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Environmental Ageing of Structural Materials in Shipbuilding and Marine Engineering – A Review

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ABSTRACT

The mechanical properties of structural materials in shipbuilding and marine engineering are significantly affected by environmental stressors such as corrosive environments, UV radiation, and chemical treatments, all leading to material degradation. This review examines nearly 1,000 studies published between 2015 and 2025 to reveal key trends in the research on the impact of environmental factors on material degradation. The review has two parts. The bibliometric review maps the structure of academic research and identifies patterns and trends, while the critical review provides research gaps and future research directions. Specifically, the study highlights that UV-C radiation accelerates surface embrittlement and strength loss in polymers, while chlorination promotes localized corrosion in stainless steels, notably AISI 316. A critical gap was identified in the limited research on combined environmental stressors, despite their real-world relevance in marine environments. The findings highlight the need for a multidisciplinary study of the interplay of various environmental effects on marine materials and structures. Also, there is a certain lack of long-term studies in the natural marine environment. Additionally, attention should be paid to the behavior of modern materials (composites, additively manufactured materials) to allow their faster uptake in the maritime industry.

1 Introduction

The durability and performance of marine structural materials are critical for ensuring operational efficiency, safety, and sustainability in maritime industry. These materials are often exposed to harsh environmental conditions, including the natural marine environment, ultraviolet (UV) radiation, and various chemical treatments, leading to material degradation, including corrosion and the deterioration of mechanical properties. . Understanding the effects of environmental ageing on such materials has become a key area of research, as the maritime industry seeks to optimize material performance and extend service life under demanding conditions. The increasing global reliance on maritime operations for transportation, energy, and commerce underscores the importance of understanding these effects.

Environmental ageing refers to the gradual deterioration of material properties due to prolonged exposure to environmental stressors. Unlike other aging mechanisms such as thermal aging, mechanical fatigue or radiation damage, environmental aging is primarily driven by external atmospheric, chemical, and maritime factors, including UV radiation, chlorination, and chemical disinfection. In the context of shipbuilding and marine engineering, this form of aging is especially significant, as materials are continuously exposed to harsh, variable, and often synergistic environmental influences. These factors make environmental aging the most impactful and practically relevant form of degradation for marine structural materials, justifying its focused analysis in this study.

Polymers, composites, and metals such as stainless steel are commonly used in marine applications due to their strength and resistance to corrosion. However, the sea environment, UV-C radiation and chemical exposure significantly impact their performance. For instance, studies have demonstrated that UV radiation accelerates surface roughness and degradation of polymer composites [1]. Similarly, chlorination processes, while effective in preventing biofilm formation, have been shown to induce localized corrosion in stainless steel under seawater conditions [2]. Recent advancements in materials science and engineering have focused on improving the resistance of marine structural materials to environmental stressors. However, comprehensive assessments of the long-term impact of these conditions remain limited, as highlighted in studies on glass-fiber reinforced polymer (GFRP) composites exposed to UV radiation and moisture [3].

Bibliometric analyses have proven to be a valuable tool in synthesizing and evaluating existing research to identify trends, gaps, and emerging areas of interest in many scientific fields [4]. This study aims to provide a systematic bibliometric analysis of research on environmental effects on materials, focusing on recent publications from 2015 to 2025. Given the multidisciplinary nature of environmental effects on materials, the search strategy encompassed research from various scientific and engineering disciplines, including material science, environmental studies, and industrial applications. Although not all identified studies directly relate to marine engineering, their findings are crucial for understanding material degradation mechanisms under extreme conditions.

Using data extracted from Scopus and analyzed with the Bibliometrix tool in R, this study explores publication trends, key contributors, and thematic clusters. The findings will provide insights into the evolution of this research area, highlight influential studies, and propose directions for future investigations.

The paper is structured as follows: the Methodology section describes the bibliometric approach and data collection process; the Bibliometric Analysis section presents the results of temporal trends, collaborations, and thematic clusters; the Critical Review section synthesizes thematic insights and assesses the implications of environmental ageing on marine materials; the Discussion section evaluates research limitations, identifies underexplored areas, and suggests key directions for future research; and finally, the Conclusion summarizes the key findings and outlines avenues for future research.

2 Methodology

A bibliometric approach was employed to understand the research landscape on environmental effects on materials comprehensively. Bibliometric analysis enables quantifying and visualizing trends, collaborations, and thematic structures within a given field. Data were extracted from the Scopus database and analyzed using the Bibliometrix package in R, which proves to be an advanced tool for citation, co-authorship, and keyword analysis [5], [6].

2.1 Data Collection

The dataset was compiled using an advanced search query to capture relevant studies published between 2015 and 2025. Boolean operators were used in constructing the query, which included keywords related to material types (e.g., "polymer*", "plastic*", "composite*", "stainless steel", "AISI 316"), environmental stressors (e.g., "UV radiation", "chlorination", "chemical disinfection", "corrosion"), and material properties (e.g., "mechanical properties", "surface roughness", "ageing"). Filters were applied to limit results to English-language, peer-reviewed journal articles from materials science and engineering.

A total of 992 articles were identified and exported in BibTeX and CSV formats for bibliometric analysis. Metadata included publication year, author names, keywords, abstracts, and citation counts. These search strategies align with recommended practices in bibliometric reviews [4].

This study's step-by-step Boolean search process is summarized below (see Table 1). For detailed search strings and all included keywords, refer to Appendix A.

Table 1 Results of the Boolean search process

Step	Description	Results
1	The initial query is to identify studies on environmental ageing	663
2	Adding material categories	6.233.759
3	Adding environmental stressors	19.054
4	Focusing on material properties	3.702
5	Applying Temporal and Thematic filters	1.318
6	Language and Publication Type Filters (Final Query)	992

2.2 Research Workflow

The research workflow follows a structured sequence of steps visually represented in Figure 1. This methodological flowchart outlines the key stages of the bibliometric analysis process, ensuring a clear and systematic approach:

1. Data Retrieval: Advanced searches were conducted in the Scopus database using a predefined search string designed to capture all relevant studies on environmental effects on marine structural materials published between 2015 and 2025.

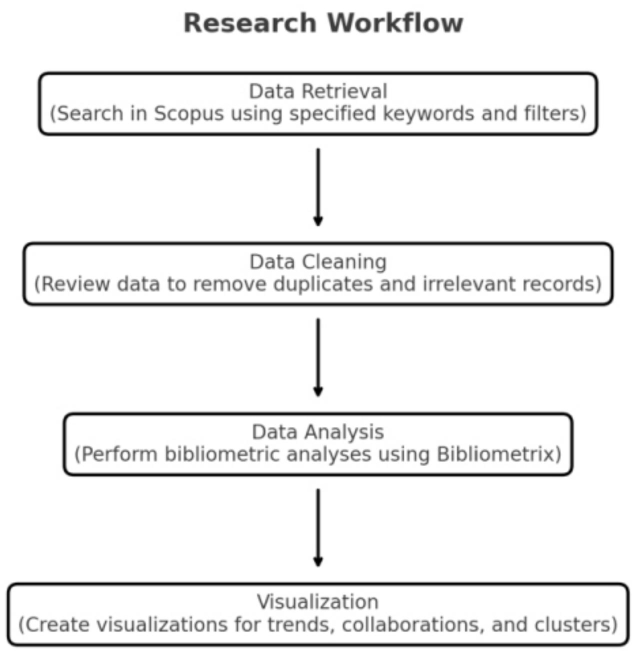

Figure 1 Methodological flowchart for bibliometric review.

2. Data Cleaning: Exported data were reviewed to remove duplicates and irrelevant records.
3. Data Analysis: Bibliometric analyses, including co-authorship, keyword co-occurrence, and citation analysis, were performed in Bibliometrix.
4. Visualization: Visualizations were generated exclusively using Bibliometrix. This tool was employed for network analysis and thematic mapping. These visualizations were instrumental in interpreting complex relationships and identifying patterns within the dataset. This structured methodology ensured a robust and replicable analysis [5].

3 Bibliometric analysis

The mathematical foundation of bibliometric analysis often utilizes network theory and descriptive statistics. For example, the prominence of entities such as authors or institutions within a collaborative network can be quantified using metrics like degree centrality (C_D). Degree centrality measures the direct connections an entity has relative to the total number of possible connections in the network. It is mathematically defined as:

$$C_D(i) = \deg(i)/(n-1) \tag{1}$$

where deg(i) represents the number of direct connections (or collaborations) of entity i, and n is the total number of entities in the network. This measure provides insight into how influential or well-connected an entity is within the overall network [7].

Another vital tool in network analysis is modularity-based clustering, which helps us discover groups or "communities" within a network. A popular method for this is the Louvain algorithm, which groups nodes or entities (like researchers, institutions, or topics) that are more closely connected while reducing links between different groups. The Louvain algorithm improves modularity, which shows how strongly a network is divided into communities. Higher modularity means the communities are well-defined, with many connections inside each group and fewer connections between groups. In simple terms, this method helps us identify natural clusters or groups in a network, making it easier to understand how the network is organized. This kind of clustering gives us deeper insights into how people or ideas are connected and helps us make sense of complex systems [8].

Additionally, the clustering coefficient C(i) quantifies the tendency of nodes to form tightly knit groups, providing a local perspective on the cohesiveness of a network. It is mathematically defined as:

$$C_{(i)} = 2T_{(i)}/[k_i \times (k_i - 1)] \tag{2}$$

where $T_{(i)}$ represents the number of triangles that include node i, and k_i is the degree of node i (the number of direct connections it has).

This measure evaluates the density of connections between the neighbors of a node, offering insights into how tightly interconnected a network's local structure is. Widely used in network science, the clustering coefficient has become a standard tool for analyzing the structural properties of networks, particularly in bibliometric and collaborative research [5], [9].

Bibliometric analyses in this study employed citation metrics, co-authorship networks, and thematic mapping to uncover key insights into the field of environmental effects on materials. The following sections detail these findings, providing both quantitative and qualitative perspectives on the scholarly landscape. Although a broad range of materials has been examined, the focus is on identifying research directions for the environmental effects on structural materials used in shipbuilding and marine engineering.

3.1 Overview of Publication Trends

The scientific interest in the environmental effects on materials has grown significantly over the past decade. An analysis of publication trends from 2015 to 2025 reveals a steady increase in published articles, with a notable acceleration in recent years. Nevertheless, it is acknowledged that not all of these studies directly pertain to maritime applications. This limitation of the bibliometric approach has been addressed by interpreting such studies with caution, focusing only on findings that are applicable or translatable to shipbuilding and marine engineering contexts.

2015, only 43 articles were published, marking the lowest point in the dataset. This number grew consistently, reaching a peak of 185 publications in 2024. The average number of articles per year during this period was approximately 90, highlighting a growing recognition of the importance of this research area.

This upward trend aligns with the increasing global focus on sustainability and the resilience of materials. It should be noted, however, that this growth may partially reflect the general increase in the number of scientific publications and journals in recent years. Therefore, while the absolute number of publications in this field has increased, the relative share of such studies within the broader scientific output has not been explicitly analyzed in this paper. The heightened interest after 2020 could be attributed to advancements in materials science. Furthermore, the increased focus might also be linked to the global emphasis on

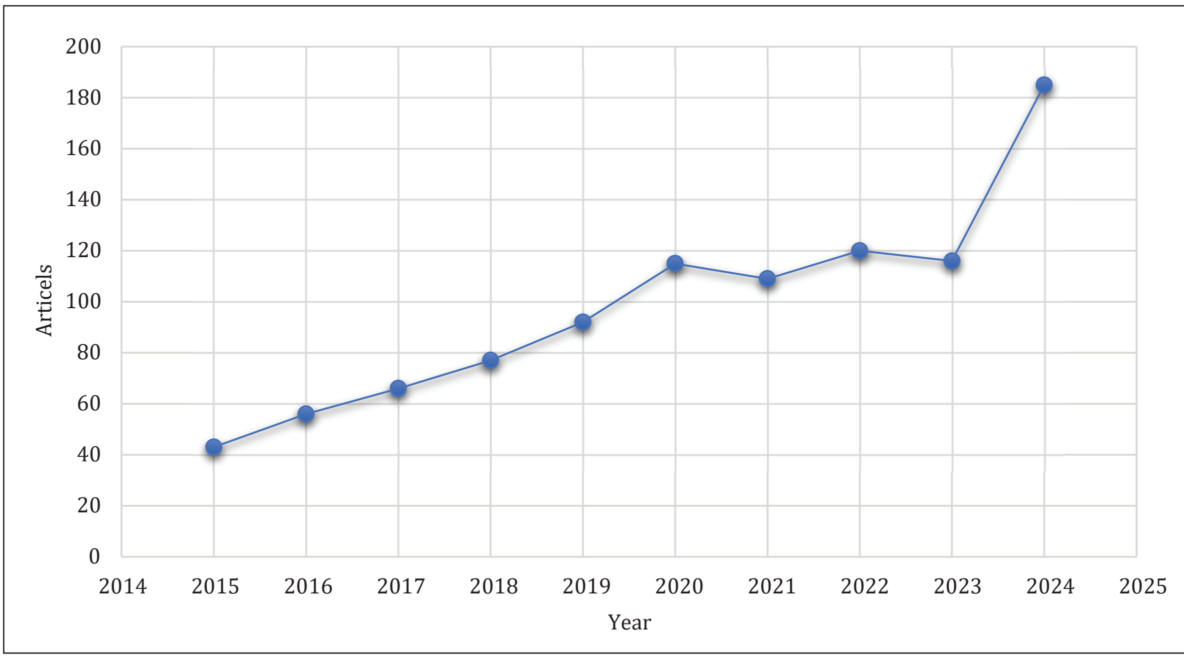

Figure 2 Annual scientific production.

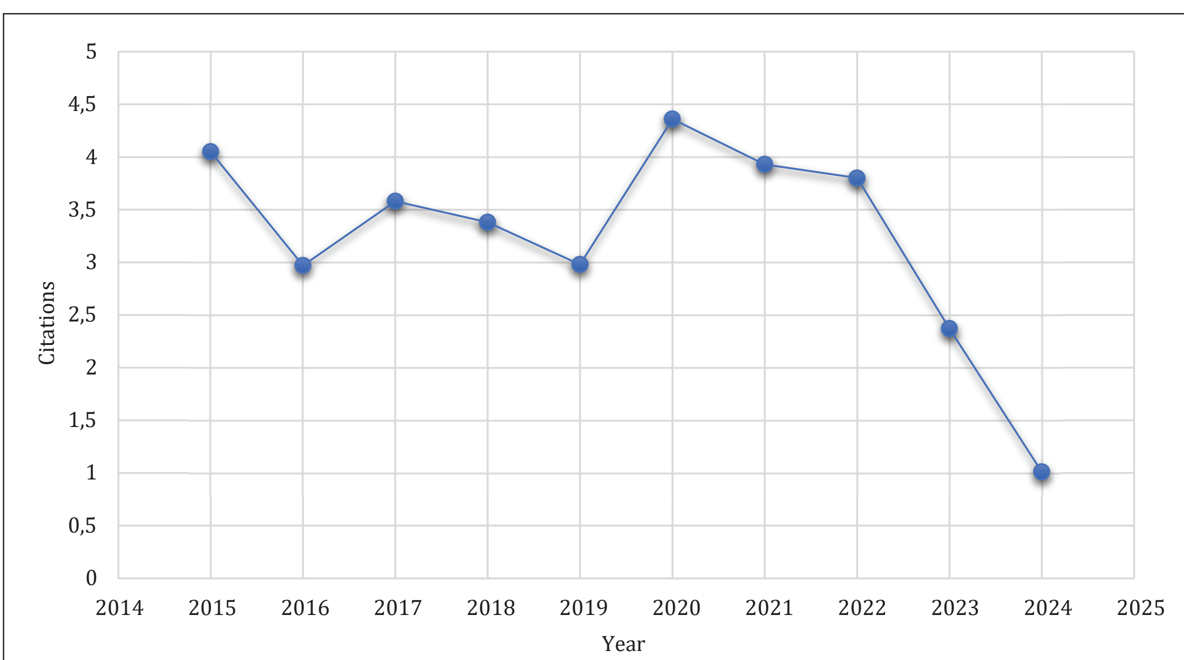

Figure 3 Average Citations per Year.

disinfection processes during and after the COVID-19 pandemic, as suggested by the inclusion of search terms such as chlorination, ultraviolet exposure, chemical disinfection, and alcohol disinfection in the analysis.

Figure 2 visually represents the annual scientific production, illustrating this positive trajectory. The data underscores a robust expansion of scholarly activity, suggesting the field is dynamic and rapidly evolving.

In addition to quantity, the quality of research in this area is reflected in citation metrics. The average number of citations per article is defined as:

$$C_{avg} = C_{total}/N \quad (3)$$

where C_{total} is the total number of citations, N is the total number of articles published in a given year.

Figure 3 illustrates the trend in average citations per article over the years, highlighting research's increasing recognition and influence in this area. The data reveal a noticeable variation in citation metrics, with earlier publications accumulating more citations due to their extended availability. However, the steady rise in recent years underscores this research field's growing impact and relevance. This upward trend in average citations is a testament to the field's academic significance and the quality of contributions over time.

3.2 Key Authors

Bibliometric analysis is crucial in identifying key contributors and assessing their impact within the field. Research productivity, citation influence, and the H-index are central scholarly contribution indicators. Zhang Y., Zhang X., and Wang Y. emerge as leading figures across all three dimensions, demonstrating a strong balance of publication output, citation impact, and overall research influence. Other authors, such as Yang Y., stand out particularly in citation impact, while Wang H. and Liu Y. also show notable presence in the H-index rankings.

Figures 4 and 5 visually represent these trends, showcasing the top authors ranked by their number of publications (see Figure 4) and total citations (see Figure 5). These graphs provide a comprehensive overview of the authors' productivity and impact, illustrating their contributions to the scientific community.

The influence of these authors is further reflected in their H-index (see Figure 6), a metric that balances productivity (number of publications) and impact (citations per publication). H-index provides a holistic measure of an author's academic influence by combining the quantity and quality of their research output. It is beneficial for comparing researchers at different career stages, offering insights into both the breadth and depth of their contributions [10].

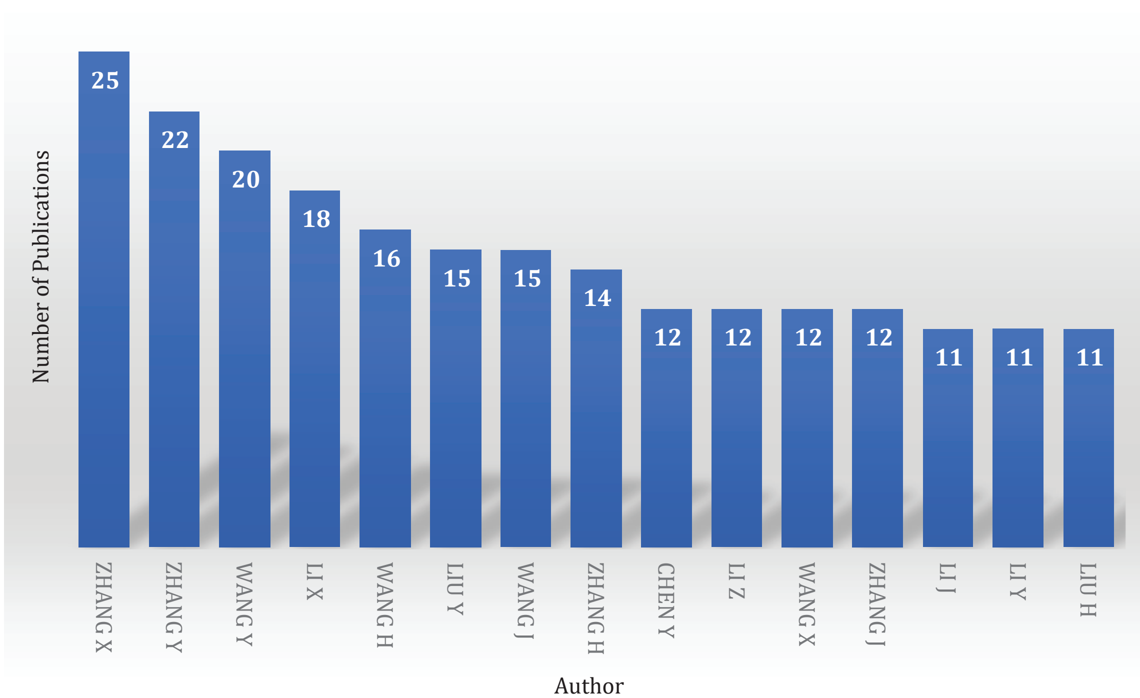

Figure 4 Top Authors by Publications.

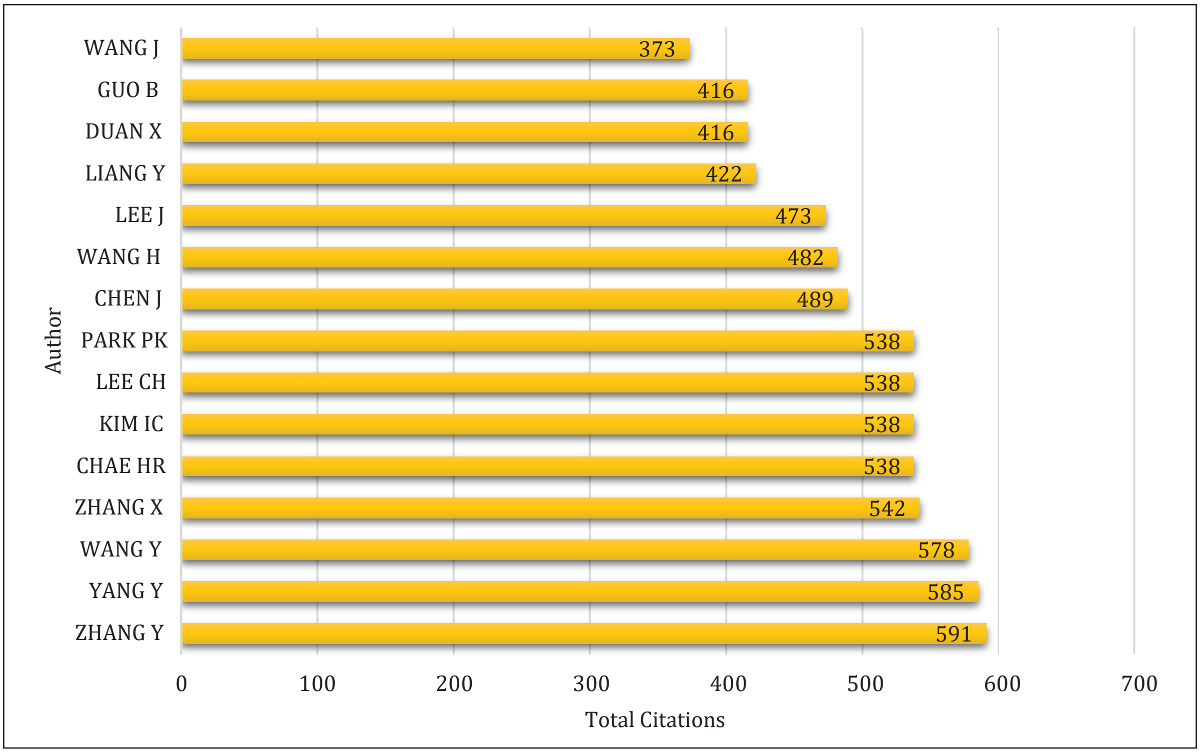

Figure 5 Top Authors by Citations.

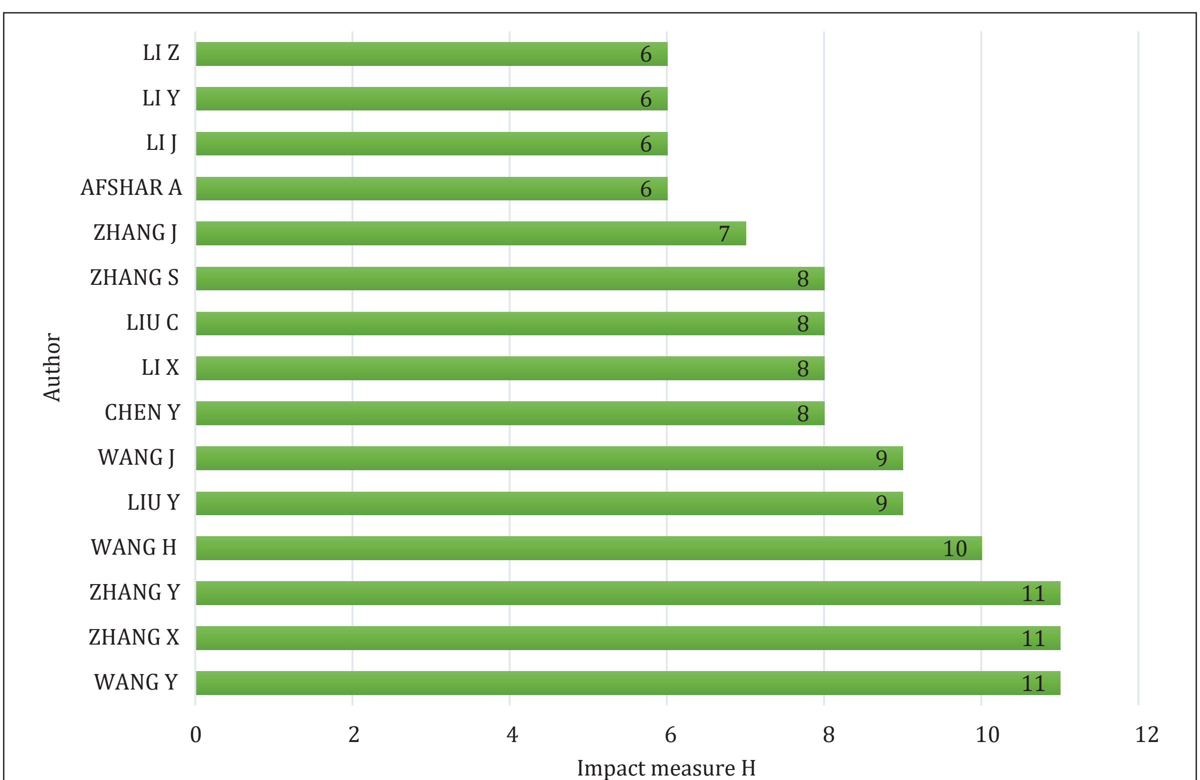

Figure 6 Authors Local Impact by H index.

3.3 Collaborative Networks

Collaborative networks provide a deeper understanding of the relationships and linkages among researchers, institutions, and regions. Analyzing collaborative networks can reveal key influencers, dominant research hubs, and the thematic focus of different collaborative groups. As shown in Figure 7, the clustering analysis visualizes connections among authors and their contributions to thematic areas within the field. In this network, node size represents the number of publications per author, link thickness indicates the strength of bibliographic coupling (shared references), and colors denote distinct thematic clusters automatically detected by the Bibliometrix tool. This network demonstrates how researchers are grouped based on their collaborations and shared focus areas. Visualization helps identify influential authors and the collaborative dynamics driving research development. Such analyses provide insights into the structure of research communities and their thematic orientations [5].

At the institutional level, Figure 8 provides a detailed visualization of the collaboration network among institutions. This network highlights key institutions such as Guangdong University of Technology, South China University of Technology, Tsinghua University, and Cracow University of Technology, which act as significant hubs of research activity and collaboration. Visualization demonstrates how institutions are interconnected through joint research efforts. These clusters also showcase opportunities for strengthening regional and international collaborations.

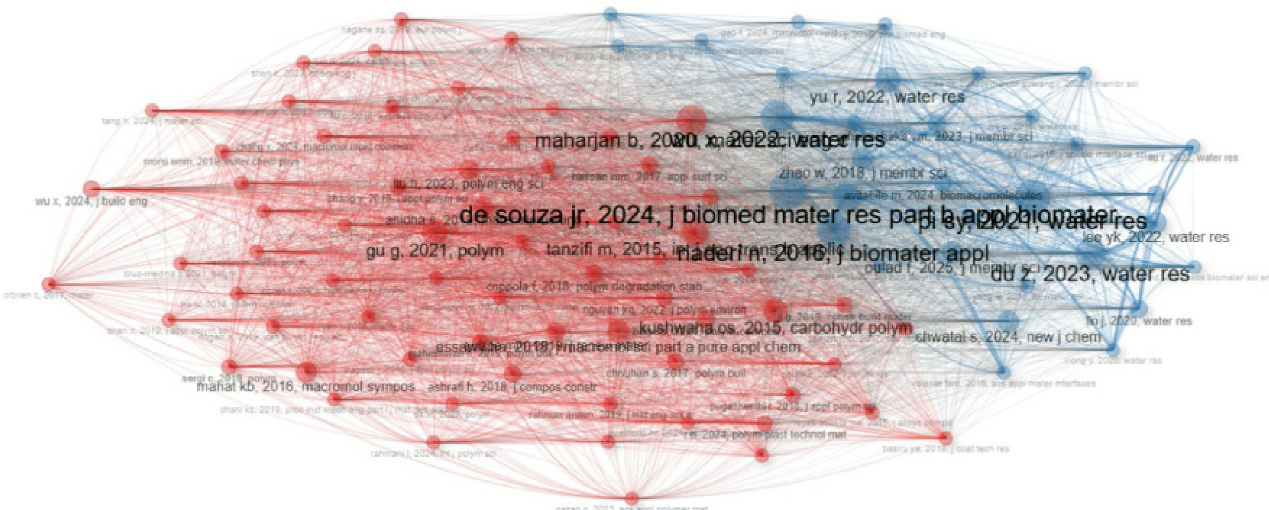

Figure 7 Clustering by coupling measure based on author contributions and thematic areas.

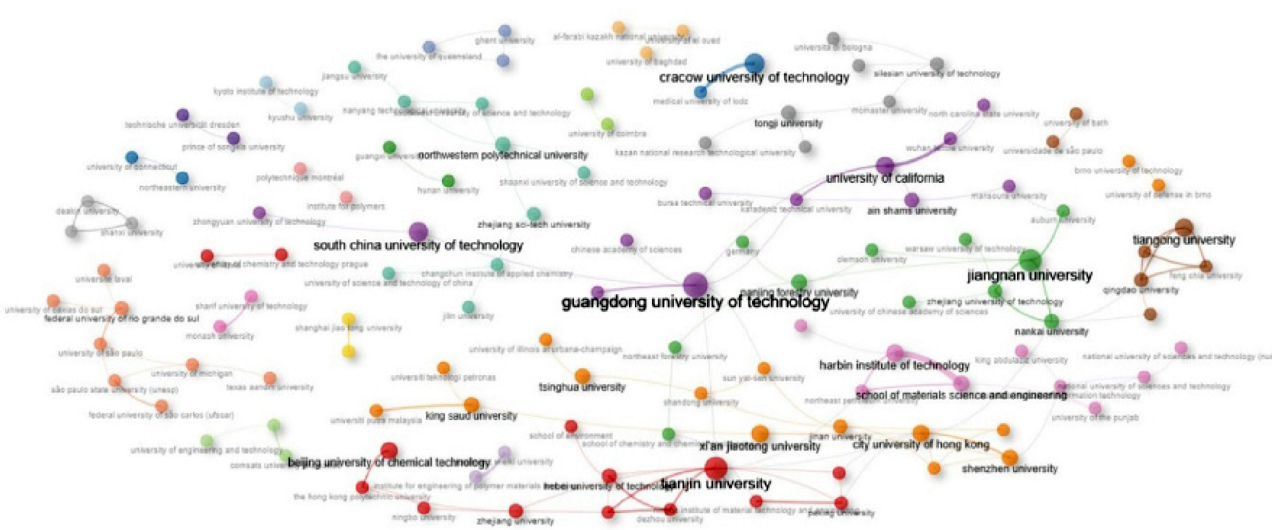

Figure 8 Clustering by coupling measure based on shared references.

An analysis of country-level contributions highlights the leadership of nations such as China, the United States, and Germany. Figure 9 provides a visualization of the collaboration density among countries, emphasizing the concentration of research activity and partnerships. The density map highlights China as the central hub, with significant collaboration extending to countries such as the United States, Japan, and Germany.

The diversity of collaborative networks also extends to thematic mapping. Figure 10 provides a co-citation network density map, highlighting influential researchers and their connections through shared citations. Larger and more central nodes represent highly cited studies that have significantly shaped research directions in materials science and degradation prevention. The visualization demonstrates how different scientific contributions are interconnected, forming key thematic clusters within the field. Instead of direct institutional collaboration, this network illustrates how knowledge develops through cumulative citations across disciplines. Such co-citation relationships reveal interdisciplinary links between research areas.

Understanding the distinction between the most published authors and the co-citation analysis provides deeper insight into research impact. While Figures 4 and 5 highlight authors with the highest publication and citation counts, such as Wang, Zhang, and Liu, Figure 10 presents a co-citation network, where frequently cited works appear together in the literature. The prominence of Kumar B.G. (2002) and Yousif E. (2013) in this analysis, despite the study focusing on 2015–2025, suggests that their foundational contributions continue to shape contemporary research [11], [12]. This differentiation underscores how scientific progress is both driven by prolific researchers and shaped by key influential studies over time.

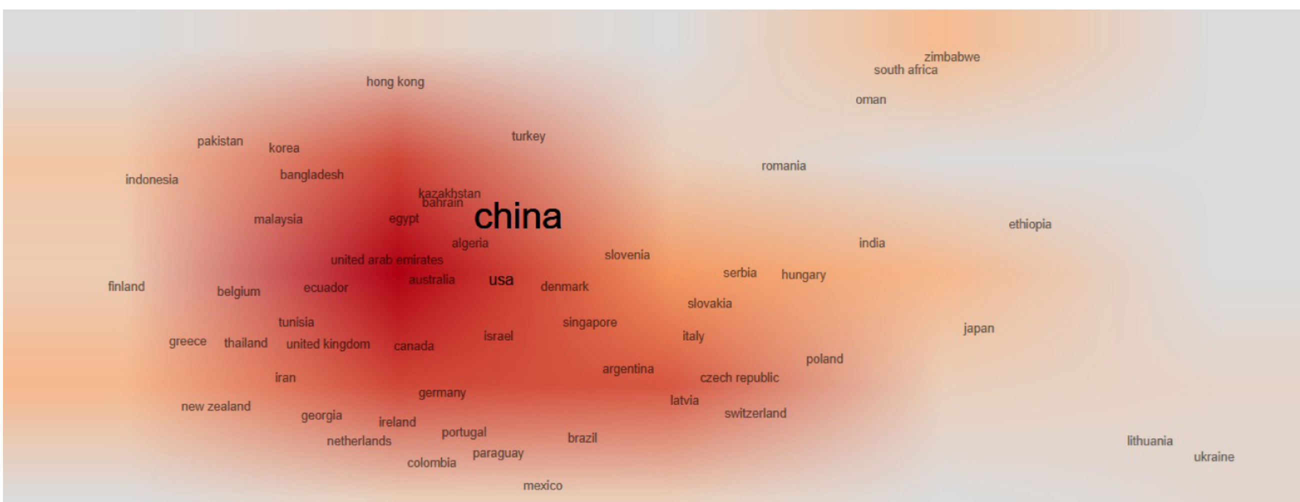

Figure 9 Country collaboration density map.

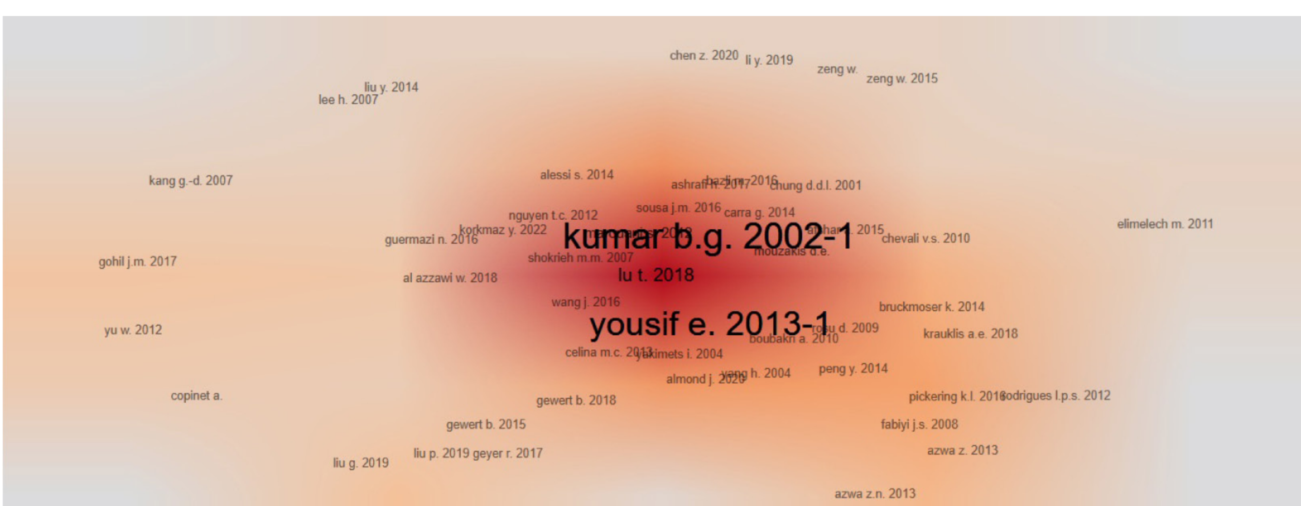

Figure 10 Co-citation network density showing influential researchers and their connections.

3.4 Leading Journals and Source Analysis

This section analyzes the most productive and influential journals in the field, their thematic focuses, and their evolution over time. Figure 11 illustrates the dynamic changes in journal productivity in this topic over the years, providing insights into the evolving trends within the publication landscape. The analysis highlights six most influential journals contributing to this research area, including Construction and Building Materials, Journal of Applied Polymer Science, Journal of Membrane Science, Materials, Polymer Degradation and Stability, and Polymers. Over the years, Polymers has shown a significant increase in published articles, reaching its peak in 2024, reflecting a growing research focus in the field. Meanwhile, Journal of Membrane Science and Materials have demonstrated steady growth, maintaining a consistent presence in academic publishing throughout the analyzed period. In contrast, Journal of Applied Polymer Science and Polymer Degradation and Stability have exhibited more variable publication patterns, with fluctuations in output, yet they have re-

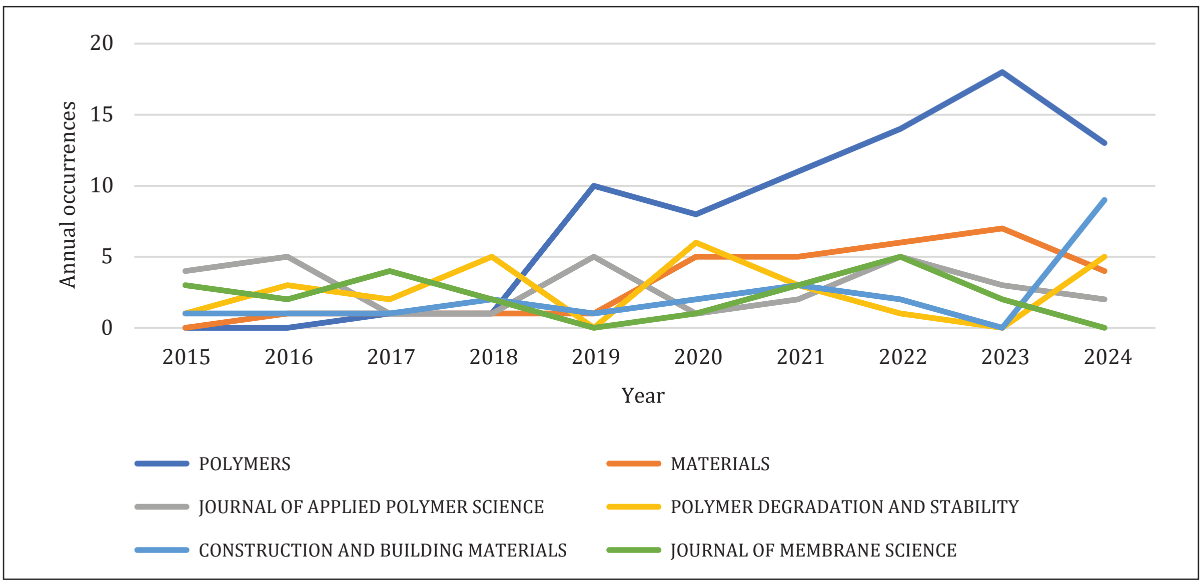

Figure 11 Dynamic changes in journal productivity over the years.

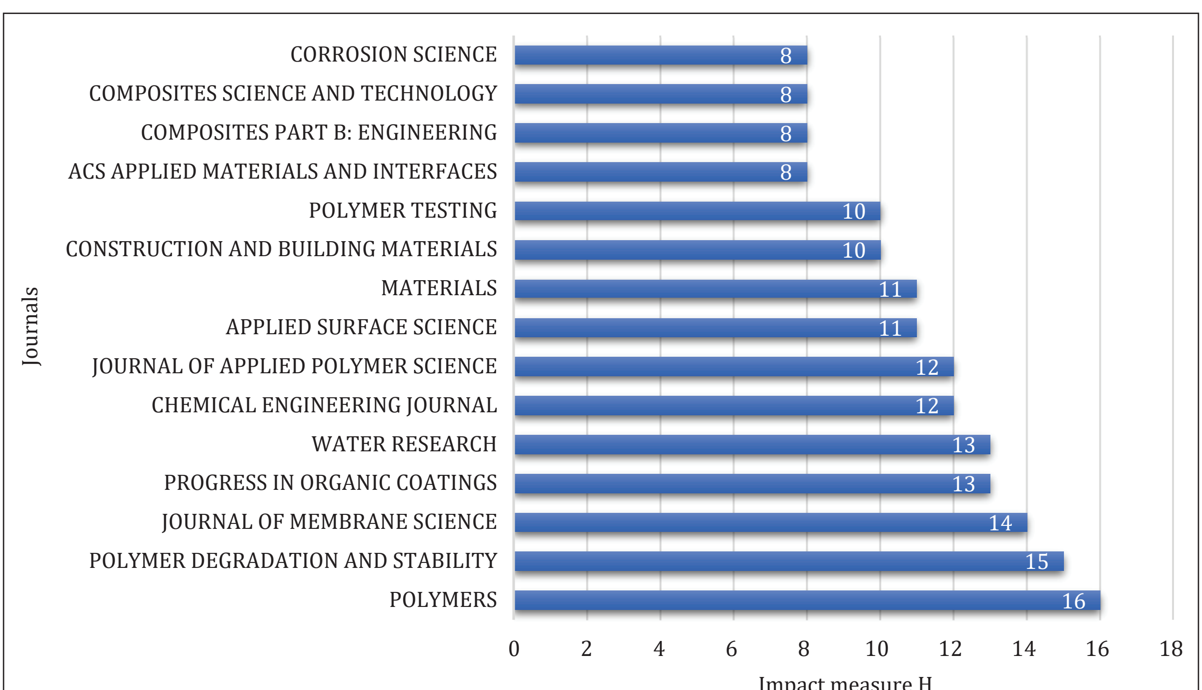

Figure 12 Impact factor analysis of sources by H index.

mained important sources of research contributions over the past decade. Construction and Building Materials have also maintained relevance in materials science, contributing consistently to the field.

In terms of impact, Figure 12 visualizes the impact factors of key journals, based on their H-index. The H-index for journals reflects both the number of published articles and their citation impact over time. It was selected as a robust indicator within the Bibliometrix environment, offering a balanced long-term view of journal influence compared to short-term metrics such as Impact Factor or Cite Score. Journals like Corrosion Science, Polymers, and Polymer Degradation and Stability stand out for their high impact, indicating their role in publishing influential studies.

In addition to analyzing journal productivity and impact, it is important to explore the connections between authors, keywords, and journals. Figure 13 presents a three-field plot (Authors, Keywords, and Sources), showing how key authors focus on specific research topics and which journals publish their work. The three-field plot reveals several notable trends:

- Prominent authors, such as Zhang Y., Liu H., and Chen Y., are heavily associated with core topics like "UV degradation", "chlorination" and "polymer composites", reflecting their significant contributions to the field.
- Keywords like "mechanical properties", "UV radiation", and "degradation" emerge as central thematic areas, underscoring the focus on material performance under environmental stressors.
- Journals such as Polymers, Materials, and Journal of Applied Polymer Science dominate the publication landscape, serving as key venues for high-impact research in this domain.

3.5 Thematic Clusters and Keyword Analysis

Thematic clusters and keyword analysis provide a comprehensive overview of the primary research areas in materials science and engineering, showcasing their evolution and interconnections. By analyzing keyword co-occurrence networks and clustering methods, the study identified three dominant thematic clusters that represent the core focus areas of the field. Environmental stressors and their impact on material performance form a significant cluster. Keywords such as "mechanical properties", "UV radiation", "degradation", "polypro-

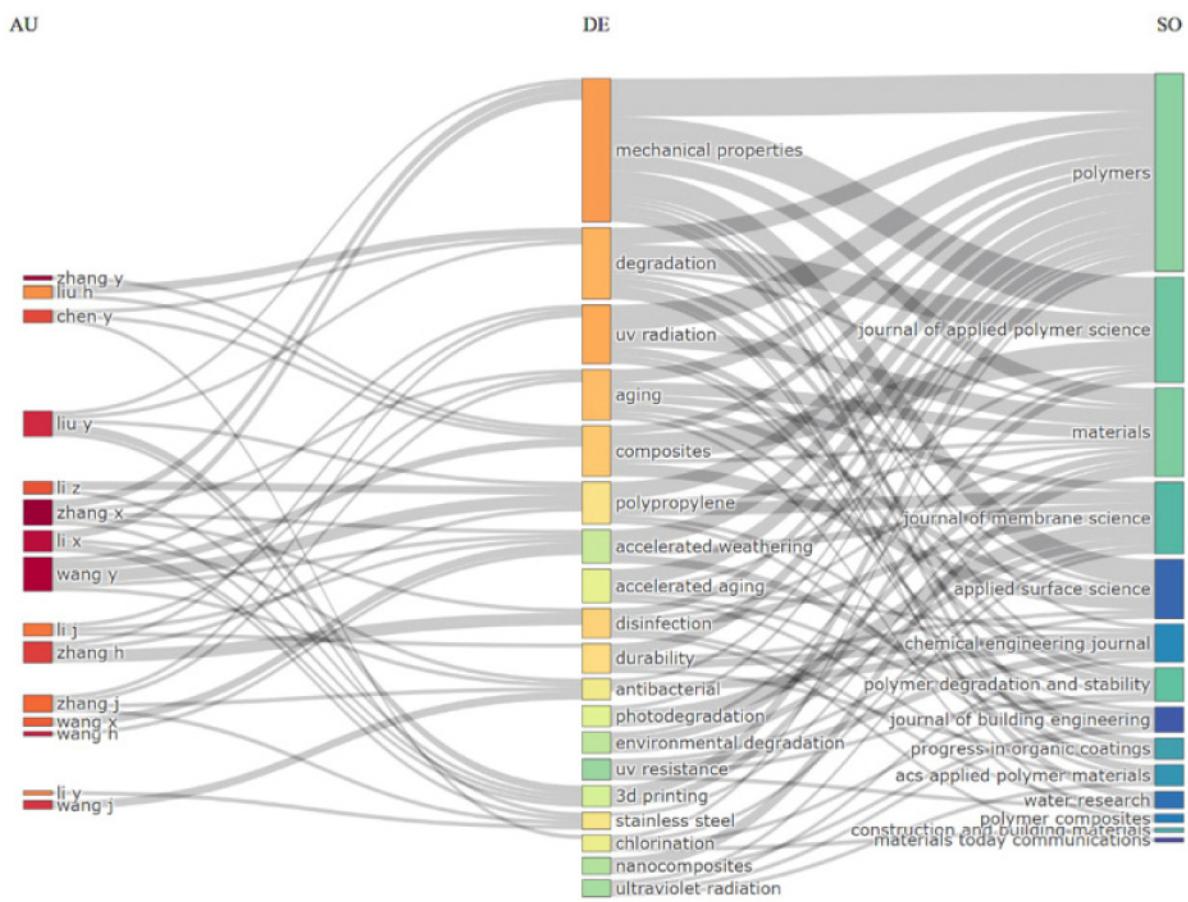

Figure 13 Three-field plot linking authors, keywords, and journals.

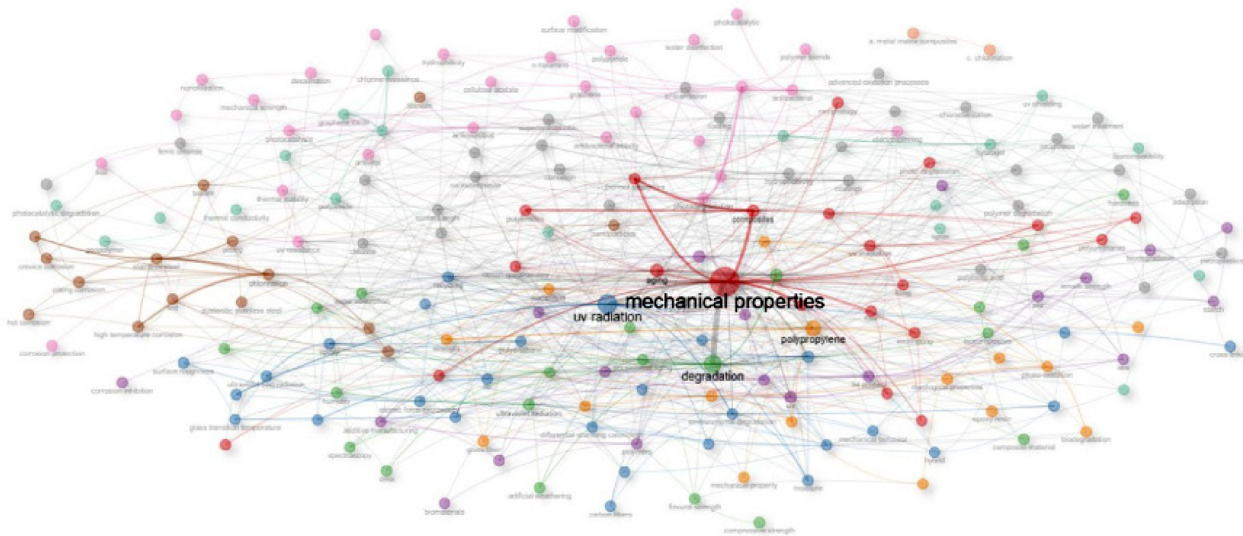

Figure 14 Keyword network linking environmental stressors to material degradation.

pylene", "corrosion resistance" and "ageing" dominate this theme, reflecting the emphasis on understanding how they degrade materials. Figure 14 provides a thematic map that visualizes these interrelated topics, showing the strong link between environmental factors and material degradation.

Alongside environmental stressors and sustainable materials, researches also explore material durability and degradation processes. Keywords such as "mechanical properties", "durability" and "environmental degradation" highlight studies examining how materials respond to factors like "UV radiation", "chlorination" and "accelerated weathering". Understanding these interactions is essential for improving material performance and longevity. Figure 15 presents a dendrogram that illustrates the hierarchical relationships between key research topics. Broad themes such as "stainless steel", "mechanical properties" and "environmental degradation" branch into more specific subtopics, revealing connections between material properties, degradation mechanisms, and environmental factors. This structure demonstrates how different areas of materials science intersect, reflecting the interdisciplinary nature of the field.

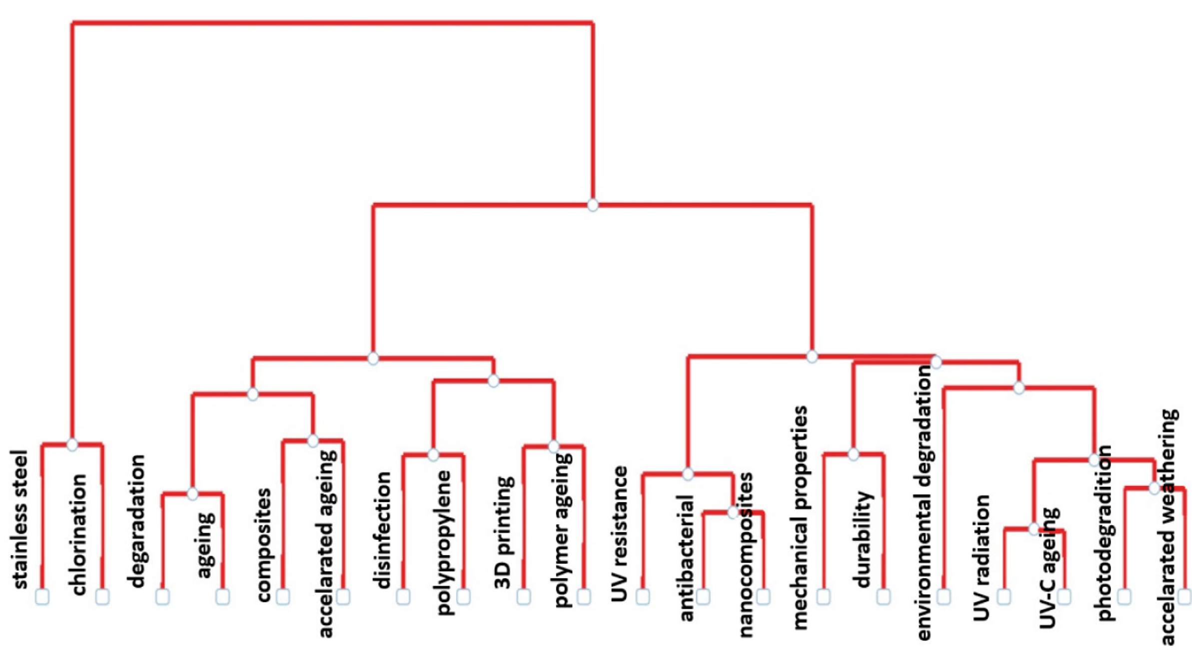

Figure 15 Dendrogram of Research Topics.

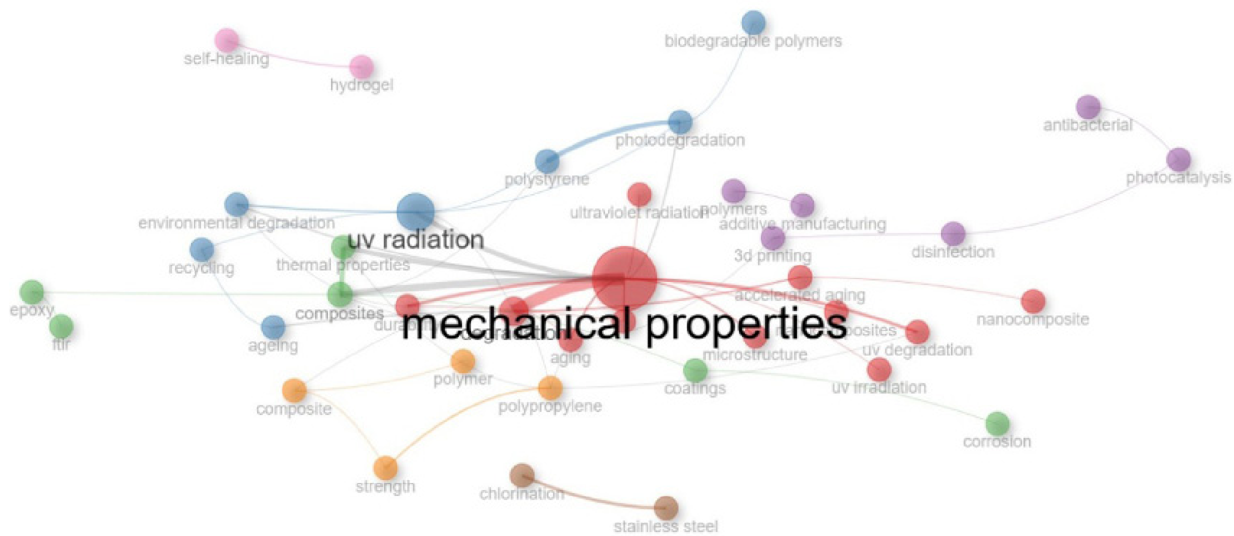

Figure 16 Keyword co-occurrence network.

Building on these insights, the analysis further explores how frequently used terms in materials science are interconnected, revealing key thematic relationships that shape the field. Figure 16 shows a keyword co-occurrence network that maps how different research topics in materials science are linked, helping to identify the most relevant areas of study. The most important term in the network is "mechanical properties", which stands out as a central theme. It has strong connections to "ageing", "composites" and "polymer" showing that much of the research revolves around modern materials used in shipbuilding and marine engineering. The close link between "ageing" and "UV radiation" highlights how exposure to sunlight and other environmental factors gradually weakens materials, leading to degradation over time. Connections to "composites" and "polymer" suggest that scientists are actively working on improving materials by making them stronger, more flexible, and more resistant to external influences. Other keywords like "coatings", "disinfection" and "biodegradable polymers" point to ongoing efforts to create protective layers and sustainable materials that can last longer while reducing environmental impact. These topics show that researchers are not only focusing on durability but also looking for eco-friendly alternatives that balance performance with sustainability.

4 Critical Review

This section provides a critical review of research on the environmental effects on materials, categorized by different types of environmental stressors. It synthesizes key findings, compares similar studies, and highlights practical implications, with a primary focus on the maritime industry. Building on the bibliometric analysis presented in Chapter 3, this review contextualizes the most cited themes and research directions by examining the experimental and engineering literature in greater depth. However, due to the need for a comprehensive bibliometric analysis, the dataset also incorporates research from broader material science and engineering disciplines, ensuring a more complete understanding of material degradation mechanisms. Understanding the effects of UV radiation, chlorination, corrosion, disinfection and their combined influences is essential for developing durable and sustainable materials for shipbuilding, offshore installations, and other marine applications [13].

4.1 Effect of Seawater and Moisture

Seawater absorption significantly impacts the mechanical properties of materials, and that is especially true for different types of polymers and polymer-based composites. In the marine industry, the most commonly used resins for composite materials include polyester, vinyl ester, and epoxy. The reinforcing fibers are typically composed of glass, carbon, or para-aramid. The most widely used composite material combinations are glass-fiber reinforced polyester (GFRP), aramid fiber composites, and carbon fiber-reinforced epoxy composites (CFRP) [14]. Water molecules interact with the matrix polymer, leading to plasticization, which in turn causes matrix cracking, void formation (potential crack initiation points), delamination, and blistering [15]. To evaluate the effect of seawater exposure on the mechanical properties of composites, a standard procedure involves submerging test samples in water, periodically measuring their weight until saturation, and then comparing the mechanical properties of dry and wet samples. However, to expedite the testing, accelerated methods have been developed. They involve heating the water to speed up diffusion and reduce the time required for full saturation. These tests are conducted in controlled ageing chambers, where parameters such as temperature, humidity, and UV exposure are monitored. Changes in mechanical properties are analyzed using techniques like energy-dispersive spectroscopy (EDS), dynamic mechanical analysis (DMA), and scanning electron microscopy (SEM). Additionally, mass variations indicate moisture content levels in the material [16].

Hakansson et al. [17] conducted a parametric study based on Det Norske Veritas (DNV) rules to determine the most weight- and cost-efficient composite materials for ship construction. Their findings suggest that a paradigm shift in shipbuilding is necessary, as incorporating composite materials early in the design process presents greater opportunities compared to traditional steel and aluminum. Furthermore, inconsistencies in DNV regulations regarding the minimum thickness of composite structural elements were identified, highlighting the need for revisions to better support composite applications.

Grogan et al. [18] investigated the effects of microstructure and hydrostatic pressure on composites used in tidal energy devices. They found that voids, which can form during the manufacturing process, significantly influence moisture diffusion rates and total water absorption. Their study examined four composite materials reinforced with glass and carbon fibers. Results indicated that while hydrostatic pressure accelerates initial water absorption, it does not alter the final uptake. Furthermore, after drying, the mass and volume remained unchanged, suggesting that the materials underwent permanent property changes, potentially affecting device performance. The complexity of the water absorption process underscores the need for further research and testing [19].

4.2 Effects of Chemical Treatments

Chemical treatments such as chlorination, alcohol-based treatments, and the application of hydrogen peroxide are widely applied for biofouling control and surface sanitation. However, these treatments may significantly alter the mechanical, structural, and chemical properties of marine structural materials over time. Chlorination is frequently employed for ballast water treatment and biofouling prevention in seawater systems. Studies indicate that while stainless steel (AISI 316L) possesses a protective passive layer, exposure to chlorine-based disinfectants can gradually degrade this layer, leading to changes in surface roughness and microstructure [20], [21]. Sodium hypochlorite (NaClO), a commonly used disinfectant, has been shown to interact with oxide films on AISI 316L, potentially reducing its resistance to further environmental stressors. Additionally, the effects of chlorination may be exacerbated by temperature fluctuations and prolonged exposure cycles [22]. Polymeric materials used in many applications, including acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), and thermoplastic polyurethane (TPU), also exhibit sensitivity to chemical disinfectants. Research has demonstrated that alcohol-based treatments and hydrogen peroxide sterilization can induce degradation by promoting surface roughness, loss of plasticizers, and microstructural changes [23], [24]. Additive-manufactured polymer components, commonly used in medical applications, are particularly vulnerable due to their porous structure, which allows disinfectants to penetrate and compromise mechanical integrity [25]. Alcohol-based disinfectants, such as ethanol and isopropanol, have been widely used due to their effectiveness in microbial control. However, prolonged exposure to alcohol-based solutions has been found to decrease the tensile strength of 3D-printed ABS and PETG parts by nearly 20%, highlighting potential risks for polymer-based coatings and structural components [24].

Incorporating protective coatings and optimizing material selection are crucial in mitigating the adverse effects of chemical disinfection. Studies on antimicrobial TiO_2 nanocomposite coatings suggest potential improvements in biofouling resistance while maintaining material integrity under chemical exposure [26]. Future research should focus on the long-term effects of repeated disinfection cycles and their impact on polymer composites and metal alloys in marine environments. To improve the durability of marine materials exposed to chemical disinfection, alternative alloys or protective coatings can be used to resist chlorine-induced degradation, polymer compositions can be optimized to minimize disinfectant absorption, routine inspections can ensure material integrity, and hybrid approaches, like UV treatment with minimal chemicals, can be explored.

4.3 UV Radiation and Photodegradation

Ultraviolet (UV) radiation is a significant environmental factor contributing to material degradation in marine structures, particularly affecting polymers, coatings, and composite materials. Prolonged UV exposure leads to photodegradation, causing surface oxidation, loss of mechanical properties, and discoloration, which can impact the longevity and performance of structural components in maritime environments. Polymeric materials used in marine applications, such as polyethylene (PE), polypropylene (PP), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG), exhibit varying degrees of susceptibility to UV-induced degradation. Studies show that UV-A and UV-B radiation cause oxidation and surface embrittlement, while UV-C exposure accelerates chain scission, leading to significant mechanical property loss [27], [28]. Research on 3D-printed polymers further highlights that prolonged UV-C exposure reduces the tensile strength of PETG by over 30%, while PLA experiences a 6–8% reduction in mechanical properties [29]. Photodegradation mechanisms primarily involve the breakdown of polymer chains, resulting in surface microcracking and increased brittleness. Studies indicate that UV-induced oxidation in low-density polyethylene (LDPE) leads to cavitation and crack propagation, reducing material integrity under mechanical stress [27]. In composite materials, such as carbon fiber-reinforced polymers (CFRP) and epoxy-based coatings, UV exposure contributes to resin matrix degradation, impacting mechanical performance. Research shows that prolonged UV radiation causes a decrease in interlaminar shear strength and fiber-matrix adhesion, leading to delamination in carbon-epoxy composites [30]. Moreover, UV exposure reduces surface gloss and increases surface roughness in epoxy-based coatings, further accelerating degradation. Mitigating UV-induced damage requires protective strategies, such as incorporating UV stabilizers, applying reflective coatings, and selecting inherently UV-resistant materials. Studies on ZnO and TiO_2 nanocomposite coatings demonstrate enhanced UV shielding, reducing the rate of photodegradation in polymer-based coatings [26], [31]. Additionally, hybrid protection approaches combining UV-blocking additives with moisture-resistant coatings show promise in extending the service life of marine structural materials [32]. To enhance the durability of marine materials under UV exposure, selecting the right materials, applying protective coatings, and performing regular maintenance can help reduce photodegradation and preserve structural integrity in the long term.

4.4 Coupled Effects

The degradation of marine structural materials is rarely caused by a single environmental factor. Instead, multiple stressors often act simultaneously, leading to complex and accelerated deterioration mechanisms. Understanding these coupled effects is crucial for predicting material performance in real-world conditions and developing more resilient materials for marine applications.

One of the most important coupled effects is the interaction between different types of surface treatments (UV, chemical) and seawater exposure, leading to corrosion [33]. Pitting corrosion is particularly concerning as it affects passive films on steel and other alloys commonly used in marine environments [34]. Research on 316L stainless steel has shown that additively manufactured components, particularly those produced via selective laser melting (SLM), exhibit increased susceptibility to localized corrosion due to the presence of lack-of-fusion (LOF) pores, which act as preferential initiation sites [35]. Furthermore, to mitigate corrosion risks, various protective coatings have been developed, including chromium diffusion layers and nickel-chromium surface treatments, which have shown significant improvements in corrosion resistance. These coatings effectively enhance the durability of ferritic-martensitic steels, particularly in chloride-rich and high-temperature environments, by forming a protective Cr-rich layer that minimizes active dissolution. In addition, Ni-based coatings have demonstrated promising resistance to KCl-induced corrosion, making them a viable option for structural materials exposed to aggressive marine conditions. Ongoing research continues to explore optimized formulations and application techniques to further enhance the longevity of these protective layers and improve their performance in extreme marine environments [36]. Looking ahead, advancements in additive manufacturing techniques present both challenges and opportunities for corrosion mitigation. Optimizing processing parameters to minimize porosity and defects is essential to improving the corrosion resistance of marine structural materials [22]. Future research should also emphasize the advancement of machine learning models for predicting long-term corrosion behavior, which could enhance the optimization of material selection and maintenance strategies for marine infrastructure [37].

Interaction between UV radiation and chemical exposure accelerates the degradation of both polymers and metals. UV exposure induces surface oxidation and embrittlement in polymeric materials such as polyethylene (PE), polypropylene (PP), and acrylonitrile butadiene styrene (ABS). When combined with chemical disinfectants, such as NaClO or alcohol-based treatments, this effect is amplified, leading to increased microstructural damage and loss of mechanical integrity. Similarly, exposure to hygrothermal cycling and SO_2 pollutants results in surface erosion, reducing hydrophobicity and accelerating the degradation of protective coatings on marine materials [38], [39]. UV exposure accelerates oxide film formation, altering electrochemical behavior in metals such as Zr alloys and galvanized steel, particularly in chloride-rich environments [40]. To mitigate these combined effects, research has focused on the development of multi-functional protective coatings that incorporate UV stabilizers, corrosion inhibitors, and hydrophobic layers to improve durability under multi-factorial exposure conditions [31]. Future research should place greater emphasis on the synergistic effects of environmental stressors, further integrating novel material design and advanced protective strategies.

5 Discussion

This section discusses the limitations of current research, identifies underexplored areas, and outlines potential directions for future investigations.

While substantial research has been conducted on individual stressors such as sea exposure, UV radiation, and chemical treatments, there remains a lack of comprehensive studies addressing their combined effects in realistic maritime conditions. However, in maritime environments, materials are simultaneously exposed to multiple stressors, and their interactions can significantly alter degradation mechanisms. This gap suggests a need for multi-factor experimental designs that assess combined effects over extended exposure periods [41], [42].

Additionally, much of the research is conducted in controlled laboratory settings, which may not accurately replicate the dynamic and often unpredictable nature of real-world marine conditions. Studies investigating field exposure in operational environments—such as ship hulls, offshore structures, and ballast water treatment systems—are relatively scarce. Without real-world validation, the applicability of existing degradation models remains uncertain [43], [44].

Another critical limitation is the lack of long-term studies. While accelerated ageing tests provide insights into short-term material behavior, the long-term effects of prolonged environmental exposure remain insufficiently understood. Given that marine structures are designed for decades of service, research should focus on developing longitudinal studies that monitor materials under continuous stressors over extended durations, as seen in investigations examining the durability of composite materials in extended exposure conditions [42], [45], [46].

Although significant progress has been made in understanding the degradation mechanisms of traditional materials such as AISI 316 stainless steel, there is limited research on how emerging materials (such as composites, advanced polymers, and nanomaterials) perform under marine environmental stressors. The increasing use of composite materials in shipbuilding and offshore engineering necessitates deeper studies into their resistance to combined degradation factors [3], [47], [48]. Furthermore, protective strategies against environmental degradation remain fragmented. While coatings and inhibitors have been widely studied for corrosion prevention, fewer studies investigate multifunctional protective layers that can simultaneously mitigate UV degradation, biofouling, and chemical attack. Recent work on antibacterial coatings suggests promising solutions for improving surface durability, while developments in graphene oxide membranes indicate a potential for enhanced resistance to biofouling and chlorine degradation [49], [50], [51].

To address existing research gaps, future studies should focus on the following key areas:

1. Investigating combined effects: Conduct experiments assessing the simultaneous impact of sea exposure, UV radiation, chemical treatments, and mechanical and thermal stress to better understand material performance in real-world conditions [3], [52]. For instance, studies have shown that combining UV irradiation with chemical disinfectants can enhance disinfection efficiency, indicating the importance of exploring such combined effects [53], [54].
2. Long-term field studies: Establish real-world testing facilities in marine environments to monitor material degradation over extended periods. Research has demonstrated that long-term marine weathering leads to significant degradation of plastic surfaces and bulk properties, underscoring the need for prolonged field exposure studies [45], [55].
3. Advanced materials research: Evaluate the durability of next-generation materials under multiple stressor conditions. A comprehensive review has highlighted the environmental degradation of composites used in marine structures, emphasizing the necessity for advanced materials research to enhance longevity and performance [56]. Furthermore, additively manufactured materials will play a significant role in the spare parts supply chain of the maritime industry, so attention should be given to their behavior in these challenging environments.
4. Developing integrated protective strategies: Explore hybrid protective coatings that offer resistance to multiple environmental factors simultaneously. Research indicates that UV radiation can significantly degrade plastic materials, suggesting the need for protective strategies that address various environmental stressors [57], [58], [59].
5. Enhancing predictive models: Explore the use of machine learning and artificial intelligence to improve the accuracy of real-time material degradation predictions. These models can help optimize mainte-

Table 2 Summary of environmental factors affecting material degradation and future research directions.

Environmental Factor	Main Impact on Materials	Current Challenges	Recommendations for Future Research
Sea exposure and moisture	Surface degradation of metals, delamination of composites	Transferability of the results from micro- to macro-scale	Multiscale modelling of the effect
UV radiation	Degradation of polymers, oxidation of metals	Insufficient long-term testing	Investigation of new UV protective coatings
Chemical treatments	Stainless steel corrosion, polymer degradation	Understanding interactions with other factors	Experimental studies in natural marine environments
Coupled effects	Corrosion, degradation on all scales	Understanding interactions with other factors	Multi-factor laboratory testing required

nance schedules in maritime applications, reducing both costs and operational risks. While existing analyses of long-term degradation trends provide a solid foundation, advanced predictive techniques offer significant potential for further improvement [37], [60], [61].

Table 2 provides a systematic overview of key environmental factors influencing material degradation, highlighting their main impacts, current knowledge gaps, and recommended directions for future research.

6 Conclusion

This research tried to provide a comprehensive assessment of the environmental effects on material degradation, incorporating bibliometric analysis and critical review to offer a dual perspective on the topic.

Given the extensive nature of bibliometric mapping, it was necessary to explore multiple research domains beyond marine structural materials. A structured bibliometric analysis was conducted using a Boolean search strategy within Scopus, allowing for the systematic identification of key contributors, thematic trends, and emerging research fronts in material degradation studies. The analysis of nearly a thousand peer-reviewed articles enabled visualization of citation networks and interdisciplinary collaborations, particularly between materials science and marine engineering. These findings highlight the increasing research focus on sea exposure, UV degradation and chemical treatments, emphasizing the necessity of a multi-disciplinary approach in addressing environmental stressors on materials.

The critical review underscores the complex interactions between environmental stressors, demonstrating that these factors do not act independently but instead amplify mutual effects, leading to accelerated material deterioration. Besides sea exposure, the impact of UV radiation in combination with chemical treatments, has been identified as a critical area of concern. The findings highlight the urgent need for improved protective strategies, particularly in applications where materials are subject to prolonged environmental stressors.

The findings of this study hold practical implications for the development of more durable marine structural materials. By understanding the synergistic effects of different environmental stressors, engineers can design protective coatings and material treatments that enhance long-term performance.

The main contribution of this study lies in identifying specific thematic trends through bibliometric mapping and linking them with real-world material degradation mechanisms relevant to shipbuilding and marine engineering. This integrative approach provides a foundation for targeted material selection and risk assessment in harsh operational environments.

It should be acknowledged that this review does not address the quantitative reduction of material thickness, which is one of the primary engineering concerns in shipbuilding. Instead, the focus was placed on surface-level and chemical degradation mechanisms, which serve as precursors to mechanical weakening. The absence of data on thickness loss is recognized as a limitation of this work, and future research should aim to integrate both surface phenomena and long-term dimensional loss into a comprehensive assessment of material ageing in marine structures.

Future studies should focus on real-world exposure testing and the integration of machine learning models to predict material degradation under combined environmental stressors.

This research is limited by its reliance on existing literature and bibliometric data, which may exclude relevant but uncatalogued studies. Furthermore, the study does not include experimental validation, which should be addressed in future research to confirm theoretical findings and strengthen practical applications.

Expanding the intersection of bibliometric insights and material science innovations will be crucial for guiding future advancements in material durability, sustainability, and cost-effectiveness.

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Appendix A: Detailed Search Strings

Step	Search String	Results
1	TITLE-ABS-KEY ("environmental aging")	663
2	TITLE-ABS-KEY ("environmental aging" OR "polymer*" OR "plastic*" OR "composite*" OR "ASA" OR "ABS" OR "PLA" OR "stainless steel" OR "AISI 316")	6.233.759
3	TITLE-ABS-KEY(("polymer*" OR "plastic*" OR "composite*" OR "ASA" OR "ABS" OR "PLA" OR "stainless steel" OR "AISI 316") AND ("chlorination" OR "chlorine exposure" OR "disinfection" OR "UV-C" OR "UV radiation" OR "ultraviolet exposure" OR "alcohol disinfection" OR "chemical disinfection"))	19.054
4	TITLE-ABS-KEY(("polymer*" OR "plastic*" OR "composite*" OR "ASA" OR "ABS" OR "PLA" OR "stainless steel" OR "AISI 316") AND ("chlorination" OR "chlorine exposure" OR "disinfection" OR "UV-C" OR "UV radiation" OR "ultraviolet exposure" OR "alcohol disinfection" OR "chemical disinfection") AND ("mechanical properties" OR "strength" OR "tensile properties" OR "surface roughness" OR "material degradation" OR "aging" OR "corrosion"))	3.702
5	TITLE-ABS-KEY(("polymer*" OR "plastic*" OR "composite*" OR "ASA" OR "ABS" OR "PLA" OR "stainless steel" OR "AISI 316") AND ("chlorination" OR "chlorine exposure" OR "disinfection" OR "UV-C" OR "UV radiation" OR "ultraviolet exposure" OR "alcohol disinfection" OR "chemical disinfection") AND ("mechanical properties" OR "strength" OR "tensile properties" OR "surface roughness" OR "material degradation" OR "aging" OR "corrosion")) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND (LIMIT-TO(SUBJAREA, "MATE") OR LIMIT-TO(SUBJAREA, "ENGI"))	1.318
6	TITLE-ABS-KEY(("polymer*" OR "plastic*" OR "composite*" OR "ASA" OR "ABS" OR "PLA" OR "stainless steel" OR "AISI 316") AND ("chlorination" OR "chlorine exposure" OR "disinfection" OR "UV-C" OR "UV radiation" OR "ultraviolet exposure" OR "alcohol disinfection" OR "chemical disinfection") AND ("mechanical properties" OR "strength" OR "tensile properties" OR "surface roughness" OR "material degradation" OR "aging" OR "corrosion")) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND (LIMIT-TO(SUBJAREA, "MATE") OR LIMIT-TO(SUBJAREA, "ENGI")) AND (LIMIT-TO(LANGUAGE, "English")) AND (LIMIT-TO(PUBSTAGE, "final")) AND (LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(SRCTYPE, "j"))	992