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Review article

A bibliometric analysis of cellulose anti-fouling in marine environments

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A B S T R A C T

Marine biofouling poses significant challenges to maritime industries worldwide, affecting vessel performance, fuel efficiency, and environmental sustainability. These challenges demand innovative and sustainable solutions. In this review, the evolving landscape of cellulose-based materials for anti-fouling applications in marine environments is explored. Through a comprehensive bibliometric analysis, the current state of research is examined, highlighting key trends, emerging technologies, and geographical distributions. Cellulose, derived from renewable resources, offers a promising avenue for sustainable anti-fouling strategies due to its biodegradability, low toxicity, and resistance to microbial attachment. Recent advancements in cellulose-based membranes, coatings, and composites are discussed, showcasing their efficacy in mitigating biofouling while minimizing environmental impact. Opportunities for interdisciplinary collaboration and innovation are identified to drive the development of next-generation anti-fouling solutions. By harnessing the power of cellulose, progress towards cleaner, more sustainable oceans can be facilitated, fostering marine ecosystems and supporting global maritime industries.

1. Introduction

Biofouling, the accumulation of marine organisms on ship hulls, has widespread consequences for the maritime industry, extending beyond just maintenance challenges. Research by Davidson et al. [1] highlights the environmental and economic impacts. Adland et al. [2] note that biofouling leads to increased fuel consumption, affecting overall vessel efficiency. For instance, substantial calcareous fouling can surge shaft power by up to 86 % during cruising, resulting in a significant 10–20 % rise in fuel consumption [3]. Calcareous fouling refers to the accumulation of calcium carbonate-based deposits on submerged surfaces in aquatic environments [4]. These deposits are primarily composed of calcium carbonate minerals, such as calcite and aragonite, which precipitate out of seawater onto submerged structures. Calcareous fouling is a common form of marine biofouling and is caused by the attachment and growth of

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organisms such as barnacles, mollusks, and corals on underwater surfaces [5].

The effects of biofouling on ship performance include increased drag, speed loss, and higher frictional resistance. Computational Fluid Dynamics studies by Song et al. [6] on containerships show up to a 93 % rise in frictional resistance due to barnacle fouling. Biofilm presence leads to a substantial 36.3% increase in delivered power [7], highlighting the nuanced impacts of biofouling on fuel consumption and vessel performance. This is evident in reported speed losses of 1.5–2 knots after six months and increased power requirements post-drydocking [8]. Biofouling not only affects operations but also has environmental consequences. Kinnaman [9] emphasizes its role in contributing to climate change, especially as the shipping industry accounts for 2.89 % of greenhouse gas emissions (Y. [10]). Heightened fuel consumption due to biofouling contributes to air pollutants and greenhouse gas emissions, aligning with global efforts to regulate shipping emissions [11].

The challenges of biofouling are compounded by the environmental impacts of hull treatment processes. Woods et al. [12] highlight issues such as blasting, paint residue, and wastewater, emphasizing the environmental and health risks. Routine underwater cleaning, as observed by Hua et al. [13], poses potential hazards. Additionally, a poorly maintained hull increases the risk of structural corrosion (Hellio et al., 2009), with microbiologically influenced corrosion and marine biofouling being principal contributors (Y. Li et al., 2019).

The maritime industry faces complex challenges from the intricate connections between biofouling, fuel consumption, environmental impact, and hull maintenance. To tackle these issues effectively, a comprehensive and holistic approach is required. This approach should encompass technological advancements, regulatory frameworks, and sustainable practices, guiding the maritime sector towards cleaner, more efficient, and environmentally responsible operations. At the heart of these challenges lies biofouling, the accumulation of marine organisms on ship hulls, presenting a significant hurdle for an industry vital to global trade and transportation. Traditional anti-fouling methods, often relying on environmentally harmful biocides, have prompted a quest for innovative, sustainable, and eco-friendly solutions [14]. This paper presents a thorough bibliographic review, navigating through the currents of contemporary research, to shed light on the evolving landscape of modern anti-fouling technologies for maritime vessels.

As the environmental impact of traditional anti-fouling practices becomes increasingly apparent, the focus of researchers, industry professionals, and policymakers has shifted towards innovative approaches that effectively combat fouling while aligning with broader sustainability goals [15]. From bio-inspired coatings and natural biocides to the integration of nanotechnology and the exploration of eco-friendly alternatives [16], this review aims to comprehensively explore the diverse strategies leading the forefront of anti-fouling innovation. Against the backdrop of historical perspectives and current ecological challenges, we navigate through the latest trends shaping the industry. Drawing upon the synthesis of numerous scholarly works, research articles, and industry reports, this review serves as a compass, guiding us through the intricacies of these emerging technologies. With a discerning focus on efficacy, durability, and environmental considerations, this review strives to provide valuable insights for those charting a course toward clean and sustainable maritime practices.

The selection of cellulose as a key player in marine anti-fouling strategies stems from its inherent properties and versatile characteristics that uniquely position it as a sustainable and effective solution [17]. Cellulose, a natural polymer abundant in plant cell walls, offers several advantages in the context of combating fouling in marine environments [18]. One of its primary attributes is its biocompatibility, ensuring minimal environmental impact compared to traditional anti-fouling agents. The biodegradability of cellulose further aligns with the growing emphasis on eco-friendly practices, making it an attractive choice for applications in sensitive marine ecosystems [19].

Cellulose's chemical structure and hydrophilic nature create an inhospitable environment for the attachment and growth of fouling organisms [20]. This inherent resistance to biofouling contributes to the longevity of anti-fouling coatings and materials, reducing the need for frequent maintenance and replacement [21]. Moreover, cellulose-based materials can be readily modified and engineered to enhance their anti-fouling properties, allowing for a tailored approach to address specific challenges presented by different marine environments [22].

The sustainable sourcing of cellulose, often derived from renewable plant-based feedstocks, adds an additional layer of environmental responsibility to anti-fouling strategies [23]. As the world seeks alternatives to traditional, environmentally detrimental anti-fouling agents, cellulose stands out as a biocompatible, renewable resource with the potential to revolutionize marine surface protection [24]. The subsequent sections of this review will delve deeper into the diverse applications of cellulose in anti-fouling coatings, exploring the mechanisms that make it an increasingly preferred choice for sustainable marine solutions.

Utilizing bibliometric analysis as a robust instrument for assessing scientific productivity and impact [25], the extensive literature on cellulose for anti-fouling techniques for maritime applications, particularly those employing modern and environmentally sustainable methods, is thoroughly examined in this study. By dissecting publication trends, identifying prolific authors, scrutinizing influential journals, and exploring emerging research themes, the objective is to offer a nuanced portrayal of the evolutionary trajectory within this field [26]. The geographical distribution of research output, the establishment of critical collaborations, and the identification of pivotal documents further contribute to delineating the global research landscape in cellulose anti-fouling for maritime with a focus on modern and green techniques. Ultimately, a valuable resource catering to the needs of researchers, practitioners, and policymakers is aspired to be provided by this review, offering insights into the advancements and future directions of cellulose anti-fouling practices for maritime employing modern and environmentally sustainable methodologies.

Therefore, various technologies employed for anti-fouling techniques for maritime applications involving cellulose are explored by this paper. The subsequent sections outline the structure of the paper. The "Methodology" section, which encompasses data collection and search techniques, is explicated. The "Data Analysis and Visualization" section addresses data processing and visualization. The research findings are deliberated upon in the "Discussion" section. The "Conclusion" section summarizes the outcomes, highlights limitations, and recommends future studies.

2. Methodology

In conducting this study, the utilization of abstract and citation database SCOPUS, renowned for its comprehensive coverage of peer-reviewed studies pertinent to our investigation, was chosen. The selection of SCOPUS as our primary platform ensured the incorporation of the most relevant and recent scholarly articles related to our research focus. Employing a meticulous search strategy, a specific search string, ("Cellulose") AND ("Anti Fouling") AND (Water), was crafted following a series of tests to maximize the relevance of the identified studies. Notably, to capture the latest developments in the field, papers released in 2023 were included, reflecting the most recent advancements, given that the data retrieval was conducted in December 2023. To enhance the precision of our dataset, papers written in languages other than English were excluded, resulting in a curated collection of 157 documents. To unravel the intricate patterns within this extensive dataset, the capabilities of SCOPUS and VOSviewer software were harnessed for bibliometric mapping and visualizations [27].

The limitations of our study are primarily rooted in the methods and scope that were employed. Firstly, reliance on existing literature and bibliometric analysis means that the latest developments and emerging trends in the field of cellulose-based anti-fouling materials may have been missed out on. This limitation is compounded by the fact that not every relevant study or approach may have been covered in our review, potentially resulting in valuable insights or alternative perspectives being overlooked, contributing to a more comprehensive understanding of the topic.

Secondly, the quality and availability of data varied across different sources, which may have introduced biases or gaps in our analysis. Certain regions or research contexts may have been overrepresented or underrepresented in the literature that was reviewed, affecting the generalizability of our findings. Additionally, the geographical coverage of our study may have been limited, which could have skewed our results towards certain regions and neglected others, thereby hindering the applicability of our conclusions on a global scale.

Lastly, the focus of our study was specifically on cellulose-based materials for anti-fouling applications, which means that other promising strategies or materials in this domain may have been overlooked. Alternative anti-fouling approaches that were not within the scope of our review could offer valuable insights and innovations that could complement or challenge the efficacy of cellulose-based solutions. Recognizing these limitations is crucial for ensuring the transparency and credibility of our study's findings and conclusions.

3. Data analysis and visualization

Table 1 provides a comprehensive overview of bibliographic statistics related to cellulose anti-fouling, offering valuable insights into the research landscape within this domain. Over the period spanning 2000 to 2023, a total of 157 documents have been identified, showcasing the prolific output and scholarly engagement in this area. The collaborative nature of this field is evident in the involvement of 776 authors, resulting in an average of approximately 494 authors per document, reflecting a rich diversity of perspectives and expertise.

In terms of scholarly impact, the documents have received an average of 30.29 citations each, underlining the significance and influence of the research conducted in cellulose anti-fouling. The extensive referencing network is further highlighted by the inclusion of 4757 references across the documents, emphasizing the depth of literature integration in this research domain. The document types encompass a variety of scholarly contributions, with the majority being articles (143), indicating a strong emphasis on original research. Additionally, there are 8 reviews, 4 conference papers, 1 book chapter, and 1 erratum, illustrating the diverse range of academic outputs contributing to the cellulose anti-fouling literature. This comprehensive statistical overview serves as a foundation for understanding the scholarly landscape and the dynamics of cellulose-based anti-fouling research over the specified time period.

Fig. 1 illustrates the yearly output of scholarly publications pertaining to cellulose anti-fouling over a specified period. The graph provides a visual representation of the annual trends in research output within this specific field. By tracking the number of publications per year, the figure offers valuable insights into the evolving interest and activity levels of researchers and scholars in the cellulose anti-fouling domain. Peaks and troughs in the graph can indicate periods of heightened research activity, emerging trends, or

Table 1
Overview of bibliographic statistics for cellulose anti-fouling.

Description	Results
Documents	157
Period	2000:2023
Authors	776
Authors per document	494
Average citations per documents	30.29
References	4757
Document types	
Article	143
Review	8
Conference Paper	4
Book Chapter	1
Erratum	1

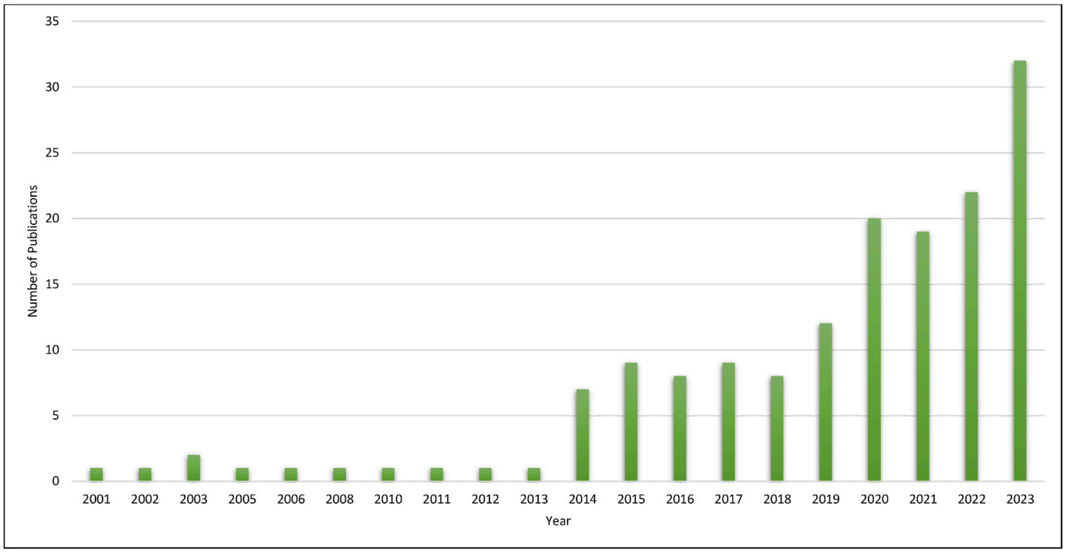

Fig. 1. Yearly output of scholarly publications related cellulose anti-fouling.

shifts in focus over the years, providing a dynamic perspective on the trajectory of scholarly contributions in this area. Overall, Fig. 1 serves as a visual tool to comprehend the temporal distribution and progression of cellulose anti-fouling research.

The provided data presents the yearly output of scholarly publications related to cellulose anti-fouling. In 2023, there were 32 publications, marking a significant increase from the previous year. The years 2020 and 2021 also show substantial research output with 20 and 19 publications, respectively. The trend indicates a noticeable rise in scholarly activity in recent years.

In the earlier part of the observed period, there is a relatively modest number of publications per year. The years 2013, 2012, 2011, 2010, 2008, 2006, 2005, and 2002 each have one publication, indicating a lower level of research output during those specific years. It is noteworthy that there is a considerable gap in the dataset from 2004 to 2009, with no recorded publications during that period. The data further highlights an overall increase in research interest and output from 2010 onwards, with a more noticeable surge in recent years. This temporal distribution provides a clear depiction of the dynamic nature of scholarly contributions in the field of cellulose anti-fouling over the specified timeframe.

The spike in 2022 and 2023 could indicate a maturing field where accumulated knowledge and technological advancements have increased research output capacity. Furthermore, the urgency to address environmental challenges and the growing global commitment to sustainable maritime practices further fueled the expansion of studies focused on cellulose anti-fouling as green coating. In summary, the observed distribution in Fig. 1 likely results from a combination of factors, including a growing recognition of the

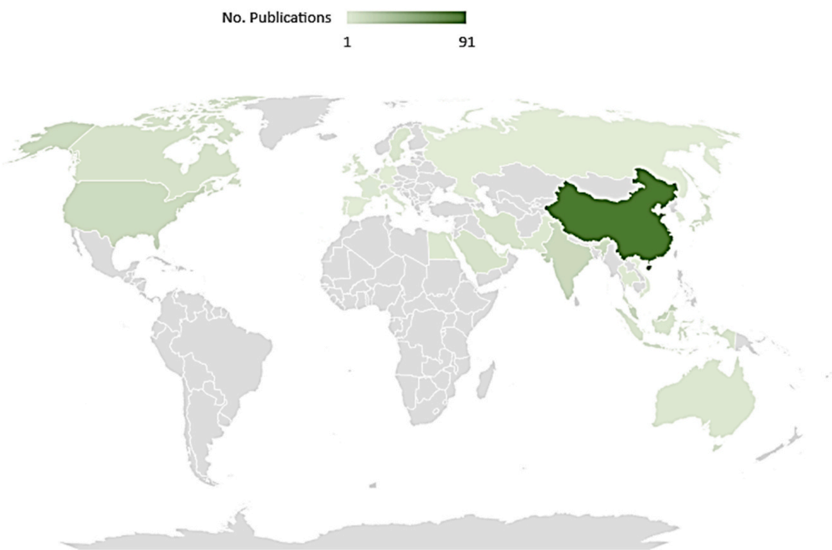

Fig. 2. The dispersion of publications across regions related anti-fouling for ships.

environmental impact of conventional anti-fouling, advancements in research methodologies and technology, increasing awareness and commitment to sustainability, and evolving regulatory landscapes.

Fig. 2 comprehensively depicts the worldwide distribution of scientific documents focused on ship anti-fouling, categorized by the affiliations of all contributing authors. Notably, the figure highlights China as a primary contributor, emphasizing a notable concentration of scholarly output in this country. The shades of green employed in the figure denote different productivity levels, creating a visual representation where each hue corresponds to a distinct intensity of research activity. Regions shaded in blue indicate an absence of articles, while darker shades signify high productivity.

The evaluation of countries' productivity is based on the quantity of academic papers originating from specific nations, focusing on the locations of corresponding authors. This method provides a nuanced perspective on the global landscape of cellulose anti-fouling, revealing varying degrees of engagement and output from different regions. Beyond the quantitative aspect of productivity, the figure underscores the importance of international collaboration and the diverse geographical origins contributing to the collective knowledge in the field. It visually emphasizes the collaborative and global nature of research efforts to advance understanding and solutions in anti-fouling practices for ships.

Table 2 presents a detailed ranking of the 20 most prolific nations contributing to the field of cellulose anti-fouling, as determined by the affiliations of corresponding authors. The ranking is based on the number of articles published by authors affiliated with institutions in each respective country. China claims the top position with a substantial contribution of 91 articles, underscoring its preeminent role in cellulose anti-fouling research. India follows closely in the second position with 14 articles, demonstrating a noteworthy presence in this research area. The United States secures the third position with 13 articles, indicating a significant research output in cellulose anti-fouling studies. Malaysia, Singapore, Canada, Iran, and Saudi Arabia also feature prominently among the top-ranking nations. This comprehensive overview provides insights into the global distribution of research efforts in cellulose anti-fouling, highlighting the substantial contributions made by diverse nations to advance knowledge and innovations in this critical field.

Table 3 compiles the 20 most highly cited documents in the realm of cellulose anti-fouling, offering a comprehensive view of authors, titles, publication years, source titles, total citation counts, and corresponding references. Among these, the top-cited document is "Nanocellulose-based materials for water purification" by Voisin, Bergström et al. [28] from the Nanomaterials journal, amassing a total citation count of 344. This work explores the application of nanocellulose in water purification, showcasing its significant impact on the scientific community. Another notable contribution is "Integration of microfiltration and visible-light-driven photocatalysis on g-C3N4 nanosheet/reduced graphene oxide membrane for enhanced water treatment" by Zhao et al. [29] with 196 citations. This research delves into the integration of advanced materials for efficient water treatment, attracting substantial attention from scholars.

Additionally, "Development and characterization of anti-fouling cellulose hollow fiber UF membranes for oil-water separation" by H.-J. Li, Cao et al. [30] holds the third position with 195 citations. This seminal work focuses on the development of anti-fouling cellulose membranes, making a noteworthy impact on the cellulose anti-fouling research landscape. The list underscores the diversity of topics, methodologies, and sources contributing to the cellulose anti-fouling literature, providing a valuable resource for researchers and practitioners seeking influential works in the field.

Fig. 3 provides a comprehensive overview of the top 10 journals with the highest citations in cellulose anti-fouling. Topping the list is the "Journal of Membrane Science" with an impressive 17 citations, underscoring its pivotal role and widespread referencing in cellulose anti-fouling research. The journal "Cellulose" closely follows with nine citations, affirming its substantial contributions to the discourse on anti-fouling techniques involving cellulose. "Separation and Purification Technology" secures the third position with seven citations, emphasizing its relevance in disseminating research on anti-fouling methodologies. Other notable journals in the top

Table 2
The 20 most prolific nations ranked by the affiliations of corresponding authors.

Rank	COUNTRY	Numbers of Article
1	China	91
2	India	14
3	United States	13
4	Malaysia	11
5	Singapore	8
6	Canada	7
7	Iran	7
8	Saudi Arabia	7
9	Indonesia	5
10	Sweden	5
11	Australia	4
12	Egypt	4
13	Japan	4
14	Pakistan	3
15	Thailand	3
16	United Kingdom	3
17	France	2
18	Qatar	2
19	United Arab Emirates	2
20	Belgium	1

Table 3
The 20 documents with the highest citation counts related cellulose anti-fouling.

Authors	Title	Year	Source title	Total Citation	Ref
Voisin H.; Bergström L.; Liu P.; Mathew A.P.	Nanocellulose-based materials for water purification	2017	Nanomaterials	344	[28]
Zhao H.; Chen S.; Quan X.; Yu H.; Zhao H.	Integration of microfiltration and visible-light-driven photocatalysis on g-C3N4 nanosheet/reduced graphene oxide membrane for enhanced water treatment	2016	Applied Catalysis B: Environmental	196	(H. [29])
Li H.-J.; Cao Y.-M.; Qin J.-J.; Jie X.-M.; Wang T.-H.; Liu J.-H.; Yuan Q.	Development and characterization of anti-fouling cellulose hollow fiber UF membranes for oil-water separation	2006	Journal of Membrane Science	195	(H.-J. [30])
Saleem H.; Zaidi S.J.	Nanoparticles in reverse osmosis membranes for desalination: A state of the art review	2020	Desalination	193	[31]
Goetz L.A.; Jalvo B.; Rosal R.; Mathew A.P.	Superhydrophilic anti-fouling electrospun cellulose acetate membranes coated with chitin nanocrystals for water filtration	2016	Journal of Membrane Science	176	[20]
Ye S.H.; Watanabe J.; Iwasaki Y.; Ishihara K.	Antifouling blood purification membrane composed of cellulose acetate and phospholipid polymer	2003	Biomaterials	135	[32]
Duong P.H.H.; Chung T.-S.; Wei S.; Irish L.	Highly permeable double-skinned forward osmosis membranes for anti-fouling in the emulsified oil-water separation process	2014	Environmental Science and Technology	133	[33]
Liu Y.; Tu W.; Chen M.; Ma L.; Yang B.; Liang Q.; Chen Y.	A mussel-induced method to fabricate reduced graphene oxide/halloysite nanotubes membranes for multifunctional applications in water purification and oil/water separation	2018	Chemical Engineering Journal	122	(Y. [34])
Yu S.; Chen Z.; Cheng Q.; Lü Z.; Liu M.; Gao C.	Application of thin-film composite hollow fiber membrane to submerged nanofiltration of anionic dye aqueous solutions	2012	Separation and Purification Technology	119	[35]
Akther N.; Phuntsho S.; Chen Y.; Ghaffour N.; Shon H.K.	Recent advances in nanomaterial-modified polyamide thin-film composite membranes for forward osmosis processes	2019	Journal of Membrane Science	115	[36]
Han G.; de Wit J.S.; Chung T.-S.	Water reclamation from emulsified oily wastewater via effective forward osmosis hollow fiber membranes under the PRO mode	2015	Water Research	108	(G. [37])
Koh J.J.; Lim G.J.H.; Zhou X.; Zhang X.; Ding J.; He C.	3D-Printed Anti-Fouling Cellulose Mesh for Highly Efficient Oil/Water Separation Applications	2019	ACS Applied Materials and Interfaces	101	[38]
Han B.; Zhang D.; Shao Z.; Kong L.; Lv S.	Preparation and characterization of cellulose acetate/ carboxymethyl cellulose acetate blend ultrafiltration membranes	2013	Desalination	99	(B. [39])
Liu Y.; Zhu M.; Chen M.; Ma L.; Yang B.; Li L.; Tu W.	A polydopamine-modified reduced graphene oxide (RGO)/ MOFs nanocomposite with fast rejection capacity for organic dye	2019	Chemical Engineering Journal	91	[40]
Hossein Razzaghi M.; Safekordi A.; Tavakolmoghadam M.; Rekabdar F.; Hemmati M.	Morphological and separation performance study of PVDF/ CA blend membranes	2014	Journal of Membrane Science	82	[41]
Li X.-L.; Zhu L.-P.; Zhu B.-K.; Xu Y.-Y.	High-flux and anti-fouling cellulose nanofiltration membranes prepared via phase inversion with ionic liquid as solvent	2011	Separation and Purification Technology	82	(X.-L. [42])
Wang Z.; Ma H.; Hsiao B.S.; Chu B.	Nanofibrous ultrafiltration membranes containing cross-linked poly(ethylene glycol) and cellulose nanofiber composite barrier layer	2014	Polymer	80	(Z. [43])
Li X.; Shan H.; Zhang W.; Li B.	3D printed robust superhydrophilic and underwater superoleophobic composite membrane for high efficient oil/water separation	2020	Separation and Purification Technology	78	(X. [44])
Norfarhana A.S.; Ilyas R.A.; Ngadi N.	A review of nanocellulose adsorptive membrane as multifunctional wastewater treatment	2022	Carbohydrate Polymers	73	[45]
Goetz L.A.; Naseri N.; Nair S.S.; Karim Z.; Mathew A.P.	All cellulose electrospun water purification membranes nanotextured using cellulose nanocrystals	2018	Cellulose	69	[46]
Zhijiang C.; Ping X.; Cong Z.; Tingting Z.; Jie G.; Kongyin Z.	Preparation and characterization of a bi-layered nano-filtration membrane from a chitosan hydrogel and bacterial cellulose nanofiber for dye removal	2018	Cellulose	67	[47]

10 include "Journal of Environmental Chemical Engineering," "Chemical Engineering Journal," "ACS Applied Materials and Interfaces," "Carbohydrate Polymers," "Desalination," "International Journal of Biological Macromolecules," and "Membranes," each contributing significantly to the scholarly discussions in cellulose anti-fouling. This figure illuminates the key journals that have played a central role in shaping and advancing research in this domain, offering valuable insights for researchers and practitioners alike.

Fig. 4 offers a perceptive depiction of authors' co-citations in cellulose anti-fouling. Notably, Zhang y. stands out prominently, having accumulated the highest number of citations, as the co-citation data analysis results revealed. This figure is a comprehensive representation, providing a nuanced perspective on collaborative networks and influential figures within the scholarly discourse on natural base anti-fouling. Fig. 4 offers a detailed depiction of the co-citation patterns among authors in the realm of natural base anti-fouling, employing a minimum citation threshold of 20 and revealing a total of 16032 links. This visualization delves into the

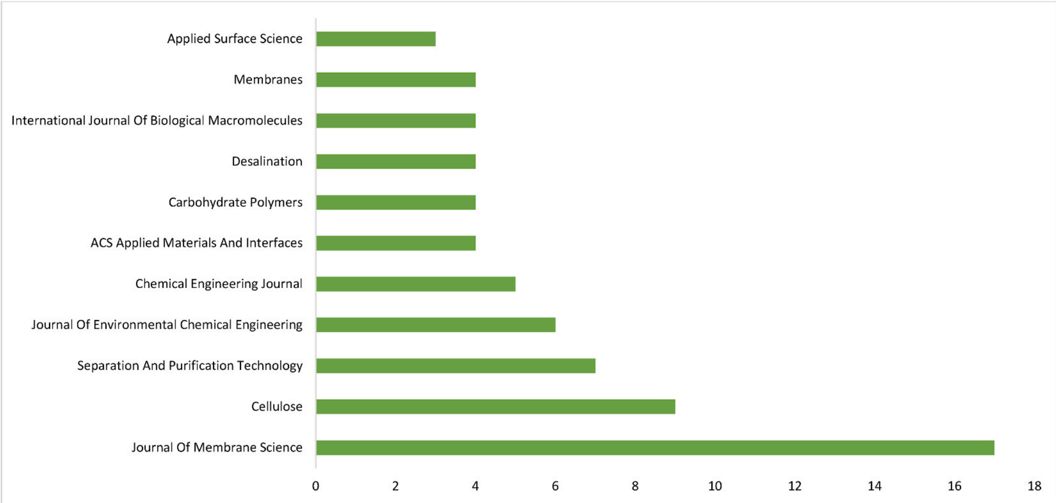

Fig. 3. The top 10 journals with the most citations related cellulose anti-fouling.

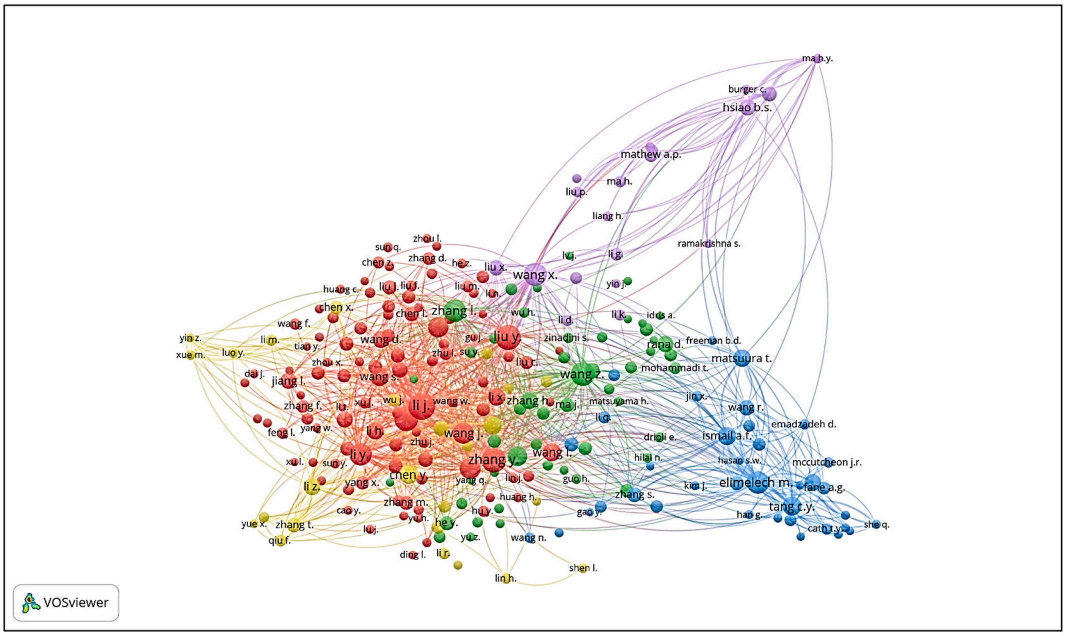

Fig. 4. Co-citation of authors: minimum citation threshold of 20 and16032 link.

collaborative relationships and shared citations among authors who have each garnered a minimum of 20 citations, ensuring that the focus is on scholars with a notable impact in the field. The links connecting these authors represent instances in the literature where they are co-cited, emphasizing the strength of their interconnected contributions and shared influence within the cellulose anti-fouling research domain. The substantial number of links, totaling 16032, underscores the intricate and extensive scholarly network that exists among these influential authors. This figure serves as a valuable tool for researchers, offering a visual roadmap of collaborative ties and the collective impact of key contributors in the field of cellulose anti-fouling.

Fig. 5 unveils the co-citation network of journals within the cellulose anti-fouling field, utilizing a minimum citation threshold of 20 and revealing 1297 links. This visual representation aims to spotlight journals that have garnered a minimum of 20 citations, emphasizing instances of co-citation and indicating shared influence and thematic connections in the scholarly discourse on natural anti-fouling. The selected minimum citation threshold ensures a focused analysis of journals with substantial impact, contributing to a more precise and insightful depiction of co-citation relationships among journals in this specific research domain.

Notably, specific journals, such as "Desalination" and "Journal of Membrane Science," emerge as central players with the highest rates of co-citation. This observation underscores their pivotal roles and widespread influence in shaping scholarly conversations about

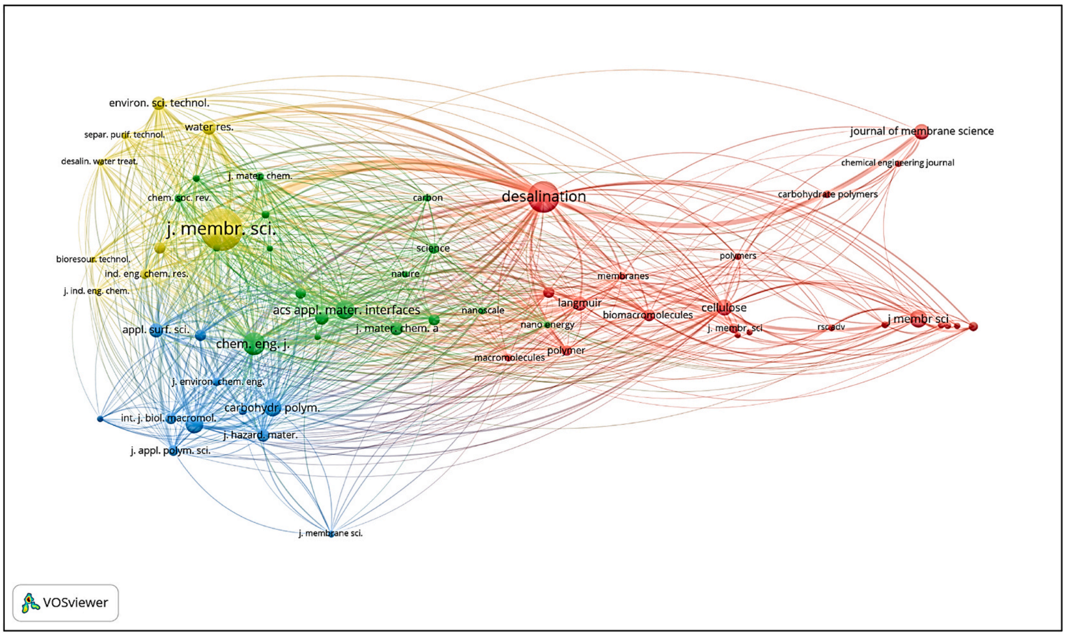

Fig. 5. Co-citation of journals: minimum citation threshold of 20 and 1297 links.

cellulose anti-fouling. The intricate network depicted in Fig. 5 serves as a comprehensive visual guide, offering researchers insights into the interwoven relationships and collaborative influences among journals. This visualization facilitates a deeper understanding of key players and thematic clusters in the anti-fouling literature.

Fig. 6 employs color-coded clusters to emphasize groups of articles with significant thematic or conceptual connections derived from bibliographic coupling. This facilitates the identification of cohesive themes and interconnected topics within natural anti-fouling literature. Setting a minimum citation threshold of 2 prioritizes articles with notable impact, refining the representation of bibliographic coupling relationships among highly cited articles. The 2137 links in the network highlight the interconnected nature of these influential articles, providing valuable insights into the cohesive literature landscape in this domain.

In Fig. 7, the bibliographic coupling of countries in the context of cellulose anti-fouling research is visually depicted. A minimum

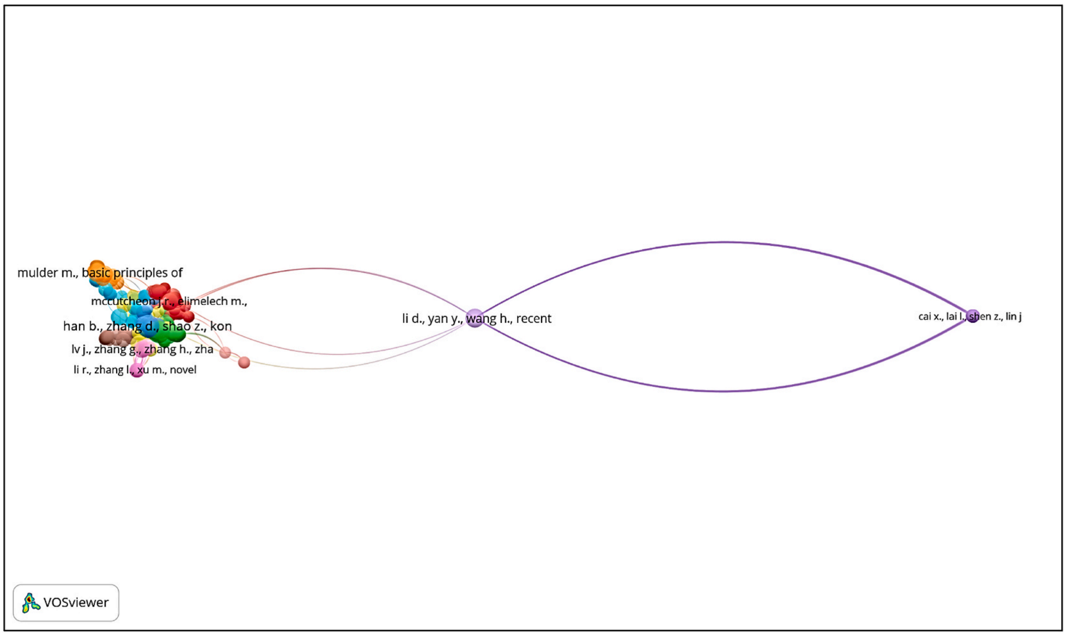

Fig. 6. Co-citation of references: threshold of 2 and 2137 link.

publication threshold of 3 documents was set, resulting in the inclusion of significant contributors to the field. The visualization showcases 98 links, representing the connections between countries based on their shared references and collaborations in research publications related to cellulose anti-fouling. Notably, China emerges as a prominent figure, represented by a large circle, indicating its substantial contribution to the scholarly discourse in this domain. The size of each circle correlates with the number of publications originating from the respective country, providing a visual representation of their research output in cellulose anti-fouling. This visualization offers insights into the collaborative networks and global distribution of research efforts aimed at addressing biofouling challenges using cellulose-based materials.

Fig. 8 offers a comprehensive network view map illustrating terms extracted from abstracts and titles of publications in natural anti-fouling research. Each circle represents a specific term, sized according to its frequency across publications. Lines between circles indicate connections between terms, with colors categorizing them into thematic clusters. The spatial arrangement reflects term relationships, with close proximity indicating strong associations. This visualization captures term diversity and thematic structure, highlighting key terms like "anti-fouling," "cellulose acetate," and "ultrafiltration." It serves as a valuable tool for researchers to explore literature themes intuitively.

Fig. 9 depicts a network view map generated by VOSviewer, showcasing four distinct clusters colored in red, green, yellow, and blue. Each cluster represents a thematic grouping based on the analysis of anti-fouling research. The red cluster is associated with surface properties relevant to anti-fouling mechanisms. In contrast, the yellow cluster focuses on the analysis of anti-fouling strategies and approaches. The blue cluster pertains to factors influencing anti-fouling effectiveness, such as environmental parameters or material characteristics. Lastly, the green cluster encompasses themes related to membranes, anti-fouling properties, and materials applicable in anti-fouling applications. This visualization aids in identifying cohesive themes and interconnected topics within the anti-fouling literature, offering insights into key areas of research focus and collaboration.

4. Discussions

Biofouling in maritime environments presents a multifaceted set of challenges that significantly impact various industries dependent on waterborne structures and vessels [48]. This phenomenon, characterized by the accumulation of marine organisms on submerged surfaces, poses several issues. One of the primary concerns is the escalation of drag and fuel consumption associated with the growth of biofouling on ship hulls and underwater components. This results in diminished fuel efficiency and increased operational costs as vessels experience heightened resistance in water [49]. Additionally, the accumulation of biofouling organisms can reduce the speed and overall performance of maritime vessels, particularly critical for industries requiring efficient and timely transportation [50]. The maintenance costs associated with the regular cleaning and removal of biofouling add further financial burdens, involving expenditures on labor, equipment, and downtime for maintenance [51].

Furthermore, biofouling contributes to corrosion and structural damage, as some marine organisms release acids that expedite the degradation of metal surfaces [52]. Beyond operational concerns, biofouling raises environmental issues, as antifouling coatings used for cleaning may contain biocides, impacting marine ecosystems and necessitating compliance with stringent regulations [53]. The spread of invasive species through biofouling organisms, coupled with the operational inefficiencies it introduces, underlines the

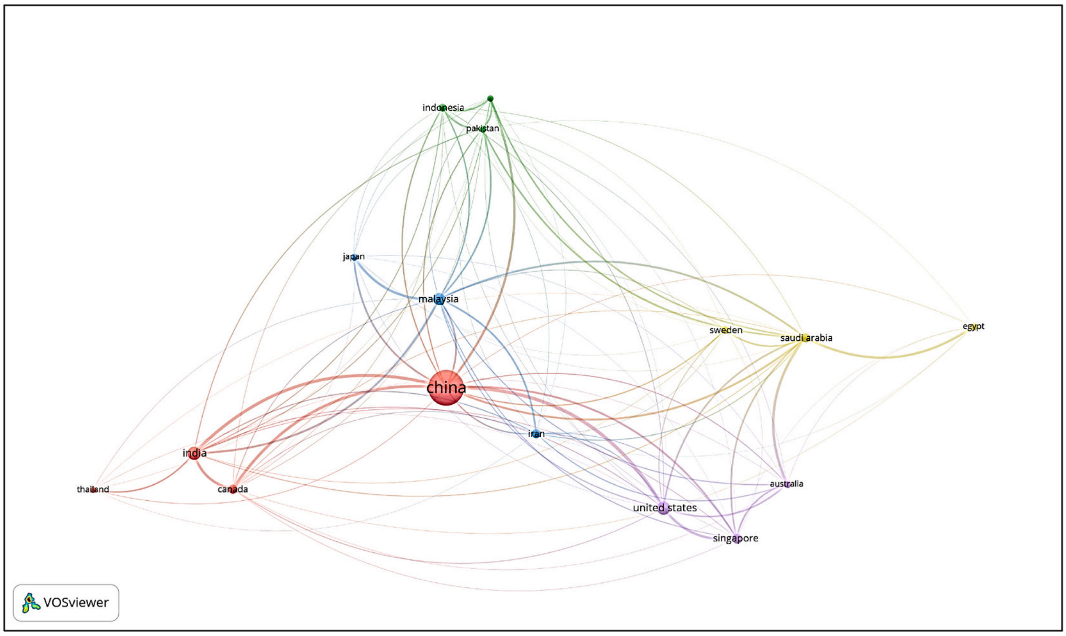

Fig. 7. Bibliographic coupling of countries: minimum publication threshold of 3 documents and 98 links.

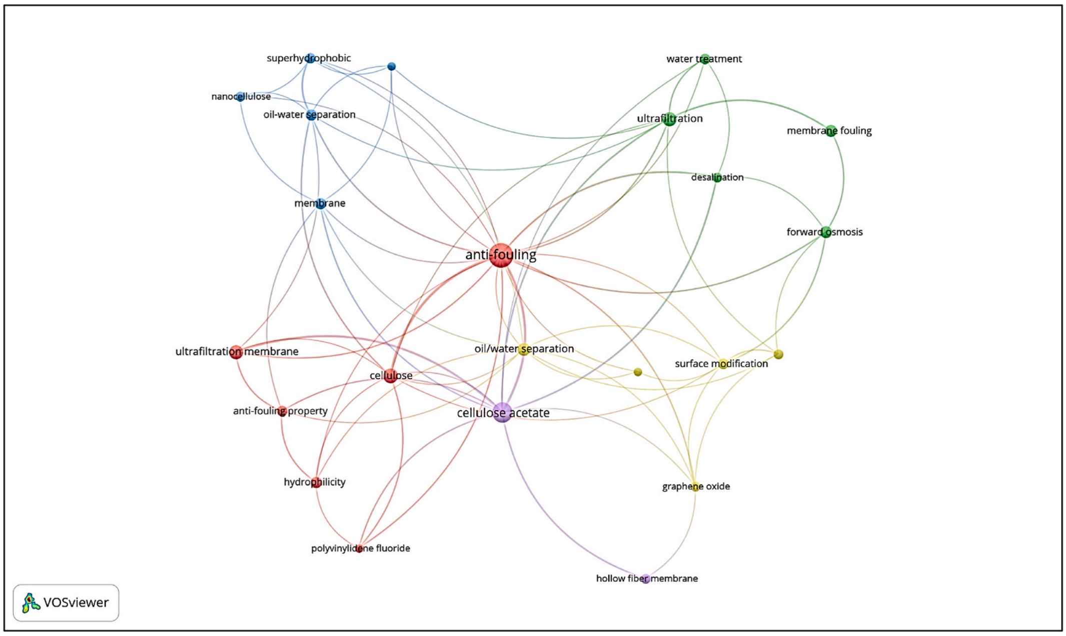

Fig. 8. Co-occurrence of authors' keywords: minimum keywords threshold of 3 and 70 link.

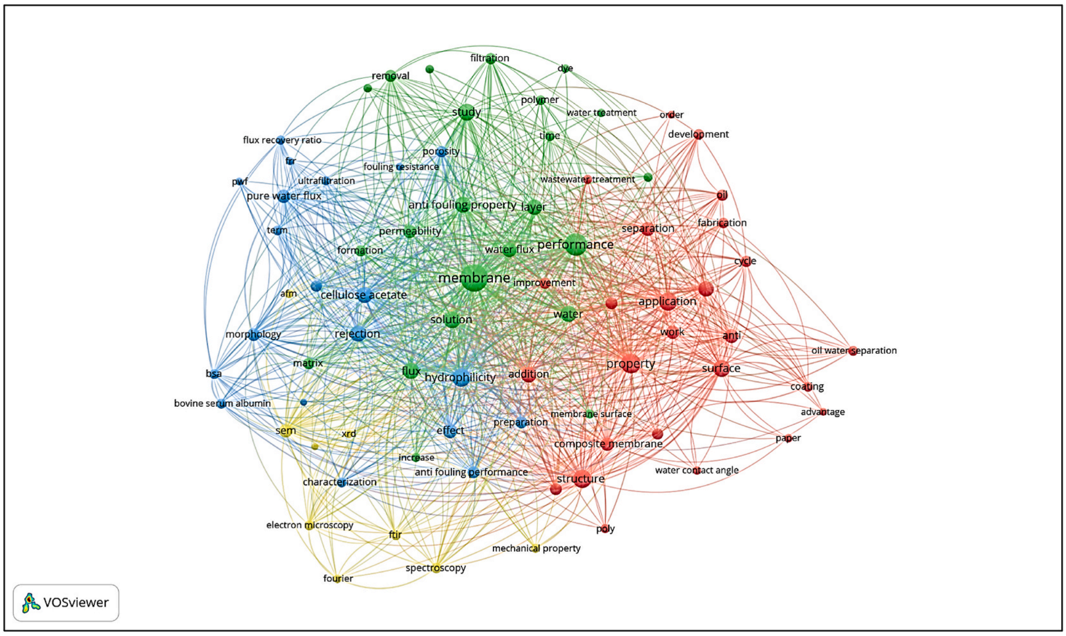

Fig. 9. Network view map generated by the VOSviewer.

complex nature of the challenges faced by maritime industries. Addressing these problems requires the development and implementation of effective antifouling technologies, sustainable practices, and rigorous adherence to environmental regulations to ensure the longevity, efficiency, and ecological sustainability of maritime operations.

Biofouling in marine systems is primarily caused by the attachment and growth of microorganisms, algae, plants, and animals on submerged surfaces. Several factors contribute to the prevalence of biofouling in marine environments. Firstly, any submerged surface in the marine environment, including ship hulls, underwater structures, and equipment, provides a suitable substrate for biofouling organisms to attach and grow [54]. Additionally, nutrients present in seawater, such as nitrogen and phosphorus compounds, serve as essential resources for the growth of biofouling organisms [55]. These nutrients can originate from natural sources like coastal runoff and anthropogenic sources such as wastewater discharge.

Warmer water temperatures, common in tropical and subtropical regions, accelerate the metabolic rates and reproductive cycles of biofouling organisms, promoting their growth [56]. Sunlight exposure provides energy for the photosynthetic growth of algae and other phototrophic organisms, contributing to biofouling development in well-lit environments [57]. Furthermore, variations in salinity levels, biofilm formation facilitated by microorganisms, and hydrodynamic conditions like water flow patterns and currents all play significant roles in biofouling accumulation [58]. Collectively, these factors create conducive conditions for biofouling in marine systems, necessitating effective management strategies to mitigate their impact on industries reliant on submerged structures.

In addition, Junbo et al. [59] highlighted the significant impact of biofouling on fishery equipment immersed in seawater environments, emphasizing its adverse effects on service life and standard functionality. Marine fishery equipment, including aquaculture gear, fishing apparatus, and aquatic processing machinery, plays a crucial role in marine economic activities. However, prolonged exposure to seawater leads to biological attachment, causing economic losses due to decreased efficiency. The attachment of organisms to marine fishing vessels results in reduced speed, increased fuel consumption, and higher operational costs. Similarly, biofouling on offshore cage netting shortens its lifespan, hinders fish survival, and poses challenges for existing prevention methods. Coating applications and manual removal have proven insufficient, with drawbacks like toxicity, labour intensiveness, and equipment damage. The study underscores the need for effective measures to control biofouling, considering the limitations of existing techniques. The classification of coatings for antifouling can be elucidated as follows, drawing upon a bibliographic review.

While the primary focus of the bibliometric study is on cellulose for anti-fouling, the derived insights and findings from the bibliographic review suggest broader applications of cellulose in the maritime industry. The study may uncover various research articles, publications, and trends that highlight the versatility of cellulose-based materials beyond their anti-fouling properties. The application of cellulose in maritime settings could extend to areas such as sustainable shipbuilding materials, environmentally friendly coatings, and innovative technologies for water treatment. For example, cellulose-based composites or nanomaterials might be explored for their potential in developing lightweight and durable materials for ship construction. Additionally, cellulose coatings or additives could offer eco-friendly alternatives for protecting ship surfaces from corrosion and fouling.

The bibliometric study may uncover research avenues exploring cellulose's use in water purification systems on ships or in desalination processes, aligning with the maritime industry's growing emphasis on sustainability and environmental responsibility. Cellulose's natural and renewable characteristics make it an appealing candidate for addressing challenges beyond fouling, contributing to the industry's pursuit of green and innovative solutions. In summary, while the bibliometric study centers on cellulose for anti-fouling, the literature it encompasses might unveil a spectrum of possibilities for the application of cellulose in various maritime contexts, ranging from ship construction materials to environmentally benign coatings and water treatment technologies.

The selection of cellulose as a solution to address the issue of biofouling stems from its unique properties and eco-friendly characteristics. Cellulose, a naturally occurring biopolymer derived from plant cell walls, offers several advantages that make it a promising material for combating biofouling in maritime applications.

4.1. Biodegradability and environmental compatibility

Cellulose stands out as a compelling solution for addressing biofouling due to its inherent biodegradability, a characteristic that dovetails seamlessly with the prevailing global emphasis on sustainable and environmentally friendly solutions [60]. This natural biopolymer, derived from plant cell walls, possesses unique properties that make it an eco-conscious alternative, particularly when compared to certain synthetic materials commonly employed in anti-fouling applications [61].

The biodegradability of cellulose implies that, over time, it can naturally break down into harmless byproducts, mitigating concerns related to persistent pollutants that might accumulate in marine ecosystems (X. [62]). This is in stark contrast to some synthetic materials used in traditional anti-fouling treatments, which can persist in the environment, potentially leading to long-term ecological consequences [63]. Cellulose-based anti-fouling approaches thus represent a departure from the use of persistent and potentially harmful substances that have raised environmental concerns. By harnessing the biodegradable nature of cellulose, these approaches seek to minimize the ecological impact associated with anti-fouling strategies. The ability of cellulose to undergo natural degradation processes aligns with broader initiatives to reduce the environmental footprint of maritime activities and adhere to sustainability principles.

Moreover, the use of cellulose in anti-fouling applications not only addresses the immediate challenges posed by biofouling but also contributes to the overarching goal of fostering responsible and sustainable practices within the maritime industry. As regulatory frameworks increasingly emphasize environmental protection and sustainability, cellulose emerges as a responsible choice that aligns with these global trends, offering a harmonious balance between effective biofouling prevention and ecological stewardship.

4.2. Renewable and abundant resource

Cellulose emerges as a highly promising solution to the challenge of biofouling, not only due to its intrinsic biodegradability but also owing to its derivation from renewable sources [22]. Sourced primarily from wood, cotton, and various plant-based materials, cellulose presents a sustainable alternative for addressing marine fouling issues [64]. This reliance on renewable feedstocks contributes to the establishment of environmentally responsible practices, aligning with global initiatives to reduce dependency on finite resources. The abundance of cellulose in nature ensures a consistent and sustainable supply, promoting resilience in the face of changing resource dynamics and providing flexibility in material selection based on regional availability. Beyond its effectiveness in combating biofouling, the utilization of cellulose in anti-fouling applications supports circular economy principles by encouraging the cyclical use of materials that can be reintegrated into the environment without causing long-term harm [65]. Ongoing advancements in biotechnological processes further enhance the sustainability profile of cellulose, positioning it as a key player in the development of eco-friendly and effective solutions for maritime anti-fouling practices [66].

Furthermore, cellulose's renewable origin not only reduces the environmental impact associated with its extraction but also supports the development of a sustainable supply chain [67]. By embracing responsible sourcing practices and emphasizing efficiency in processing, cellulose-based anti-fouling solutions contribute to the broader goal of fostering sustainability throughout the production lifecycle [68]. The diverse array of plant sources from which cellulose can be derived enhances its adaptability to different environmental contexts and underscores its potential role in promoting regional and ecological considerations in anti-fouling strategies. The utilization of cellulose aligns with the principles of a circular economy, where materials are designed to be reused, repurposed, or naturally reintegrated into the environment. As a biodegradable substance, cellulose encourages a closed-loop system that minimizes waste and aligns with evolving environmental regulations emphasizing a shift away from persistent and harmful substances.

Moreover, ongoing research exploring biorenewable processes holds the promise of optimizing the sustainability profile of cellulose-based materials even further. Biotechnological advancements may offer opportunities to enhance extraction methods, improve production efficiency, and explore innovative applications, reinforcing cellulose's position as a versatile and environmentally friendly solution for biofouling challenges in the maritime industry. In essence, the renewable and sustainable attributes of cellulose not only make it an effective anti-fouling material but also position it as a key contributor to the broader paradigm of sustainable practices within the maritime sector.

Trisnawati et al. [69] explored the continuous development of cellulose derivatives from natural resources with a focus on enhancing the performance of hydrophobic polymer-based membrane technology. Cellulose acetate (CA) synthesized from screw pine (*Pandanus tectorius*) leaf cellulose was employed to improve the hydrophilicity, performance, and anti-fouling characteristics of polyvinylidene fluoride (PVDF) membranes. The Fischer esterification mechanism was utilized for CA synthesis, and PVDF membranes were fabricated using the phase inversion method with a 0.3 % CA concentration. The addition of CA resulted in notable improvements, enhancing the hydrophilicity and anti-fouling properties of PVDF membranes by up to 86.45 %. Moreover, CA significantly increased water permeability, achieving 2–3 times higher values compared to pristine PVDF membranes. The presence of CA contributed to enhanced membrane porosity, making the PVDF membrane more effective for filtering substances like methylene blue (MB). This research highlights the promising potential of CA derived from screw pine leaf cellulose as a filler for PVDF membranes, positioning it as a natural anti-fouling solution for maritime applications.

4.3. Low toxicity and biocompatibility

Cellulose stands out as a promising solution for biofouling challenges in maritime applications due to its remarkable attributes of low toxicity and high biocompatibility (S. [34]). Derived from plant cell walls, cellulose is a natural biopolymer with a minimal environmental footprint [70]. Its low toxicity profile ensures that anti-fouling strategies based on cellulose are less likely to harm non-target organisms and aquatic ecosystems [71]. Unlike conventional anti-fouling treatments that often rely on biocides with potential ecological risks, cellulose-based approaches offer a safer alternative that minimizes adverse effects on marine life, promoting environmental stewardship in the maritime industry ([63]).

In addition to its environmentally friendly characteristics, cellulose's biocompatibility further enhances its appeal for anti-fouling applications. When incorporated into formulations, cellulose is less prone to induce harmful reactions in living organisms, making it a safer choice for marine ecosystems. This biocompatible nature aligns with a holistic approach to anti-fouling, considering the broader ecological systems in which maritime activities take place. By choosing cellulose over traditional biocides, the maritime industry not only addresses biofouling effectively but also upholds a commitment to preserving marine biodiversity and supporting sustainable practices.

4.4. Resistance to microbial attachment

Certain cellulose-based materials showcase a remarkable ability to resist microbial attachment and deter fouling organisms, positioning them as valuable assets in the ongoing battle against biofouling in maritime settings [72]. At the core of this effectiveness lies the unique molecular composition of cellulose, which lacks the chemical cues that attract and support microbial colonization. This microbial resistance not only mitigates the initial stages of biofouling but also contributes to the creation of surfaces less prone to microbial settlement [73]. Beyond microbes, certain cellulose-based materials extend their anti-fouling prowess to larger organisms such as barnacles, algae, and mollusks. The surface characteristics of these materials actively discourage the adhesion and growth of fouling organisms, offering a comprehensive defense against biofouling.

To harness the inherent properties of cellulose for anti-fouling purposes, researchers and engineers utilize surface modification techniques. Cellulose can be incorporated into coatings, paints, or surface treatments for maritime structures, creating environments that resist the attachment of fouling organisms. This surface modification not only leverages the microbial resistance of cellulose but also tailors its properties to specific environmental conditions and operational requirements. The result is a proactive and sustainable approach to anti-fouling that actively combats biofouling challenges, contributing to the longevity and operational efficiency of maritime structures.

The effectiveness of cellulose-based anti-fouling strategies not only addresses immediate challenges but also draws inspiration from nature's biofouling-resistant mechanisms. By mimicking the strategies employed by marine organisms, cellulose-based materials contribute to the development of bio-inspired technologies. These technologies not only combat biofouling effectively but also align with eco-friendly and sustainable principles, marking a paradigm shift in the quest for innovative and environmentally responsible anti-fouling solutions in the maritime industry.

P. Wang et al. [74]'s research underscores the significance of cellulose acetate (CA) as an environmentally friendly and biodegradable material with intrinsic natural anti-fouling properties, particularly suitable for single-use membranes, especially in bioprocess applications. The study focuses on the preparation of CA membranes using Vapor-assisted Nonsolvent Induced Phase Separation (VNIPS). Through systematic evaluations of composition ratios and membrane preparation conditions, the research reveals the critical influence of acetone/N,N-Dimethylacetamide and glycerol/CA ratios on the cross-section structure, showcasing the potential to consistently achieve a membrane with a homogeneous sponge-like porous structure within specific ratio limits. These findings hold promise for developing high-performance membranes with controllable surface morphology and a natural resistance to fouling, making them valuable for bioseparation processes where anti-fouling capabilities are essential.

Z. Yin et al. [75]'s research has illuminated the burgeoning demand for flexible and multifunctional cellulose-based membranes (CM) in marine wastewater treatment, particularly due to their effective and ecologically benign nature. The study focused on a specially prepared CM sample that exhibited extraordinary properties, including superhydrophobicity with a water contact angle of $162 \pm 2^{\circ}$ and superoleophilicity with an oil contact angle of 0°. Notably, this biomimetic sample displayed exceptional stability in hostile environments, including resistance to acid and alkali solutions, high temperatures, wear resistance, underwater writing, and self-cleaning. Additionally, the sample demonstrated a notable 2.6 % increase in tensile strength. In the context of anti-microbial properties, the research findings are particularly compelling. The study showcased the CM sample's robust resistance to microbial adherence, underscoring its potential as an anti-microbial agent in the maritime environment. This attribute is crucial in preventing the growth of harmful microorganisms, further contributing to the overall efficacy of the CM sample in combating biofouling challenges. The environmentally friendly, cost-effective, and scalable nature of this methodology positions the superhydrophobic CM sample as a promising solution with multifaceted applications, not only in anti-biofouling but also in addressing microbial concerns in maritime settings.

4.5. Current application of cellulose for anti-fouling can be applied for maritime

The current application of cellulose for anti-fouling presents promising opportunities for addressing biofouling challenges in maritime environments. As the maritime industry grapples with the detrimental impact of biofouling on vessel performance, fuel efficiency, and environmental sustainability, the exploration of cellulose-based solutions emerges as a significant avenue for innovation. Cellulose, derived from renewable resources, offers a sustainable and eco-friendly alternative to conventional anti-fouling methods that often involve the use of biocides with environmental repercussions. Its inherent biodegradability aligns with global trends toward environmentally responsible practices. Furthermore, cellulose-based approaches showcase low toxicity, biocompatibility, and resistance to microbial attachment, providing a multifaceted solution to mitigate the adverse effects of biofouling on maritime infrastructure. This introduction sets the stage for a comprehensive examination of the current applications of cellulose for anti-fouling and its potential implications for the maritime industry.

In a recent study by Jamshaid et al. [76],they developed innovative mixed matrix membranes by combining polyvinyl chloride-*co*-vinyl acetate/cellulose acetate (PVCA/CA) with nano-particles of pristine zeolite (p-zeolite) and 3-aminopropyl triethoxysilane functionalized zeolite (f-zeolite) for desalination purposes. The research suggests potential applications for these membranes in preventing fouling in maritime settings. The membranes infused with f-zeolite showed improved uniformity, reduced microscopic voids, and increased hydrophilicity, as evidenced by contact angle measurements. They also exhibited enhancements in mechanical properties and an improved balance between water flux and salt rejection. Notably, membranes with 5 wt % f-zeolite demonstrated the highest salt rejection (99.56 %) and increased water flux by $\sim$24% compared to the neat PVCA/CA membrane. The study concluded that these membranes, particularly those with APTS f-zeolite, could be promising for high-performance desalination with potential antifouling applications in maritime environments.

Xue Yang et al. [77] discovered that cellulose nanocrystals (CNCs) derived from corn husks could enhance the hydrophilicity and anti-fouling characteristics of polysulfone (PSf) membranes. They used an immersion phase inversion method to create PSf/CNC blend membranes. The findings indicated that CNCs extracted from corn husks were a promising additive for modifying PSf membrane properties, enhancing mechanical strength, thermal stability, hydrophilicity, and anti-fouling performance. The optimal properties were achieved with two wt % CNCs content in the blend membrane, exhibiting 2.76 times higher pure water flux and 1.57 times higher flux recovery ratio (FRR) than the pure PSf membrane. Notably, the PSf-2 blend membrane also maintained a relatively high rejection of bovine serum albumin (BSA). This application shows promise for maritime use.

Furthermore [78], \ developed an advanced nanocomposite ultrafiltration membrane with enhanced water flux and anti-fouling properties by incorporating quaternary ammoniumpropylated polysilsesquioxane (QAPS) into cellulose acetate (CA) through in situ sol-gel processing and subsequent quaternization with methyl iodide (CH3I). The nanocomposite membrane with 7 % QAPS@CA demonstrated improved wettability (46.6° water contact angle), increased water uptake (113 %), and a high pure water permeability of approximately 370 L m^2/h bar. Importantly, the 7 % QAPS@CA nanocomposite membrane exhibited outstanding bactericidal properties, inhibiting approximately 97.5% of Escherichia coli (*E. coli*) growth compared to the bare CA membrane (0 % growth inhibition). The exceptional performance of the 7 % QAPS@CA nanocomposite membrane makes it a promising choice for anti-fouling applications and suggests its potential use in maritime settings.

In conclusion, the diverse applications of cellulose for anti-fouling, as demonstrated by the mentioned studies, underscore its potential significance in supporting sustainability goals within the maritime industry. These innovative approaches showcase the versatility of cellulose-based solutions and their adaptability to address biofouling challenges in diverse maritime applications.

4.6. Comparison potential cellulose anti-fouling with other marine coatings

In this section, a comparative analysis will be undertaken between potential cellulose-based anti-fouling solutions and other existing marine coatings. While cellulose presents promising attributes for mitigating biofouling in marine environments, its efficacy and practicality will be contextualized alongside established marine coating alternatives. By examining the advantages, limitations, and practical considerations of cellulose in comparison to other coatings, insights will be provided into its feasibility and potential areas of improvement within the broader landscape of marine anti-fouling strategies. Through this comparative assessment, the unique characteristics and challenges associated with cellulose-based solutions will be elucidated, and perspectives on their suitability for addressing biofouling in marine systems will be offered.

Table 4 presents a comparison of the advantages, limitations, and practical considerations of potential cellulose anti-fouling solutions with other marine coatings. Under the "Advantages" category, cellulose anti-fouling exhibits several beneficial attributes. Firstly, it is renewable and biodegradable, aligning with sustainable practices [65]. Additionally, cellulose offers a wide range of options and is eco-friendly [79,80]. It is effective in preventing biofouling and demonstrates low toxicity, making it suitable for marine applications [81,82]. Moreover, cellulose coatings are durable, long-lasting, biocompatible, and adaptable to various substrates (X. [83–85]).

In terms of limitations, cellulose anti-fouling faces challenges related to its field application and potential environmental impact ([86]; [63]). Effectiveness may vary depending on the application method and environmental conditions [87]. Additionally, concerns about toxicity may arise, although efforts are being made to address these issues [88]. This comparative analysis sheds light on the unique characteristics and challenges associated with cellulose anti-fouling solutions, providing valuable insights for their potential adoption in marine environments.

5. Recommendation for future research

In the realm of cellulose-based anti-fouling for maritime applications, future efforts should prioritize interdisciplinary collaboration to leverage expertise from materials science, marine biology, and engineering. Establishing research consortia that span international boundaries can enhance the collective understanding of cellulose applications globally [89,90]. By promoting diverse collaborations, researchers can address the multifaceted challenges posed by biofouling in maritime environments, leading to innovative and effective solutions.

Sustainability should remain a central focus for future research endeavors. Emphasizing environmentally friendly methodologies aligns with the global push for sustainable practices. Exploring alternative materials and technologies, particularly those with reduced ecological impacts, can contribute to the development of anti-fouling strategies that are not only effective but also aligned with broader environmental goals. Long-term monitoring studies under real-world maritime conditions are crucial to assessing the durability and performance of cellulose-based solutions over time and adapting them to varying environmental challenges.

To bridge the gap between research and practical applications, fostering public-private partnerships is essential. Collaborations between academia, industry, and governmental bodies can accelerate the translation of research findings into scalable, commercially viable solutions. Developing standardized testing protocols ensures consistency in evaluating the efficacy of different cellulose anti-fouling approaches. Education and outreach initiatives should accompany these efforts to disseminate knowledge and promote awareness of the benefits of cellulose-based anti-fouling, engaging stakeholders at various levels. Lastly, incorporation of emerging technologies, adaptation to climate change, and the utilization of big data and artificial intelligence can further enrich the development and application of cellulose-based anti-fouling strategies in the maritime sector.

6. Conclusion

Marine biofouling, characterized by accumulating organic substances, microorganisms, and marine organisms on submerged surfaces, poses a significant challenge to various industries. Traditional anti-fouling methods involve coatings with biocides, but there is a shift towards sustainable solutions. This shift has led to exploring natural products as anti-fouling agents. Preet et al. highlighted the potential of Anthraquinones (AQs) in anti-fouling paint, offering an eco-friendly approach. Other studies focused on specific natural agents like lysozyme, Sinularia flexibilis extract, and vanillin for their anti-fouling properties.

Additionally, cellulose acetate from screw pine leaf cellulose demonstrated improved PVDF membrane hydrophilicity and anti-fouling characteristics. Despite these advancements, the natural anti-fouling research landscape is expansive, presenting

Table 4
Comparison advantages and limitations and practical considerations potential cellulose anti-fouling with other marine.

Aspect	Cellulose Anti-Fouling	Ref	Other Marine Coatings	Ref
Advantages	Renewable and biodegradable	[65]	Wide range of options available	[79]
	Eco-friendly	[80]	Effective in preventing biofouling	[81]
	Low toxicity	[82]	Durable and long-lasting	(X. [83])
	Biocompatible	[84]	Adaptable to various substrates	[85]
Limitations	Limited field application	[86]	Potential environmental impact	[63]
	Varied effectiveness	[87]	Toxicity concerns	[88]

opportunities for interdisciplinary approaches, adaptation of technologies, and identification of novel compounds. Future research should focus on molecular interactions, sustainable coating technologies, real-world applicability, environmental impact assessment, and collaborative initiatives to contribute to effective, environmentally conscious natural anti-fouling solutions for diverse marine applications.

Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

CRediT authorship contribution statement

Nicky Rahmana Putra: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Funding acquisition, Conceptualization. **Abdi Ismail:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Dian Purnama Sari:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Nurcholis Nurcholis:** Writing – review & editing, Writing – original draft. **Totok Triputrastyo Murwatono:** Writing – review & editing, Project administration, Conceptualization. **Rina Rina:** Writing – review & editing, Data curation, Conceptualization. **Yuniati Yuniati:** Writing – review & editing, Writing – original draft, Conceptualization. **Endah Suwarni:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Agus Sasmito:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Putri Virliani:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Shinta Johar Alif Rahadi:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Irianto Irianto:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization. **Alfa akustia Widati:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Quilbott in order to paraphrase the language and check the language grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Irianto reports article publishing charges was provided by Rabdan Academy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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