A Bibliometric Analysis of the Application of Biomimicry in Water Conservation

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Article Info

Article history:

Received June, 2026
Revised June, 2026
Accepted June, 2026

Keywords:

Biomimicry
Bibliometric Analysis
Water Conservation
Sustainable Water Management
Scopus

ABSTRACT

This study conducts a bibliometric analysis of research on the application of biomimicry in water conservation to map its intellectual structure, thematic evolution, and global collaboration patterns. Data were retrieved from a selected scientific database and analyzed using bibliometric techniques, including co-occurrence analysis, co-authorship mapping, and density visualization. The findings reveal that biomimicry serves as a central interdisciplinary framework connecting materials science, environmental engineering, and sustainability studies. Keyword analysis identifies surface science concepts such as hydrophobicity, wettability, and contact angle as the foundational knowledge base, while applied themes including water filtration, membranes, and water treatment represent the primary technological focus. Overlay visualization indicates a temporal shift from fundamental physicochemical studies toward application-driven research in sustainable water management and biomimetic materials. Network analysis further demonstrates a highly collaborative global research structure dominated by leading countries such as the United States and China, alongside contributions from Europe and emerging economies, though with uneven participation levels.

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1. INTRODUCTION

Water scarcity has become one of the major global environmental problems in the modern era. Population growth, urbanization, industrial development, climate change, and improper use of resources have contributed significantly to water resource strain around the world [1], [2]. Based on global sustainability studies, there is evidence that many parts of the world are facing water scarcity, poor quality of water resources, and competition for water resources among different sectors such as agriculture, industry, and residential uses. Therefore, the imbalance of water demand and supply has generated concern over environmental sustainability, ecosystem stability, and human well-being [3], [4].

Conventional water conservation techniques have tended to use engineering solutions like reservoirs, pipes, desalination equipment, sewage treatment plants, and irrigation techniques [5]. While all these methods have played a great role in improving water security, a large number of them are expensive in terms of cost, energy usage, and the environment. The environmental problems being experienced have become increasingly sophisticated, leading to the realization that any sustainable solution ought to be not only functional but also natural in its approach. Nature-inspired solutions can therefore be seen to be a new trend in addressing some of the environmental issues that are emerging. Biomimicry represents one such solution [6], [7].

Biomimicry is defined as the science of learning from and mimicking nature's form, process, and ecosystem in order to come up with sustainable solutions to human problems. The field of study became widely known because of the work done by Janine Benyus, who defines biomimicry as an innovation paradigm that considers nature as model, measure, and mentor [8]. Instead of using natural resources, biomimicry strives to learn how nature has been able to adapt and survive through billions of years and how its lessons could be used in technology and organizational innovations. Studies have shown that biomimicry may help in achieving sustainability in terms of reducing waste production, resource efficiency, environment protection, and creation of circular resource flows.

The application of biomimicry in water conservation has garnered increased academic attention because of the high level of effectiveness demonstrated in the way nature conserves water. Various species and ecosystems have developed elaborate means of collecting, storing, filtering, transporting, and conserving water in different environments. Examples of such biological means include the use of special surface properties in desert beetles to collect water from fog, the evolution of adaptive characteristics in cacti to effectively store water, the ability of mangrove ecosystems to filter salty water naturally, and the role of wetlands as efficient water purification systems. There have been many inventions and developments based on such biological mechanisms, including water harvesting from the atmosphere, biomimetic filtration, green technologies, permeable surfaces, wastewater treatment, and nature-based urban water conservation.

During the last 20 years, an increase in scientific publications dedicated to biomimicry and their water-related applications can be observed. Development in such fields as sustainability science, environmental engineering, ecological design, and climate change adaptation research contributed to widening the scope of biomimicry studies in water conservation. Various topics were considered, starting from technological means of water harvesting, bioinspired materials, ending with ecosystem-based water management and circular water systems. However, despite the growing number of publications, the intellectual structure, thematic dynamics, collaboration network, and research trends in this area are not sufficiently known at the moment. Current review papers concentrated more on certain technologies or cases rather than on overall scientific field analysis. That is why there is a necessity of conducting a systematic bibliometric study aimed at revealing development, research hotspots, most significant publications, and research trends in biomimicry applications for water conservation. Bibliometric analysis represents an appropriate methodological tool for solving this task because of quantitative evaluation and visualization possibilities.

Despite the substantial growth of research activities concerning the connection between biomimicry and water conservation, there is a need for an integrative bibliometric review to systemically examine the intellectual basis, thematic structure, important authors, and future research directions within this sphere. Earlier works usually focused either on conceptual issues, novel technologies, or particular applications of biomimicry in water management but did not give any detailed information on the evolution of research within this field. Thus, researchers find it difficult to identify key themes, collaborative patterns, knowledge gaps, and potential directions for future research. Lack of bibliometric analysis impedes efforts to systematize available literature and construct a research agenda in terms of further application of biomimicry in sustainable water conservation. The purpose of this study is to conduct a bibliometric analysis of the global scientific landscape of biomimicry applications in water conservation.

2. METHODS

The bibliometric analysis methodology has been used to conduct an analysis of the development and the intellectual structure of studies regarding biomimicry applied in water conservation. Bibliometric analysis is a quantitative approach that is used to analyze scientific literature and research trends; it helps to identify knowledge structures and relationships between publications, authors, institutions, and research areas. The source of the data used in this study has been chosen by the fact that the Scopus database is considered to be one of the biggest and multidisciplinary citation indexes. Scopus was chosen because of the broad representation of high-quality peer-reviewed journals and due to its applicability in bibliometric studies. Literature search has been performed using keywords "biomimicry," "biomimetic," "bio-inspired," "water conservation," "water management," "water harvesting," and other relevant terms. Only journal articles, conference papers, and reviews have been used for the literature search in the Scopus database. After literature search, duplicates and irrelevant articles have been excluded from the dataset.

The bibliometric data were analyzed using the software known as VOSviewer, which is a popular tool for creating and visualizing bibliometric networks. VOSviewer allows for the mapping of scientific knowledge through several methods of analysis, such as co-authorship analysis, citation analysis, co-citation analysis, bibliographic coupling, and keyword co-occurrence analysis. In the present case, keyword co-occurrence analysis was used to reveal important research themes and clusters in the field of water conservation based on biomimicry. Overlay visualization was used to analyze the development of research themes over time and to reveal new research themes, whereas density visualization was used to reveal the concentration and significance of research themes.

3. RESULTS AND DISCUSSION

3.1 Keyword Co-Occurrence Network Visualization

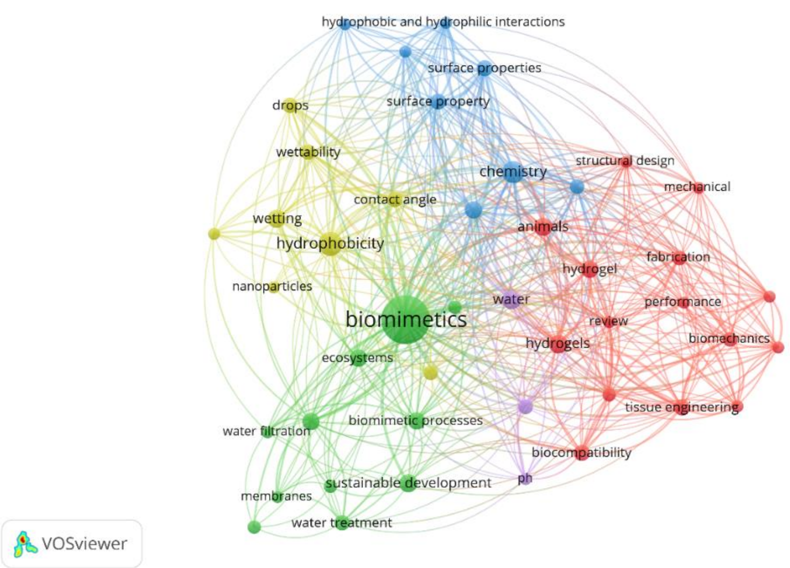

Figure 1. Network Visualization

Source: Data Analysis, 2026

Figure 1 illustrates the intellectual structure of research on biomimetics, with "biomimetics" positioned as the dominant central node. Its large size and high connectivity indicate strong co-occurrence across multiple thematic domains, confirming that biomimicry functions as an interdisciplinary bridge rather than a standalone field. The network density around the central term suggests that research in this area is highly integrative, linking environmental engineering, materials science, chemistry, and biomedical applications. In the context of water conservation, this centrality indicates that biomimetic principles are increasingly used as foundational design logic rather than peripheral inspiration.

A first major cluster (green) is strongly associated with environmental and water-related applications, including terms such as "water filtration," "membranes," "water treatment," "ecosystems," and "sustainable development." This cluster represents the applied sustainability dimension of biomimicry, where biological systems are translated into engineered solutions for water purification and resource efficiency. The presence of ecosystem-related terminology suggests that many studies draw from ecological functioning principles rather than isolated biological structures, emphasizing system-level imitation for water conservation technologies.

A second prominent cluster (blue/yellow) focuses on surface science and wetting phenomena, with keywords such as "hydrophobicity," "wettability," "contact angle," "surface properties," and "hydrophobic and hydrophilic interactions." This indicates a strong materials science foundation underlying biomimicry research. These concepts are essential for designing water-repellent or water-attracting surfaces inspired by natural systems (e.g., lotus leaf effect). The prominence of these terms shows that a significant portion of biomimicry research in water conservation is driven by micro- and nanoscale surface engineering.

A third cluster (red) is oriented toward advanced engineering and biomedical material applications, including "hydrogels," "tissue engineering," "fabrication," "mechanical properties," and "biomechanics." While not directly water-conservation focused, this cluster reflects methodological and material transferability of biomimetic approaches across disciplines. Hydrogels, in particular, are relevant to water retention and controlled release systems, indicating partial overlap with water-related applications. This cluster demonstrates how biomimicry research is often embedded in broader material innovation ecosystems.

The overall structure shows a highly interdisciplinary but unevenly balanced field, where fundamental material science and biomedical engineering clusters are more densely developed than direct water conservation applications. However, the bridging role of biomimetics between surface chemistry, environmental systems, and engineering design suggests a growing convergence toward sustainable water technologies. From a bibliometric perspective, the map indicates an emerging consolidation phase in which biomimicry is transitioning from conceptual inspiration into applied engineering solutions for water management and sustainability challenges.

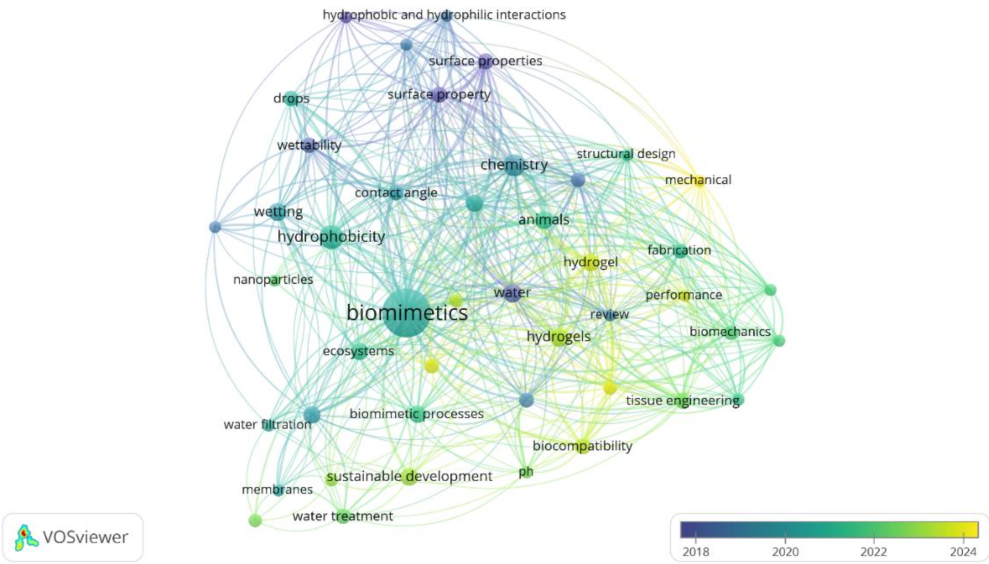

Figure 2. Overlay Visualization

Source: Data Analysis, 2026

Figure 2 represents an overlay co-occurrence network of biomimicry-related research, with "biomimetics" acting as the dominant and most interconnected node. Its central position indicates that it functions as a conceptual hub linking multiple disciplinary streams, including materials science, environmental engineering, surface chemistry, and biomedical applications. The network density around this term reflects a highly interdisciplinary knowledge structure, where biomimicry is not confined to a single application domain but operates as a cross-cutting design paradigm.

A major thematic concentration appears in surface science and interface phenomena, indicated by terms such as "hydrophobicity," "wettability," "contact angle," "surface properties," and "hydrophobic and hydrophilic interactions." This cluster represents the foundational physical-chemical mechanisms that underpin many biomimetic water-related technologies, particularly those inspired by natural non-wetting surfaces. Closely connected terms like "nanoparticles" and "drops" further suggest that nanoscale engineering and interfacial fluid dynamics are key research drivers within this domain.

A second major application-oriented structure is visible in environmental and engineering systems, with keywords such as "water filtration," "membranes," "water treatment," and "sustainable development." This indicates a direct translation of biomimetic principles into water conservation technologies. The color gradient overlay (2018–2024) suggests temporal evolution, with earlier research more concentrated in fundamental surface science and more recent work increasingly shifting toward applied systems such as hydrogels, tissue engineering, and functional materials.

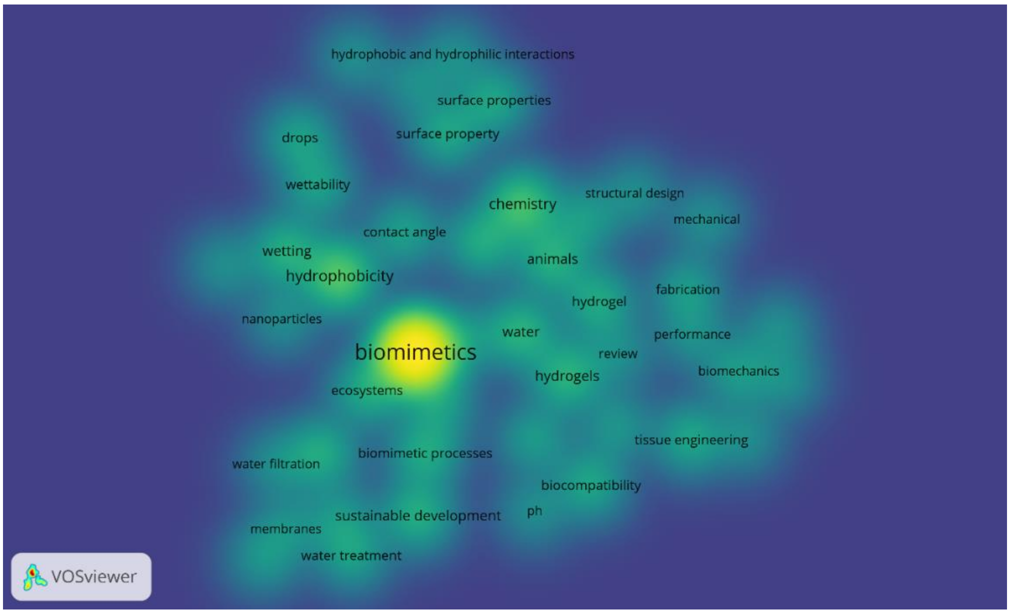

Figure 3. Density Visualization

Source: Data Analysis, 2026

Figure 3 shows the intellectual concentration of research on biomimetics, where "biomimetics" itself appears as the highest-density region (yellow core). This indicates that it is the primary conceptual anchor of the literature, with the strongest frequency of co-occurrence across publications. Surrounding it are moderately dense regions such as "hydrophobicity," "contact angle," "wettability," "surface properties," and "water," suggesting that surface science and interfacial phenomena form the dominant foundational layer of the field. These areas are tightly clustered, implying frequent joint usage and a well-established research stream focused on mimicking natural non-wetting and wetting behaviors for functional material design.

A second concentration of moderate intensity is visible in application-oriented domains, including "water filtration," "membranes," "water treatment," and "sustainable development." These indicate that biomimicry research is not purely theoretical but strongly directed toward environmental engineering solutions, particularly in water management systems. Additional clusters around "hydrogels," "tissue engineering," and "biocompatibility" suggest cross-domain diffusion into biomedical and material science applications. The spread of medium-density regions around these terms implies that while these topics are active, they are still secondary compared to the core surface science cluster.

3.2 Citation Analysis

Table 1. Top Cited Documents

Citations	Authors and Year	Title
378	[9]	Condensation on superhydrophobic surfaces: The role of local energy barriers and structure length scale
323	[10]	The dream of staying clean: Lotus and biomimetic surfaces
166	[11]	Biomimetic anisotropic hydrogels: Advanced fabrication strategies, extraordinary functionalities, and broad applications
131	[12]	Biomimetic self-cleaning surfaces: Synthesis, mechanism and applications
127	[13]	Large-Area Direct Laser-Shock Imprinting of a 3D Biomimic Hierarchical Metal Surface for Triboelectric Nanogenerators

96	[14]	Oceanic Challenges to Technological Solutions: A Review of Autonomous Underwater Vehicle Path Technologies in Biomimicry, Control, Navigation, and Sensing
89	[15]	A grand challenge for membrane desalination: More water, less carbon
83	[16]	Exploring the Role of Habitat on the Wettability of Cicada Wings
77	[17]	Time-Dependent Wetting Behavior of PDMS Surfaces with Bioinspired, Hierarchical Structures
71	[18]	CeO2-: X nanorods with intrinsic urease-like activity

Source: Scopus, 2026

3.3 Co-Authorship Analysis

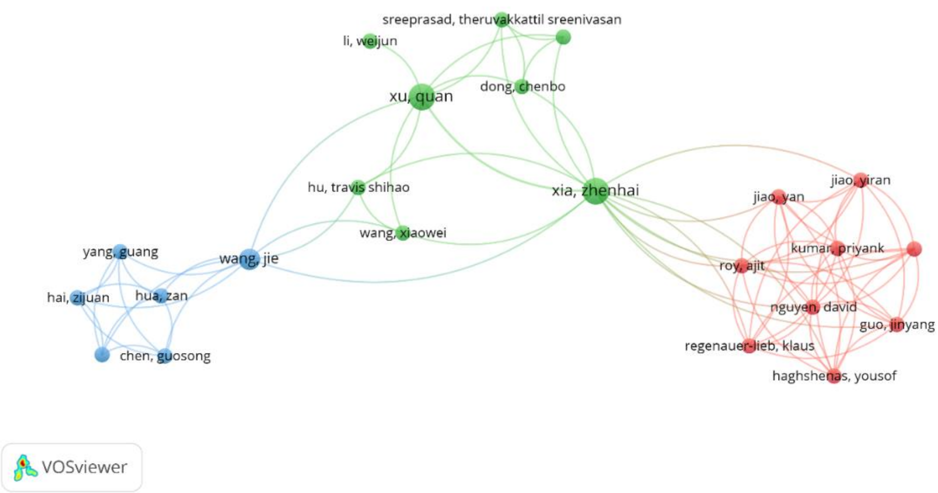

Figure 4. Author Visualization
Source: Data Analysis, 2026

Figure 4 represents a co-authorship structure in biomimicry-related research, showing three clearly separated but partially interconnected collaboration clusters. The green cluster (center) is the most structurally dominant, with Xia Zhenhai acting as a key hub that bridges multiple groups and connects peripheral authors such as Xu Quan, Dong Chenbo, and Sreenivasan. This suggests that Xia Zhenhai's group functions as an intermediary or coordinating node within the broader research ecosystem, facilitating cross-group collaboration and knowledge diffusion. The red cluster on the right, anchored by authors such as Nguyen David, Kumar Priyank, Roy Ajit, and Reganaeur-Lieb Klaus, appears to be a tightly interconnected international collaboration group with dense internal links but weaker external connections to other clusters. This indicates a relatively cohesive research team or thematic specialization that is more internally focused. The blue cluster on the left, centered around Wang Jie and connected authors such as Chen Guosong and Hua Zan, is smaller and more isolated, suggesting a more localized or specialized collaboration network.

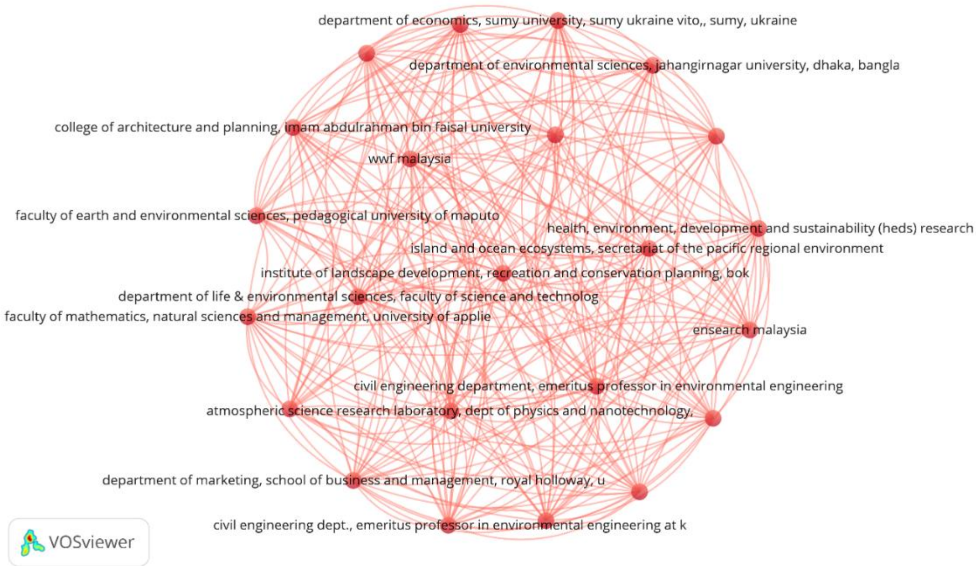

Figure 5. Institution Visualization

Source: Data Analysis, 2026

Figure 5 represents an institutional collaboration network in the biomimicry–environmental sustainability research domain. The structure is highly dense and centralized, indicating a strongly interconnected global research ecosystem with relatively low fragmentation. Most institutions are linked through a large dominant cluster (red), suggesting that collaboration is broadly distributed rather than segmented into clearly separated sub-networks. Key contributing nodes include universities and research centers from Malaysia, Ukraine, Bangladesh, and other regions, such as Sumy State University, Jahangirnagar University, Imam Abdulrahman Bin Faisal University, and Royal Holloway University of London, alongside thematic institutions like WWF Malaysia and ENSEARCH Malaysia. Their central positioning and high connectivity imply active participation in multi-institutional and cross-border research initiatives. The density of links around environmental science departments, civil engineering units, and sustainability-focused research centers indicates that biomimicry applications in this dataset are strongly embedded within environmental management, engineering, and sustainability science. Institutions related to ecosystem conservation, climate research, and environmental planning form a core thematic backbone, reflecting the applied nature of the field, particularly in water-related and ecological sustainability studies.

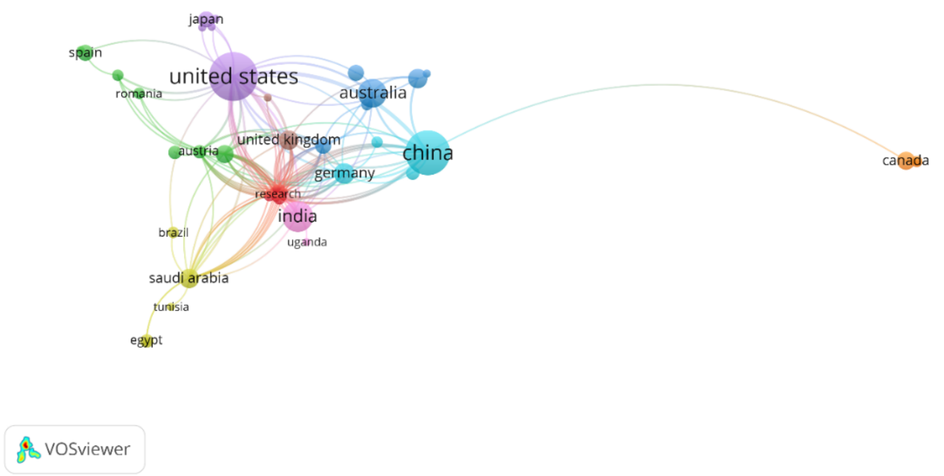

Figure 6. Country Visualization
Source: Data Analysis, 2026

Figure 6 shows a country-level co-authorship/collaboration network in biomimicry-related research, where the United States and China function as the two dominant central hubs with the highest connectivity and strongest link density. The United States occupies a slightly more central bridging position, linking multiple clusters including Europe (United Kingdom, Germany, Austria, Spain, Romania) and Asia-Pacific partners, while China appears as another major hub strongly connected to Australia, the United Kingdom, and Germany, indicating intensive bilateral and multilateral research collaboration. India is also relatively central within the network, acting as a secondary connector between developed and developing country clusters, particularly linking to the UK, Saudi Arabia, and other emerging research nodes. In contrast, countries such as Canada appear more peripheral and weaklier connected, suggesting more isolated or specialized collaboration patterns.

4. CONCLUSION

This bibliometric study on the application of biomimicry in water conservation reveals a rapidly evolving and highly interdisciplinary research landscape characterized by strong integration between materials science, environmental engineering, and sustainability studies. The keyword and thematic analyses indicate that surface science concepts such as hydrophobicity, wettability, and contact angle form the foundational core of the field, while applied domains such as water filtration, membranes, and water treatment demonstrate the practical translation of biomimetic principles into environmental solutions. Overlay and density visualizations further show a temporal shift from fundamental physicochemical mechanisms toward more application-oriented innovations, particularly in sustainable water management and advanced biomaterials. At the same time, the co-authorship, institutional, and country-level networks highlight a globally collaborative research structure dominated by a few central actors, notably the United States and China, with significant contributions from Europe and emerging economies, though with uneven participation across regions.

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