al., 2013).

Additional research examined the defensive mechanisms of *Navicula* in response to various circumstances. Diatoms exhibit a sensitivity to hydrogen peroxide that is tenfold lower than that of cyanobacteria during growth (Drábková et al., 2007), and in dark conditions, diatoms are able to increase the production of carbohydrate-rich exopolysaccharides as a locomotive mechanism and for sediment stabilization (Smith & Underwood, 1998). (Larsen & Patterson, 1990) investigated flagellates in various sediments, particularly heterotrophic flagellates that predominantly devour diatoms in tropical marine environments. *Navicula* is recognized for its involvement in mercury methylation inside periphyton in river lakes (Hamelin et al., 2011).

From 2014 to 2023, the most referenced document, with 180 citations, was a study by Maadane et al. (2015). The findings indicated that ethanol extracts from all varieties of diatoms exhibited significant antioxidant capacity (Maadane et al., 2015). Additionally, the article with 175 citations is a study by Al-Naamani et al., (2017) regarding the advancement of antifouling coatings examined a chitosan Zn/O nanocomposite coating utilizing *Navicula* as a fouling-releasing agent (Al-Naamani et al., 2017). Several researchers also investigated the application of *Navicula* as a biodegradation agent to address water pollution caused by pharmaceutical waste (Ding et al., 2017, 2019), and as an environmental indicator (Bai & Acharya, 2016; De Wilt et al., 2016). *Navicula* possesses the capability to function as a risk mitigation and removal agent for developing pollutants, including pharmaceuticals, in natural water systems (Ding et al., 2020). The subsequent most referenced discourse examines the environmental variables influencing *Navicula* growth, which impact lipid production and bioactivity (Meng et al., 2019).

In the health sector, research on microalgae has expanded beyond antioxidant potential to encompass a wide range of therapeutic applications. *Navicula* species, in particular, have shown promise in anticancer research, with stigmasterol extracted from *Navicula* demonstrating cytotoxic effects against HepG2 liver cancer cells (Kim et al., 2014). Recent studies have further broadened this scope. An *in silico* investigation by Febrina et al. (2023) revealed that polyunsaturated fatty acids (PUFAs) derived from *Navicula salinicola* exhibit strong molecular interactions with STAT3, a key regulator in benign prostate hyperplasia (BPH), suggesting their potential as natural inhibitors of BPH through modulation of androgen signaling pathways (Febrina et al., 2023). Additionally, Ruiz-Cruz et al. (2022) explored the erythroprotective, anti-inflammatory, and antiproliferative properties of pigment-rich extracts from *Navicula incerta*, demonstrating selective inhibition of oxidative stress and cancer cell proliferation in relation to ABO and Rh blood group phenotypes. These findings underscore the emerging biomedical relevance of *Navicula* species, positioning them as valuable sources of bioactive compounds for both preventive and therapeutic interventions (Ruiz-Cruz et al., 2022).

Further subjects concerning *Navicula* include biofouling and morphology, typification, and critical investigation of certain ecologically minor *Navicula* (Wetzel et al., 2015 ;2017), as well as taxonomy utilizing unverified data from the International Nucleotide Sequence Database Collaboration (INSDC). Despite the limited availability of reference genomes, recent sequencing initiatives have started to enrich public databases, including National Center for Biotechnology Information (NCBI) and the INSDC, with mitochondrial, plastid, and nuclear genomic information for species such as *Navicula incerta* and *Navicula pelliculosa*. Nonetheless, discrepancies in taxonomic annotation endure, highlighting the necessity for integrative taxonomy. Moreover, it is important to note the limitations in strain availability, which may constrain reproducibility and broader application. Taxonomic identification of *Navicula* strains remains challenging, with several databases such as AlgaeBase (Guiry & Guiry, 2025), Diatom.org (Kociolek et al., 2025), etc serving as key references, though inconsistencies persist. Another example, study by (Zimmermann et al., 2014) examines the taxonomic consistency of *Navicula* diatom taxa at the species level by comparing the DNA sequences identified with those published in the International Nucleotide Sequence Database Collaboration (INSDC) repository. Their findings indicate that the current taxonomic assignments in INSDC remain inadequate, with a misidentification rate reaching 30% and only about 20% showing clear matches. One of the primary causes is taxonomic annotation that still relies on morphological assumptions or initial identifications without molecular validation. Furthermore, morphological identification using microscopy has several limitations in determining taxonomy. The lengthy process required and the results being highly dependent on each individual's taxonomic expertise may lead to differing conclusions among taxonomists. These differences can also arise from variations in taxonomic concepts, limited diagnostic morphological features, the presence of cryptic species, the availability of reference floras, and the quality of microscopes used (Mann et al., 2010). As an alternative, the use of molecular markers through DNA barcoding offers a faster, more universal, and reliable identification approach. This method does not rely on pre-existing morphological species concepts and can be adapted to various taxonomic frameworks (Rach et al., 2008).

The disparities in the publishing years of the ten texts, relative to the citation counts throughout these two eras, present multiple discussion subjects. During the initial period, the predominant topic of discussion and citation was the environmental circumstances of diatoms, particularly *Navicula*, which exhibit resilience to harsh environments such as elevated temperatures, high turbidity, and low oxygen levels (Çelekli et al., 2018; Céspedes Vargas et al., 2016). The subject of biofouling has remained prominent across both periods, indicating its ongoing relevance and significance as a field of study. From 2014 to 2023, the research with the highest citation counts showed greater diversity compared to the preceding era. Numerous exploratory investigations have been conducted in the health industry over the past decade about natural antioxidants and the creation of anticancer pharmaceuticals (Fimbres-Olivarria et al., 2018). Furthermore, within the domain of renewable energy, *Navicula* has been examined as a potential biodiesel source in the past; however, it was less favored from 2014 to 2023 in comparison to other study areas. The primary distinction between these two periods is in the increased sophistication and variety of approaches and equipment employed. In addition, popular taxonomic research on the *Navicula* subject from 2014 to 2023 emphasizes erroneous identifications or identification ambiguities, whereas earlier research was constrained by inadequate data due to the identification of only a few species (Chudaev & Georgiev, 2016).

Research conducted from 1873 to 2013 faced various difficulties in distinguishing centric diatom taxa using light microscopes due to limited tools. Algae identification in water samples was also restricted to the 20 most common species or genera, with complexity in describing all flagellate variants due to high species diversity. In the last decade, research has developed various methods using molecular techniques to identify species with high accuracy. Subsequent challenges include classification errors in available databases using microscope images and difficulties in obtaining and culturing species for identification.

In ecotoxicological research, Early and recent studies on *Navicula* found that its growth can enhance mercury methylation occurring in fluvial lakes. Additionally, increased diatom growth also contributes to the rise in neurotoxin BMAA levels. Meanwhile, the impact of ibuprofen on microalgae growth can reduce the photosynthesis rate of *Navicula*. In the field of biofouling, early studies with *Navicula* continue to concentrate on elucidating the mechanisms of macroalgal fouling. Amphiphilic surfaces were seen to enhance the detachment of foulers, and the mobility of macroalgae is unrelated to its adhesive strength. Basic investigations on macroalgal characteristics, including the synergistic impact of hydrogen peroxide and light-selective effects, as well as the locomotion mechanism, were also conducted. Recent leading studies from 2014 to 2023, however, have concentrated on the antifouling efficacy of materials, including chitosan/ZnO, polymer coatings, and silicone oils. Co-word analysis is performed on both timestamps in order to achieve a more in-depth and objective comprehension of the patterns of study that are present in both timestamps.

Co-Word Analysis

To have a better understanding of the primary study issues in an area, it is helpful to identify phrases that are both intriguing and influential. This method, which makes use of keyword co-occurrence networks and overlays, is regarded as being quick, objective, and straightforward to reproduce (Arifah et al., 2022; Bamel et al., 2020; Grames et al., 2019). This investigation makes use of fractional calculations at the network level, which have the potential to enhance the relative weights of links and offer results that are more accurate (Vargas-Quesada et al., 2017). The selection of keywords for this study makes use of "all keywords," which is a combination of the author's keywords and the keywords that have been indexed within the database. The use of author keywords frequently produces biased results for the purpose of increasing the visibility of the authors' papers, and the use of indexed keywords frequently produces highly comprehensive results for the visualization of the information in the paper (Bonaccorsi, 2008; Vargas-Quesada et al., 2017; J. Zhang et al., 2016). In addition, it is essential to eliminate keywords with a low frequency of occurrence in order to achieve the best possible visualization of relevant keywords. The minimum number of documents was set to ten, and synonymous keywords were merged using the Thesaurus file, such as alga and algae becoming alga.

The results of this visualization of the co-word analysis are shown in Figure 6, which represents the period between 1973 and 2013 (Figure 6A) and 2014 and 2023 (Figure 6B). The distance that separates nodes is a representation of the relationship that exists between terms. The greater the size of the node, the greater the frequency with which the keyword appears, and vice versa. On the other hand, the color of the node is utilized to categorize each keyword into a specific cluster. Out of a total of 7859 terms, 321 keywords meet the threshold criterion between 1973 and 2013. These keywords were then further narrowed down to 235 by using the Thesaurus file. The overall number of clusters that were found was five, and the total link strength was as high as 4466.5. There were a total of 12124 linkages discovered, which is a significantly high number. Within the most recent span (2014-2023), a total of 8450 keywords were found; however, only 319 keywords adequately meet the criteria. Through the process of thesaurus merger, the number of keywords was reduced even further, reaching 232. The keywords integrated with the Thesaurus file are accessible in S3 Appendix. Additionally, a total of four clusters were discovered, each of which had a total link strength of 4145 and a total link number of 14034. The findings of this study indicate that there may have been a reduction

in the scope of research topics, which led to the elimination or consolidation of one or more themes that were often discussed between the years 1873 and 2013. Furthermore, subject saturation was seen through the disproportionate increase in connection density compared to keyword variety, indicating heightened intra-cluster connectedness without the development of new theme lines.

The list of keywords, clusters, and differences in themes derived from the clusters from two different time periods is presented in S4 Appendix. Notwithstanding the disparity in the number of clusters, the principal themes of the two timestamps were comparable, and the frequency of the terms was surprisingly the same. The themes "Diatom Ecology and Biogeography" and "Diversity and Ecology of Algal and Cyanobacterial Communities" from 1873-2013 are also present in 2014-2023, consolidated into a cluster addressing "Diatom Diversity and Biogeography in Marine and Freshwater Ecosystems." Diatoms are a category of microalgae that serve as important indicators of environmental conditions, especially in aquatic ecosystems. This area primarily addresses diatom species and taxonomy, ecological indicators, habitats and geographical distribution, environmental and ecological aspects, research methodologies and analyses, specialized habitats, and historical and geological settings.

The theme of marine biofouling and antifouling technology is evident throughout both study periods. This issue is essential for preserving the efficacy and durability of marine buildings and vessels, as well as safeguarding marine ecosystems from the detrimental effects of biofouling (Ali et al., 2021; Benda *et al*., 2021).

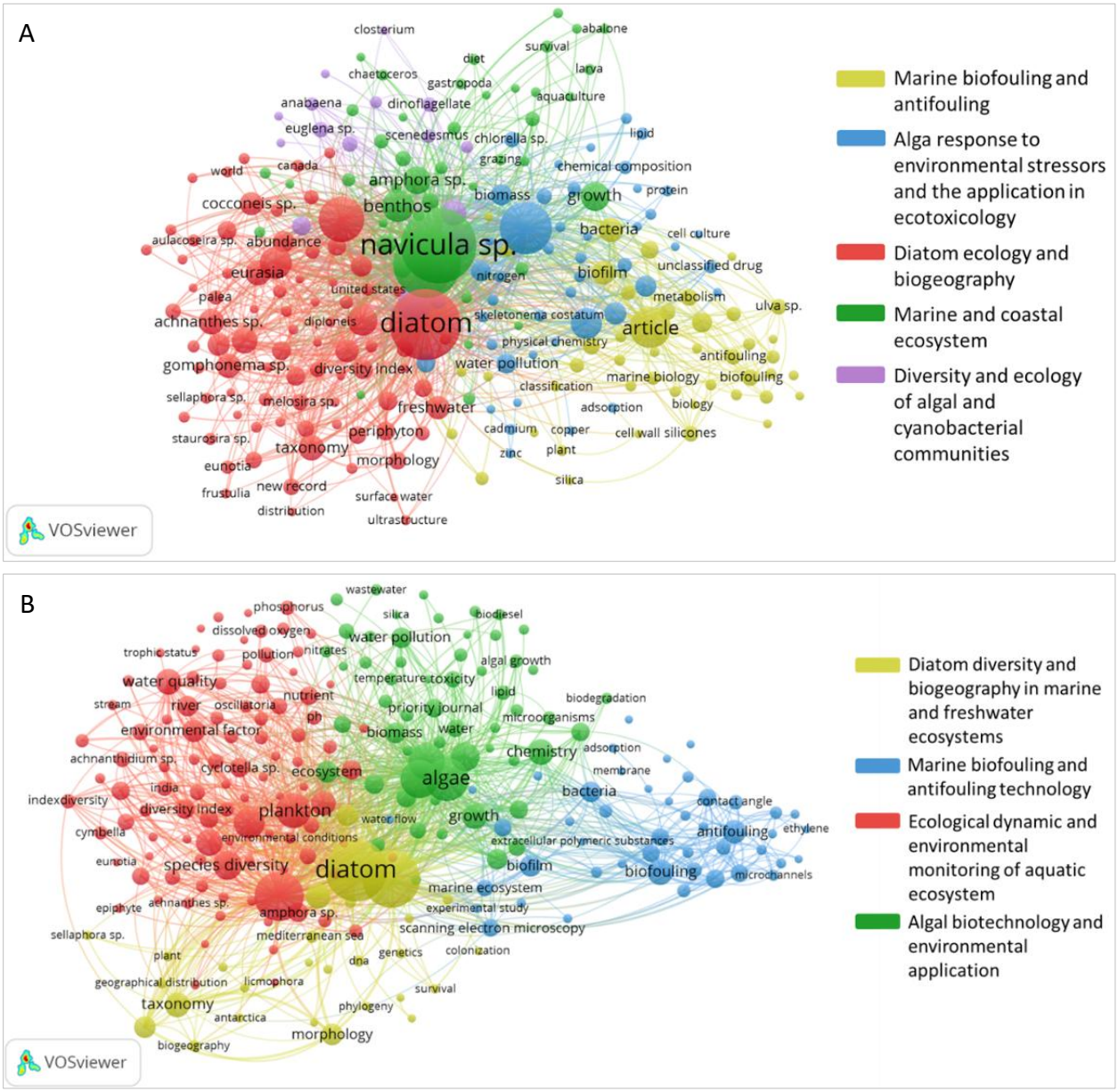

Figure 6. The co-word analysis for the years 1973–2013 [A] and 2014–2023 [B] (Distinct clusters are designated with varying colors, while the label size is proportional to keyword co-occurrences.).

Navicula is esteemed as a model organism in biofilm and surface-interaction research owing to its distinctive biological and ecological traits. A significant characteristic is its adhesion mechanism, which depends on the secretion of extracellular polymeric substances (EPS). These EPS are essential for adhering to diverse substrates (Tong et al., 2022), enabling *Navicula* to efficiently colonize surfaces in aquatic habitats. EPS are intricate combinations of polysaccharides, proteins, and other biopolymers excreted by microalgae such as *Navicula*, facilitating microalgae adhesion by providing chemical groups that adhere to cell surfaces, augmenting surface roughness, thereby improving mechanical interlocking, and forming a hydrophilic, adhesive layer that resembles natural biofilm environments (Tong & Derek, 2023). Moreover, its capacity to generate and regulate EPS is crucial for comprehending biofouling and heavy metal remediation processes. Elleuch et al., 2025 reported that the EPS produced by *Navicula salinicola* can bind and remove lead (Pb^{2+}) from aqueous solutions with an adsorption capacity of 2211.029 mg/g, indicating significant potential for EPS as a natural biosorbent in wastewater treatment. (Elleuch *et al*., 2025). Combined with its rapid growth, ease of cultivation, and well-characterized cellular structure, Navicula serves as an ideal model for investigating diatom-surface interactions, anti-fouling material testing, heavy metal remediation, and ecological biofilm dynamics.

The themes of algal responses to environmental stressors and their applications in ecotoxicology exhibited identical keywords to those of "Ecological Dynamics and Environmental Monitoring of Aquatic Ecosystems" from 2014 to 2023. This study investigates the function of algae as bioindicators, essential in ecotoxicological research for assessing and monitoring the health of aquatic ecosystems. The physiological and biochemical responses of algae to various stimuli provide insights into their potential applications in bioremediation and environmental management (Mobin *et al*., 2022). This demonstrates that the issue of water body contamination remains prevalent and is a significant focus of research, especially in employing *Navicula* as a bioindicator for environmental monitoring.

Cluster 2 on 1873-2013, however, has distinct keywords and themes of research compared to the other clusters on the different timestamps. The presence of diverse species, including abalone, *Amphora* sp., *Chaetoceros* sp., copepods, crustaceans, gastropods, and zooplankton, underscores a concentration on marine biodiversity. Furthermore, terms such as aquaculture, abalone, and *Haliotis corrugata* indicate the cultivation and rearing of marine creatures, which is essential for sustainable seafood production. This subject is supplanted with a more particular focus emphasizing *Navicula* in biotechnology and its application in addressing environmental issues (Cluster 2 in timeframe 2014-2023)

Co-Citation Analysis

Co-citation is a method utilized to evaluate the correlation between papers based on the frequency of their simultaneous citation by other works. This scientific mapping technique seeks to clarify the intellectual structure of foundational texts (Öztürk *et al*., 2024). A minimum citation requirement of 20 is set for each referenced work to identify the most relevant foundational research, with 4 and 8 sources satisfying this criterion for the periods 1873-2013 and 2014-2023, respectively. Upon closer investigation, there are two duplicates of similar articles or books, arising from the differing citation forms. Table 6 summarizes the ten seminal articles or books pertinent to the *Navicula* study domain, highlighting their significance, relevance, and principal results relating to the subject matter.

Among the 10 documents that satisfy the criteria, 3 are the most frequently cited in publications published between 1873 and 2013. The three documents are publications from the 1900s. These volumes provide a thorough introduction to diatoms, elucidating their biology, ecology, and historical research. The discussion also encompasses phenomena associated with algae, including rhythmic behavior, nitrogen fixation, and environmental implications. Furthermore, the book authored by Shannon et al. (1949) elucidates that the idea of entropy can be employed to quantify variety in ecological research.

During the period from 2014 to 2023, there are a total of seven documents that match the citation threshold and are the most referenced in published articles. These documents comprise essays and certain books. These foundational works, referenced from original and review papers, primarily address biofouling and strategies for creating environmentally sustainable anti-fouling solutions. Moreover, Schultz et al. (2011) investigated the influence of biofouling from various organisms on escalating fuel consumption expenditures. This discovery is noteworthy since it serves as a benchmark for determining the reasonable expenditure of funds (Schultz et al., 2011). This finding signifies a transition in foundational studies from book-based sources to papers addressing the issue of biofouling. Simultaneously, the publication by Hasle et al. (1997) functions as a reference for the identification of marine diatoms and dinoflagellates (Hasle et al., 1997). The book by Round et al. (1990) is unexpectedly considered important in two contexts, emphasizing broader themes in biology, ecology, and historical research, such as the structure of diatom cells (Round et al., 1990).

Discussion

Research regarding the use of microalgae has increased in recent years. Microalgae are an interesting topic for extensive study because of their ecological function in marine and freshwater environments and their possible use as a source of feed, food, cosmetics,

Table 6. Foundational Works Related to Navicula Research Theme

1873-2013					
Title	Author (Year)	Publisher	Type	Description or Key Findings	Ref
The Diatoms: Biology and Morphology of the Genera	F.E. Round, R.M. Crawford & D.G. Mann (1990)	Cambridge University Press	Book	The book encompasses several key points, including a comprehensive introduction to diatoms, detailing their biology, ecology, and historical studies; the structure of diatom cells, addressing the cell wall, cellular contents, and facets of the life cycle and cell division; and an extensive classification of diatoms, featuring illustrated descriptions of over 250 genus.	(Round *et al*., 1990)
The Ecology of Algae	F.E. Round (1981)	CUP Archive	Book	This book offers a comprehensive examination of the various habitats and ecological roles of algae. The book covers various critical subjects, including an overview of algal ecosystems, phenomena associated with algae such as rhythmic behavior, nitrogen fixation, and buoyancy, ecological interactions, symbiotic connections, and environmental effects.	(Round, 1981)
The Mathematical Theory of Communication	Claude E. Shannon and Warren Weaver (1949)	University of Illinois Press	Book	This book serves as a fundamental framework for comprehending information transmission, applicable across several scientific disciplines. Shannon's entropy notion is employed to quantify variety in ecological research. In Navicula research, entropy is utilized to evaluate the variety and abundance of diatom species across various habitats, offering insights into ecosystem health and stability.	(Shannon & Weaver, 1998)
2014-2023					
Title	Author (Year)	Publisher	Type	Description or Key Findings	Ref
Trends in the Development of Environmentally Friendly Fouling-resistant Marine Coatings	James A. Callow & Maureen E. Callow (2011)	Nature Communications	Review Article	The creation of eco-friendly coatings devoid of biocides can be conducted depending on the physicochemical and material characteristics of the coating. Advancements in nanotechnology and polymer science have created potential to develop novel binding systems that are more efficient in mitigating biofouling.	(Callow & Callow, 2011)
Adhesion and Motility of Fouling Diatoms on a Silicone Elastomer, Biofouling	R Holland, T M Dugdale, R Wetherbee, A. B. Brennan, J. A. Finlay, James A. Callow, Maureen E. Callow (2004)	Biofouling	Original Article	The motility of diatoms (Craspedostouros, Amphora, and Navicula) is not correlated with adhesion strength, so it does not function as a reliable predictor of surface preference among diatoms.	(Holland *et al*., 2004)
Fouling Release Coatings: a Nontoxic Alternative to Biocidal Antifouling Coatings	Marlène Lejars, André Margaillan, Christine Bressy (2012)	Chemical Reviews	Review Article	The principal methods for biocide-based coatings that prevent fouling include the discharge of biocidal substances into the marine environment and the application of non-toxic fouling-release coatings. Considering its antifouling efficacy, which relies on minimal adhesion strength and the facile detachment of fouling organisms from the layer.	(Lejars *et al*., 2012)
The Biology of Biofouling Diatoms and Their Role in the Development of Microbial Slimes, Biofouling	Paul J Molino, Richard Wetherbee (2008)	Biofouling	Review Article	Research on the development of diatom slime on antifouling (AF) and fouling-release (FR) surfaces has primarily aimed at understanding the initial adhesion processes to the substratum. This includes examining the morphology and biochemistry of adhesion structures, the mechanical properties of adhesives, and the adhesion strength of entire cells to various surface chemistries.	(Molino & Wetherbee, 2008)
The Diatoms. Biology and Morphology of the Genera	F.E. Round, R.M. Crawford & D.G. Mann (1990)	Cambridge University Press	Book	The book encompasses several key points, including a comprehensive introduction to diatoms, detailing their biology, ecology, and historical studies; the structure of diatom cells, addressing the cell wall, cellular contents, and facets of the life cycle and cell division; and an extensive classification of diatoms, featuring illustrated descriptions of over 250 genera.	(Round *et al*., 1990)
Economic Impact of Biofouling on a Naval Surface Ship	M P Schultz, J A Bendick, E R Holm, W M Hertel (2011)	Biofouling	Original Article	The main increase in costs due to hull fouling is due to increased fuel consumption due to increased frictional resistance due to fouling. Increased fouling increases fuel consumption by 10.3% and fuel costs by approximately $1.15 million per ship per year.	(Schultz *et al*., 2011)
Identifying Marine Phytoplankton	Grethe R. Hasle, Erik E. Syvertsen, Karen A. Stedinger, Karl Tangen, Jahn Throndsen, Berit R. Heimdal (1997)	Academic Press	Book	This book serves as a definitive reference for the identification of marine diatoms and dinoflagellates.	(Hasle *et al*., 1997)

biofuels, nanomaterials, and medicines (Spolaore et al., 2006). Since the 1950s, when a microalgae growth system that allows for laboratory and industrial scale production was first developed, research on microalgae has increasingly developed in western countries (Oswald et al., 1957; Rumin et al., 2020). Microalgae are microscopic photosynthetic organisms that have a fast growth time and contain various active compounds. To date, approximately 72,500 species of microalgae have been discovered, and approximately 30,000 have been identified (Guiry, 2012). The diversity of microalgae makes it a potential source for producing various chemical products that can be applied in the nutrition, cosmetics, pharmaceutical, and medicine industries (Kurnia, 2020). The widespread diversity of microalgae has made researchers increasingly interested in conducting further research regarding the use of microalgae.

We have analyzed the study on the prominent microalga, *Navicula* sp., by comparing the research trends across two time periods: the recent decade and the years from 1873 to 2013. The volume of publications has escalated exponentially from 1964 to 2013, indicating a substantial increase in the production of new publications over time. This exponential phase, however, ceases, and the publication is increasing linearly over the current period from 2014 to 2023. This phenomenon indicates that the *Navicula* study issue has garnered interest; yet, although the number of publications continues to rise, it cannot sustain its exponential growth pattern (Figure 2A and Figure 2B). Most relevant sources (Table 2) and affiliations (Figure 3A and Figure 3B) also change when the two timestamps are compared. The examination of the author's collaboration network at two distinct timestamps (Figure 4A and Figure 4B) reveals a significant collaboration pattern, as demonstrated by the rise in the number of the largest connected authors, and indicates improved consistency in their thematic focus, evidenced by the reduced presence of solitary authors within a cluster. International collaboration among nations has progressed markedly in the past decade compared to the period from 1873 to 2013, as seen by the increase in the number of countries, total links, and total link strength when analyzing co-country networks (Figure 5A and Figure 5B).

From 1873 to 2013, the predominant focus of globally cited articles was the ecological circumstances of diatoms, particularly *Navicula*, which exhibit tolerance to harsh environments, such as elevated temperatures, high turbidity, and low oxygen levels. In several ways, this discovery could help achieve the SDGs. For example, in point 13 on Climate Action, investigating the resilience of diatoms like *Navicula* to extreme environmental circumstances helps to elucidate the effects of climate change on aquatic ecosystems and inform adaptation measures. *Navicula* acts as a bioindicator of changes in the aquatic environment, providing critical insights for the protection and management of marine resources, thereby facilitating the attainment of Sustainable Development Goal 14: Life Below Water (Purba & Ariesyady, 2022). Through certain mechanisms, *Navicula* can break down organic pollutants such as phenol (Elhamji et al., 2023) and some pharmaceutical waste (Ding et al., 2017, 2019, 2020). Furthermore, research on *Navicula* can contribute to water quality management and technological advancements to guarantee access to clean water, aligning with point 6 of the SDGs.

Simultaneously, biofouling has persisted as a key issue across both periods, underscoring its continual relevance and importance as a research domain. Approximately 5 of the 20 studies from both periods, which address the topic, receive worldwide citations. Biofouling constantly appears as a keyword in both times depicted in Figure 6, with other results indicating that research on biofouling continues to persist until today. This is also supported by the results of the examination of the most cited documents. Table 6 further reveals that five out of the seven fundamental research studies concentrated on investigating biofouling and antibiofouling technologies. This conclusion implies a regular, if not trending, approach to the biofouling research issue, which makes it eligible for incorporation into the foundational research's intellectual framework. Culturing *Navicula* species, however, presents notable technical challenges that can limit their broader application and experimental reproducibility. As benthic diatoms, *Navicula* strains are often sensitive to light, salinity, pH, and nutrient fluctuations, and require specific growth media enriched with silica and trace metals (Telussa & Rahayu, 2022).

This study's results, in addition, possess certain limitations. Initially, we evaluated the bibliographic characteristics only using the Scopus database. Examining multiple databases, like Google Scholar and Web of Science, may lead to varying results. Secondly, we solely chose articles composed in English and restricted to particular timestamps. Investigating varying ranges of timestamps or languages may result in a different outcome. Thirdly, in the current analysis, the co-citation network is only based on publications. Employing an alternative unit of analysis for network design could yield more diverse results. Finally, enhancing the keywords utilized in the literature search by incorporating prevalent terms such as “diatom” or “Bacillariophyceae” can expand the search and encompass more pertinent publications. A more stringent article exclusion screening is necessary, as common phrases may result in a broader array of unrelated articles to the study's topic.

Conclusion

A shift in trend has emerged about this topic, focusing on broadening the applications of *Navicula* by the decade's conclusion. Co-authorship and

international collaboration have markedly progressed in the last decade relative to the period from 1873 to 2013, evidenced by the increase in the number of countries, total connections, and overall link strength within co-country networks. Keyword clustering indicates that the research theme persists consistently across both study eras, including biofouling, ecological, environmental, ecotoxicological, and taxonomical studies. Biofouling consistently emerges as a prominent term in both temporal and foundational research focused on the examination of biofouling and antibiofouling technology. Regarding the frequently examined topics from these two timeframes, research on biofouling continues to be predominant, but studies on marine ecosystems have not surfaced in the past decade.

While *Navicula* is predominantly utilised negatively as a model in biofouling research, it also generates diverse chemical compounds applicable in the nutrition, cosmetics, pharmaceutical, bioremediation, and medical sectors. The versatility and extensive cellular divisions can result in swift population growth, establishing it as a viable resource for future research initiatives.

Ethical Statement

No animals were utilized in the composition of this manuscript.

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Author Contribution

Conceptualization: ARAM, DF; Data Curation: ARAM, DF; Formal Analysis: ARAM, DF; Funding Acquisition: ARAM; Methodology: ARAM; Project Administration: ARAM; Resources: DF; Software: DF; Supervision : RM, EPS; Validation: RM, EPS; Visualization : ARAM, DF, EPS; Writing – Original Draft Preparation: ARAM, DF, RM EPS.

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose

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