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Bibliometric Analysis of Eco-Friendly Product Design

Loso Judijanto[1], Tati Handayani[2]
[1] IPOSS Jakarta, Indonesia
[2] STIE Triguna Tangerang

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ABSTRACT

This study conducts a bibliometric analysis of eco-friendly product design research to map its intellectual structure, collaboration patterns, and thematic evolution. Data were analyzed using keyword co-occurrence, co-authorship, country collaboration, and density visualization techniques. The findings reveal that the research field is primarily centered on "eco-friendly," "product design," and "sustainable development," which serve as the core conceptual foundations. Emerging themes such as green chemistry, lifecycle assessment, circular economy, and materials performance indicate a shift toward more applied and technologically driven sustainability research. Temporal analysis further shows a transition from conceptual sustainability frameworks toward quantitative and experimental approaches in eco-design and product optimization. At the collaboration level, the co-authorship network demonstrates a relatively fragmented structure composed of several distinct research clusters with limited cross-group integration. However, certain authors and institutions act as bridging nodes that connect different clusters. At the country level, China and India emerge as dominant contributors and central hubs in global collaboration networks, while Europe maintains a stable secondary presence and other regions contribute in more peripheral but growing roles.

Corresponding Author:

Name: Loso Judijanto
Institution: IPOSS Jakarta
Email: losojudijantobumn@gmail.com

1. INTRODUCTION

The issues of environmental degradation, climate change, resource depletion, and growing amounts of industrial waste have emerged as serious global problems in the recent years [1]–[3]. The industries that cause greenhouse gas emissions and use a lot of resources have received increasing attention of the government, consumers, and environmental organizations. It has resulted in the implementation of sustainability principles into the process of creating products and the emergence of eco-friendly product design. Eco-friendly product design can be defined as the consideration of environmental aspects in the process of product creation and its entire life cycle, from the selection of materials to the usage and disposal of products [4]–[6].

In recent times, eco-product design is becoming increasingly significant in relation to sustainable development. After the introduction of [7], sustainability has become a significant issue within many academic disciplines such as engineering, industrial design, business management, and environmental science. It is now required from product designers to take into account environmental, social, and economic perspectives during the development stage. There has been emergence of some significant concepts like Design for Environment (DfE), Green Design, Sustainable Design, Eco-Design, Circular Design, and Life Cycle Design in terms of developing environmentally sound products [8]. Eco-design of products has turned out to be a multi-disciplinary research area that attracts researchers from many different disciplines.

The development of eco-friendly products has been greatly facilitated by technological advancements. The appearance of new materials, energy, digital manufacturing, artificial intelligence, and lifecycle assessment techniques has made it possible for designers to maximize environmental benefits during each stage of the product development process. Additionally, the shift from the linear approach in economics to the circular economy model has expanded the boundaries of eco-design research. The circular economy approach focuses on resource efficiency, durability, remanufacturing, repair, and recycling, which motivates designers to reconsider traditional approaches to production and consumption [9], [10]. This area of knowledge has attracted considerable academic attention and produced many publications.

The increasing number and diversity of articles related to this area have made it essential to comprehend the intellectual structure and development of the research on eco-friendly product design. The need for a complete overview of the most relevant research topics, influential articles, collaboration networks, new areas of interest, and future directions of research is necessary for scholars, policymakers, and practitioners. Bibliometrics presents an analytical tool which allows the examination of publication patterns, citation linkages, keyword co-occurrence, and thematic development in a specific field of science [11]. The use of bibliometric tools helps researchers to detect knowledge clusters, assess the level of scholarly productivity, and discover trends that would be hard to uncover using traditional methods of literature review. In this regard, a bibliometric study of eco-friendly product design literature will yield valuable results.

While the number of studies dedicated to eco-friendly product design increases, the literature still appears to be scattered among a range of fields, such as industrial engineering, environmental sciences, sustainable manufacturing, product innovation, circular economy, and consumer studies. There are many studies on certain issues associated with eco-friendly product design; nevertheless, there is not much information about the intellectual structure, evolution of topics, research streams, and trends in the field. Moreover, the fast increase in the number of publications makes it difficult for researchers to determine the dominating themes, gaps in knowledge, and future directions of the study. While some review papers have considered sustainable product development, there is a lack of bibliometric analysis of the literature specifically dedicated to eco-friendly product design. Thus, there is a need for bibliometric mapping of the field. This study aims to analyze the scientific development and intellectual structure of eco-friendly product design research through a comprehensive bibliometric analysis.

2. METHODS

This study employs a bibliometric analysis approach to systematically examine the development of research on eco-friendly product design. Bibliometric analysis is a quantitative method used to evaluate and map scientific literature by analyzing publication metadata, citation relationships, and keyword patterns [11]. The data for this study were obtained from the Scopus database, which is recognized as one of the most comprehensive and reliable sources of peer-reviewed academic publications. Scopus was selected because of its extensive coverage of high-quality journals across multiple disciplines, including environmental science, engineering, sustainability, and product design. Relevant publications were retrieved using the keyword phrase "eco-friendly product design" and related terms in titles, abstracts, and keywords. The search was limited to journal articles, conference papers, and review articles published within the selected study period. After the retrieval process, the bibliographic data, including authors, titles, abstracts, keywords, citations, affiliations, and references, were exported in CSV format for further analysis.

The bibliometric data have been analyzed through VOSviewer, a well-known tool for generating and mapping bibliometric networks [12]. VOSviewer has been employed for the purpose of conducting co-occurrence analysis of author keywords so as to find out the key themes and intellectual structures within the eco-friendly product design studies. Network visualization technique has been applied for finding the relations between keywords and thematic groups, while the technique of overlay visualization has been employed for studying the dynamics of research topics and discovering new trends. Furthermore, density visualization technique has been used to discover the most intensive research areas.

3. RESULTS AND DISCUSSION

3.1 Keyword Co-Occurrence Network Visualization

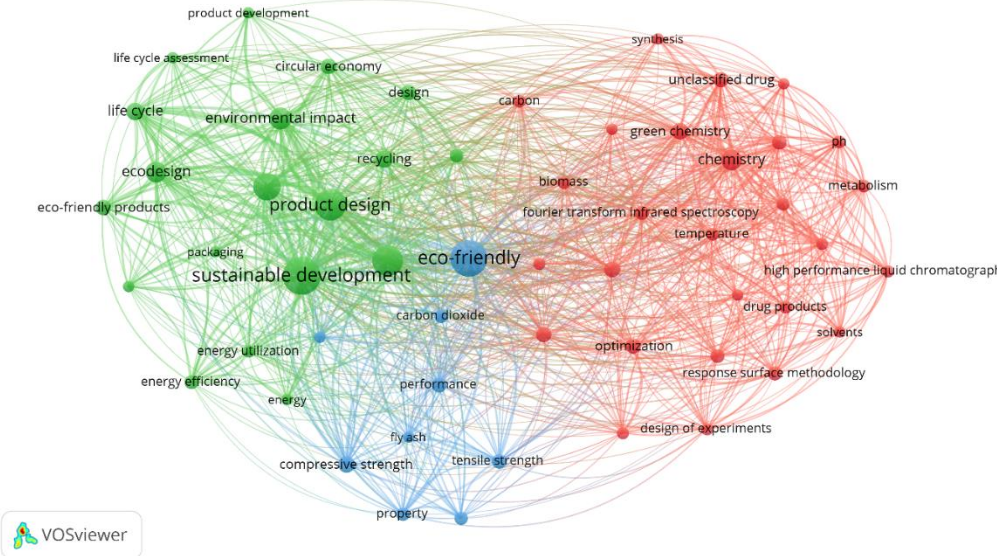

Figure 1. Network Visualization

Source: Data Analysis, 2026

Figure 1 illustrates the conceptual structure of research on eco-friendly product design through keyword co-occurrence mapping. The central node, "eco-friendly," functions as a bridging construct connecting three dominant thematic clusters. The density of links indicates a highly interconnected research field, where sustainability-oriented product development is not isolated but strongly integrated with adjacent scientific and engineering domains. The size of nodes reflects frequency of occurrence, with "product design," "sustainable development," and "environmental impact" emerging as dominant conceptual anchors.

The green cluster represents the core sustainability and design-oriented literature. It is centered on terms such as "product design," "sustainable development," "environmental impact," "ecodesign," "life cycle," and "recycling." This cluster reflects the mainstream eco-design paradigm, which emphasizes lifecycle thinking, circular economy principles, energy efficiency, and waste reduction. The prominence of these terms indicates that the dominant discourse remains anchored in environmental engineering and sustainable product lifecycle management.

The red cluster reflects a more technically oriented and chemistry-driven research stream. Keywords such as "chemistry," "green chemistry," "optimization," "response surface methodology," "design of experiments," and "high performance liquid chromatography" suggest a strong methodological and experimental science orientation. This indicates that eco-friendly product design is also deeply influenced by process optimization, material synthesis, and laboratory-based validation approaches, particularly in chemical and pharmaceutical contexts. The presence of "drug products" and "solvents" further confirms cross-domain penetration into applied chemistry and industrial formulation research.

The blue cluster represents a materials and mechanical performance dimension of eco-friendly product research. Terms such as "compressive strength," "tensile strength," "performance," "carbon dioxide," and "fly ash" suggest a focus on material substitution, structural performance, and low-carbon construction materials. This cluster is typically associated with sustainable engineering applications, particularly in construction materials and industrial product optimization, where environmental benefits must be balanced with functional performance requirements.

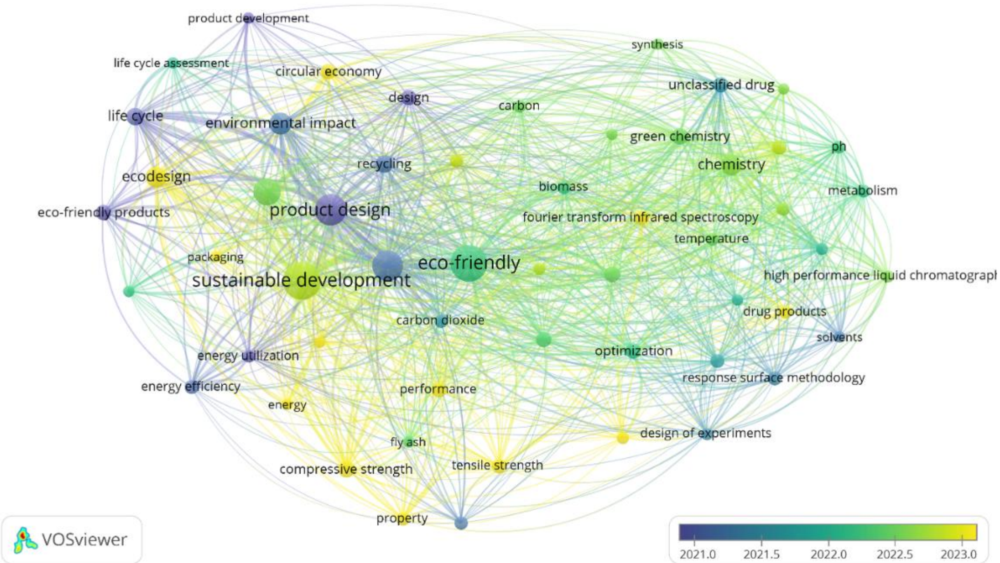

Figure 2. Overlay Visualization
Source: Data Analysis, 2026

Figure 2 presents a VOSviewer keyword co-occurrence network with an overlay temporal dimension, mapping research on eco-friendly product design. The term "eco-friendly" functions as the central hub, linking multiple high-frequency concepts such as "product design," "sustainable development," and "environmental impact." The density of connections indicates a mature and highly interdisciplinary research field, where sustainability-oriented design is strongly integrated with environmental science, materials engineering, and chemical process optimization.

Three dominant thematic clusters can be identified. The green cluster is anchored in sustainability and lifecycle-oriented concepts, including "ecodesign," "life cycle assessment," "recycling," and "circular economy," reflecting foundational environmental design principles. The yellow–

blue transitional cluster centers on "product design," "energy efficiency," "performance," and "compressive/tensile strength," indicating a strong engineering and materials-performance orientation. The green–teal cluster on the right is more chemistry- and process-intensive, containing terms such as "green chemistry," "optimization," "response surface methodology," and "high performance liquid chromatography," suggesting increasing methodological sophistication and laboratory-driven product development approaches.

The overlay color scale (2021–2023) indicates temporal evolution of research themes. Earlier studies (bluish tones) are more associated with structural performance, lifecycle assessment, and general sustainable development frameworks, indicating a focus on foundational sustainability concepts. More recent publications (yellowish tones) shift toward "green chemistry," "optimization," and experimental design methodologies, reflecting a transition toward applied, data-driven, and process-optimized eco-friendly product development.

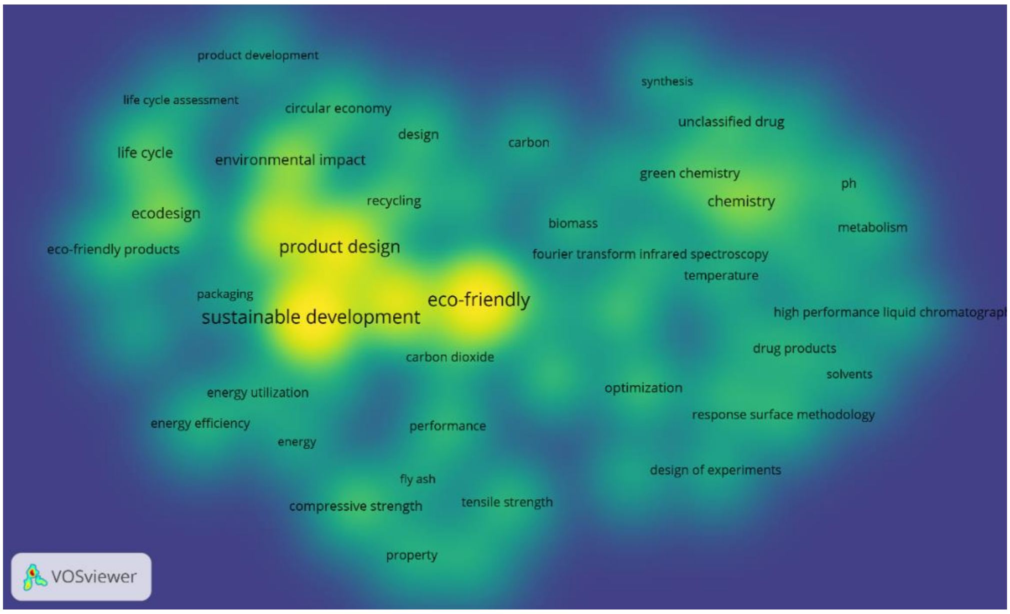

Figure 3. Density Visualization

Source: Data Analysis, 2026

Figure 3 represents the concentration of keyword occurrences within the eco-friendly product design literature. High-intensity (yellow) areas indicate the most dominant research focus, primarily centered on "eco-friendly," "product design," and "sustainable development." This confirms that the core of the field is strongly anchored in sustainability-oriented product innovation, lifecycle thinking, and environmental impact reduction. Surrounding medium-intensity zones such as "environmental impact," "ecodesign," "circular economy," and "recycling" indicate that these concepts function as secondary but structurally important pillars supporting the central research domain.

Lower-density (green to blue) regions reflect more specialized or emerging subtopics that are less frequently co-occurring but still relevant to the network structure. These include engineering-performance terms ("compressive strength," "tensile strength," "energy efficiency"), as well as chemistry- and methodology-driven concepts ("green chemistry," "response surface methodology," "design of experiments"). The spatial diffusion of these terms suggests that the field is expanding beyond conceptual sustainability discussions toward applied, technical, and experimental domains.

3.2 Citation Analysis

Table 1. Top Cited Documents

Citations	Authors and Year	Title
1570	[13]	Mediterranean diet pyramid today. Science and cultural updates
1100	[14]	Biodegradable films and composite coatings: Past, present and future
729	[15]	Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution?
579	[16]	Review on hydrometallurgical recovery of rare earth metals
531	[17]	Current developments in solid-state fermentation
525	[18]	Potential applications of geopolymer concrete in construction: A review
514	[19]	Structural and material performance of geopolymer concrete: A review
500	[20]	Effect of graphitic carbon nitride microstructures on the activity and selectivity of photocatalytic CO2 reduction under visible light
476	[21]	Advances in cellulose nanomaterials
466	[22]	Enzymatic biodiesel: Challenges and opportunities

Source: Scopus, 2026

3.3 Author Visualization

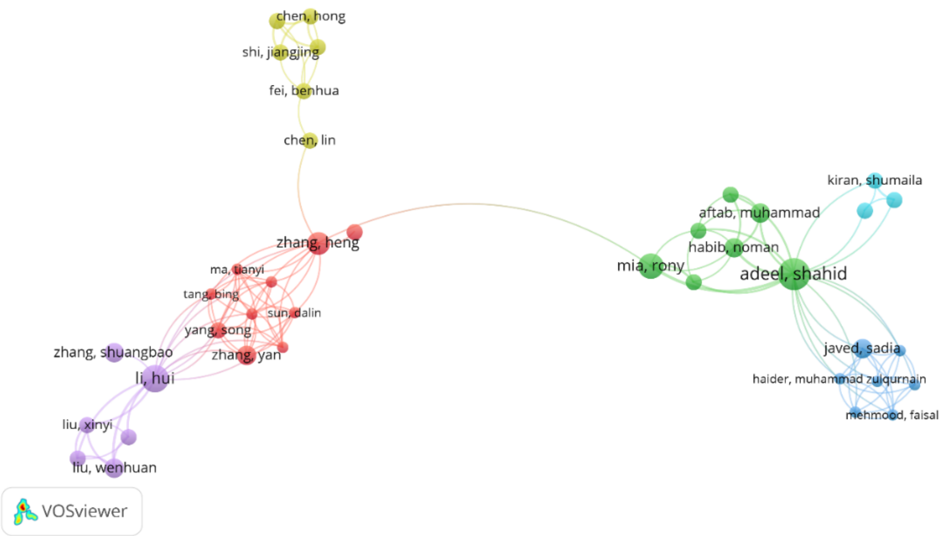

Figure 4. Author Visualization
Source: Data Analysis, 2026

Figure 4 illustrates a co-authorship structure segmented into several relatively distinct research clusters, indicating moderate fragmentation with limited cross-group collaboration. The central green cluster, anchored by "adeel, shahid," shows the highest connectivity and functions as a major collaboration hub, linking closely with authors such as "habib, noman," "mia, rony," and "aftab, muhammad," suggesting a relatively cohesive research group with strong internal collaboration. On the right, a blue cluster including "javed, sadia," "haider, muhammad zulqurnain," and "mehmood, faisal" forms a secondary network that is partially connected to the green cluster, indicating some inter-group collaboration but still maintaining distinct authorship boundaries. On the left side, a red cluster centered around "zhang, heng" and associated authors ("ma, tiany," "sun, dalin," "yang, song," "zhang, yan") represents another tightly knit collaboration group with dense internal links but minimal external connectivity. Below it, a purple cluster (e.g., "li, hui," "mu, wenhuan," "liu, xinyi") shows a smaller but coherent sub-network, likely representing a specialized or institutionally bounded research team. At the top, a smaller yellow cluster (e.g., "chen, hong," "shi, jiangjing," "fei, benhua") appears more isolated, suggesting limited integration into the broader collaboration landscape.

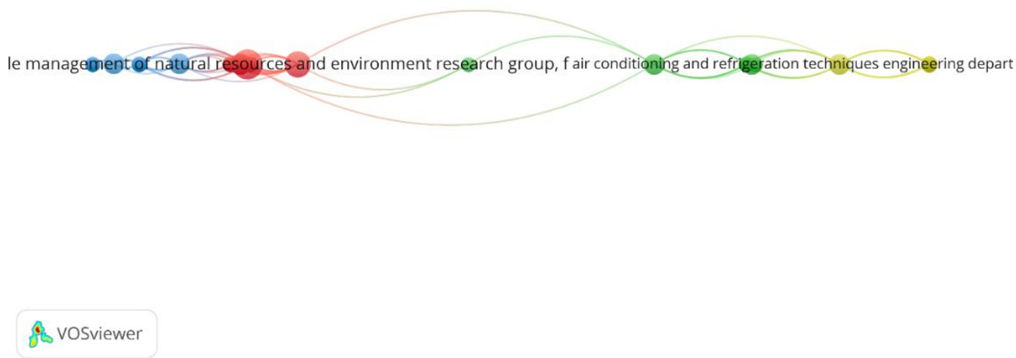

Figure 5. Institution Visualization
Source: Data Analysis, 2026

Figure 3 represents an institutional collaboration network with a relatively linear and hierarchical structure, indicating limited multi-directional interaction across institutions. On the left side, the cluster begins with a research entity related to "natural resources and environment research group," which appears to act as an initial hub with stronger internal connectivity (red/blue nodes). This suggests a foundational research unit focused on environmental and resource management themes. The network then transitions through intermediate nodes, showing weak but continuous linkage toward other institutional entities. In the central portion, collaboration flows into institutions associated with engineering applications, particularly those related to "air conditioning and refrigeration techniques engineering department." This middle segment acts as a bridge, connecting environmental research-oriented institutions with more applied engineering departments. The curvature and sparsity of links suggest that collaboration is present but not dense, indicating sequential rather than highly integrated cooperation patterns. On the right side, the network terminates in a more specialized engineering cluster (green/yellow nodes), which appears more isolated and discipline-specific. This final segment suggests that research output becomes increasingly technical and application-oriented, but with reduced cross-institutional integration.

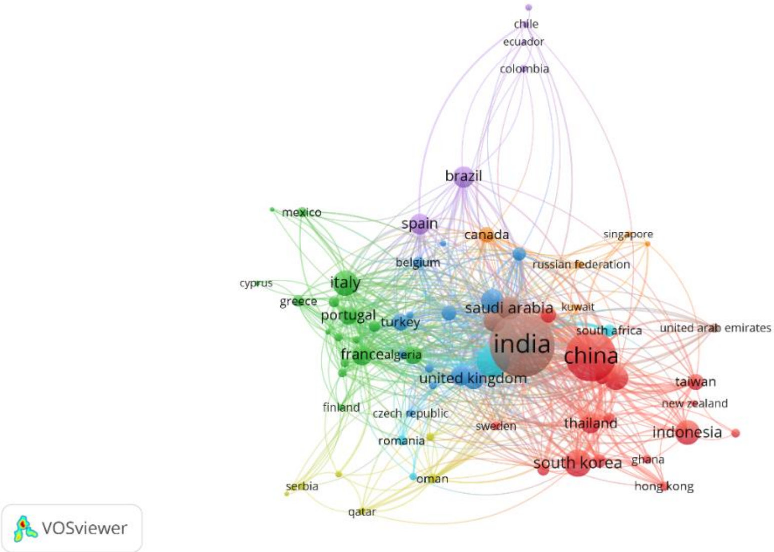

Figure 6. Country Visualization
Source: Data Analysis, 2026

Figure 6 presents a country-level co-authorship network in eco-friendly product design research, highlighting the global distribution of scientific collaboration. The most prominent nodes are China and India, indicating their central roles in publication volume and international connectivity. Both countries function as major hubs, with dense links to multiple regions including Southeast Asia (e.g., Indonesia, Thailand), the Middle East (e.g., Saudi Arabia, Kuwait, United Arab Emirates), and Europe (e.g., United Kingdom, Italy). This suggests that research activity in this field is strongly concentrated in Asia, while simultaneously maintaining broad international collaboration networks.

The clustering structure shows clear regional groupings. A strong red cluster around China, South Korea, Indonesia, and Thailand reflects a high-intensity East and Southeast Asian collaboration axis. A green European cluster including Italy, France, Portugal, Greece, and Spain indicates a relatively cohesive but secondary research bloc. Meanwhile, countries such as Brazil, Chile, Colombia, and Ecuador form a smaller Latin American cluster, positioned more peripherally, suggesting emerging but less dominant participation in this research domain.

4. CONCLUSION

This bibliometric study on eco-friendly product design reveals a rapidly growing and highly interdisciplinary research field shaped by strong interactions between sustainability science, materials engineering, and chemical process optimization. The keyword and density analyses demonstrate that the core intellectual structure is anchored in "eco-friendly," "product design," and "sustainable development," while progressively expanding toward specialized domains such as green chemistry, lifecycle assessment, and mechanical performance evaluation. The temporal overlay further indicates a clear research shift from foundational sustainability concepts toward more applied, data-driven, and experimentally optimized approaches to eco-design. The co-authorship and institutional networks show a relatively fragmented collaboration structure, with several distinct but internally cohesive research groups and limited cross-cluster integration. However, certain authors and institutions function as bridging nodes, facilitating partial knowledge exchange across regions and disciplines. At the country level, the analysis highlights a dominant contribution from China and India, which serve as central hubs of global collaboration, while Europe maintains a stable secondary role and other regions remain more peripheral but increasingly involved.

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