Information Research Communications, 2026; 3(2):119-131.
https://inforescom.org

Review Article

Scientometric Mapping of Copper-Doped Hydroxyapatite Coatings for Biomedical Applications: Knowledge Structure, Collaboration Patterns, and Emerging Research Fronts

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ABSTRACT

This study presents a scientometric analysis of research on copper-doped Hydroxyapatite (HA-Cu) coatings for biomedical applications covering the period 2004-2025. The aim was to evaluate publication trends, collaboration patterns, thematic evolution, and the intellectual structure of the field. Bibliographic records retrieved from Web of Science and Scopus were cleaned, merged, and analyzed using the Bibliometrix R-package and the Tree of Science (ToS) framework. Bibliometric indicators, including annual scientific production, citation impact, Bradford's law, Lotka's law, and collaboration metrics, were computed. Science mapping techniques, including co-authorship and keyword co-occurrence analyses, were applied to identify thematic and relational structures. The results reveal a sustained annual growth rate of 7.64%, with a marked increase in publication activity after 2020. China and India lead in scientific production, while the United States and Japan exhibit higher citation impact. Thematic analysis highlights strong research interest in material modification, biodegradable magnesium substrates, and advanced coating technologies. The Tree of Science model identifies a hierarchical intellectual structure progressing from foundational studies on ion-doped ceramics and biocompatibility toward emerging research fronts involving Plasma Electrolytic Oxidation (PEO/MAO), copper-based nanostructures, and multifunctional implant surfaces. Overall, the study demonstrates that research on HA-Cu coatings has evolved into a consolidated and dynamically expanding interdisciplinary field and provides a structured scientometric framework applicable to related domains in biomaterials and surface engineering.

Keywords: Bibliometric mapping, Bio-medical coatings, Copper-doped hydroxyapatite, Research trends, Scientometric analysis, Tree of Science.

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Received: 21-02-2026;
Revised: 07-03-2026;
Accepted: 15-04-2026.

INTRODUCTION

Materials developed for biomedical implants and surface coatings must combine biocompatibility, corrosion resistance, and antibacterial performance to ensure favorable interaction with biological tissues and reduce long-term adverse effects (Abbasi *et al*., 2025; Aktug *et al*., 2019; DEVECİ *et al*., 2020; Gutsalova *et al*., 2021; Ling *et al*., 2023; Raju and Biswas, 2025). Among the most studied materials, hydroxyapatite (HA) has attracted sustained attention due to its chemical similarity to the mineral phase of bone, osteoconductive character, and generally acceptable biological behavior (Kokubo and Takadama, 2006). Nevertheless, pure HA presents important limitations, particularly low mechanical strength and limited antimicrobial activity, which may restrict its clinical performance in infection-prone environments (González-Torres *et al*., 2021; Imran *et al*., 2024; Supandi *et al*., 2024).

To overcome these limitations, research has increasingly focused on doping or functionalization of hydroxyapatite-based coatings with metallic ions to enhance antibacterial behavior while preserving biocompatibility (Huang *et al*., 2021; Jadalannagari *et al*., 2013; Safarzadeh *et al*., 2019; Zhang *et al*., 2017). Among these strategies, copper incorporation has emerged as a particularly relevant approach because it can inhibit bacterial growth through multiple mechanisms and support the development of multifunctional implant surfaces (Eremina *et al*., 2022;

DOI: 10.5530/irc.3.2.13

Friederichs *et al*., 2015; Liu *et al*., 2024; Ye *et al*., 2025). As a result, research on copper-doped hydroxyapatite coatings has expanded toward a broader and more technologically diversified field.

Scientometric and bibliometric methods have become essential tools for understanding the structure, evolution, and dynamics of scientific fields (Geng *et al*., 2024). These approaches enable identification of influential works, collaboration networks, emerging topics, and field maturity through quantitative indicators and science mapping techniques (Donthu *et al*., 2021; Glänzel and Schubert, 2004; Guan *et al*., 2012; Przybilla *et al*., 2023; Zhang *et al*., 2021). In materials science and biomedical engineering, bibliometric studies have examined areas such as bioceramics, biomaterials, and biomedical coatings (Chen, 2006; Ciobanu *et al*., 2024; Huang *et al*., 2014; Jia *et al*., 2023; Prosolov *et al*., 2023; Samani *et al*., 2013; Small, 1999), titanium implants (Bartmański *et al*., 2021; Liao *et al*., 2025; Mollaei and Varshosaz, 2023; Sivaraj *et al*., 2020; Tao *et al*., 2021), and antimicrobial coatings (Hadidi *et al*., 2017; Huang *et al*., 2017; Karthika, 2021; Tian *et al*., 2015). However, no dedicated scientometric study has yet focused on copper-doped hydroxyapatite coatings, despite their growing relevance.

Given this rapid development, a structured scientometric assessment is needed to clarify field evolution, key contributors, and emerging thematic directions. Such analysis is essential for identifying knowledge gaps, collaboration patterns, and the intellectual organization of the domain.

In this context, this study provides a comprehensive scientometric analysis of research on copper-doped hydroxyapatite coatings for biomedical applications. It integrates bibliometric indicators, science mapping, and the Tree of Science model to examine temporal evolution, collaboration structure, thematic organization, and intellectual development. The study identifies emerging research fronts-including biodegradable magnesium-based substrates, advanced coating technologies, and multifunctional implant systems-and offers a structured perspective to support future research in materials science, surface engineering, and biomedicine.

METHODOLOGY

Data sources and search strategy

This scientometric study was conducted using bibliographic records retrieved from Web of Science (WoS, Clarivate Analytics) and Scopus (Elsevier). These databases were selected due to their broad coverage, standardized indexing practices, and widespread use in scientometric research. Their combined use mitigates database-specific bias and enhances the representativeness of the analyzed corpus, particularly in interdisciplinary and emerging fields.

The search was performed on May 7, 2025, covering the period from 2004 to 2025 to include both the early development and subsequent expansion of research on copper-doped hydroxyapatite coatings for biomedical applications. A structured search strategy was designed to capture publications addressing four core conceptual dimensions: coating technologies, hydroxyapatite-based materials, copper incorporation, and biocompatibility. The final Boolean search query was formulated as follows: ("coat" OR "coating*" OR "recubrimient*") AND ("hydroxyapatite" OR "hidroxiapatita" OR "HA") AND ("copper" OR "Cu") AND ("biocompatib*")*

The query was applied to the TITLE, ABSTRACT, and KEYWORDS fields (TITLE-ABS-KEY) in both databases to ensure that retrieved documents explicitly addressed the central topic. This restriction balances comprehensive coverage with thematic relevance. The document types included research articles, review papers, book chapters, and conference proceedings, reflecting common publication formats in materials science and biomedical engineering. No language restrictions were applied.

The initial retrieval resulted in 122 records from Web of Science and 136 from Scopus. The use of both databases was justified by the presence of unique documents in each source. The merged dataset served as the basis for subsequent data cleaning, deduplication, and scientometric analysis, as detailed in the following section. Table 1 summarizes the main search and integration parameters.

Data cleaning and corpus construction

Following data retrieval, records from Web of Science and Scopus were merged into a single dataset and subjected to systematic data cleaning and refinement to construct a reliable and representative corpus for scientometric analysis. This process followed the general principles of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, adapted to bibliometric and scientometric studies to ensure transparency, consistency, and reproducibility, following the proposal by Liberati *et al*. (2009).

The initial dataset comprised 195 records (122 from Web of Science and 136 from Scopus). Duplicate documents were identified and removed using a combination of Digital Object Identifier (DOI) matching, title comparison, and author information. When DOI data were unavailable, titles and bibliographic metadata served as the primary matching criteria. Through this deduplication process, 63 duplicate records were excluded. The resulting dataset consisted of 132 unique documents, forming the final corpus for subsequent analyses. No additional exclusion criteria based on subject category, journal ranking, or citation thresholds were applied at this stage to preserve field integrity and avoid introducing selection bias. All retained documents explicitly addressed copper-doped hydroxyapatite coatings or closely related systems within a biomedical or biocompatibility context, as ensured by the initial search strategy.

After corpus consolidation, bibliographic metadata-including authors, affiliations, keywords, references, publication years, and source titles-were standardized and formatted for analysis using the Bibliometrix package in R. This preprocessing step enabled construction of citation, co-authorship, and keyword co-occurrence networks, ensuring consistency across subsequent bibliometric and science mapping procedures.

Bibliometric performance analysis

The bibliometric performance analysis was conducted to characterize the productivity, impact, and collaboration patterns of research on copper-doped hydroxyapatite coatings for biomedical applications. This stage focused on the quantitative assessment of publication and citation indicators, providing a descriptive overview of scientific output and its temporal evolution.

The analysis included standard bibliometric indicators commonly used in scientometric studies, such as annual scientific production, total citations, average citations per document, and author productivity metrics. In addition, classical bibliometric laws were applied to evaluate structural regularities in the literature, including Bradford's law for journal dispersion and Lotka's law for author productivity distribution.

Country-level and institutional analyses were performed based on author affiliations, enabling identification of leading contributors and geographic patterns of scientific production. Collaboration indicators were computed to assess co-authorship dynamics, including Single-Country Publications (SCP) and Multiple-Country Publications (MCP), as well as indices reflecting the degree of international cooperation.

Journal performance was evaluated through publication counts and citation impact, complemented by quality indicators derived from Scimago Journal Rank (SJR) quartiles. This approach enabled identification of core publication venues and their relative influence within the research domain. All bibliometric indicators were computed using the Bibliometrix package in R, which provides standardized and reproducible procedures for descriptive analysis. The results of this stage form the basis for subsequent science mapping and network-based analyses aimed at uncovering the intellectual and conceptual structure of the field.

Science mapping and network analysis

To explore the intellectual and conceptual structure of research on copper-doped hydroxyapatite coatings, science mapping and network analysis techniques were applied. Unlike bibliometric performance indicators, which provide descriptive measures of productivity and impact, science mapping focuses on relational patterns within the literature, enabling identification of knowledge structures, thematic clusters, and collaboration dynamics.

Several types of bibliometric networks were constructed from the consolidated corpus, including co-authorship, co-citation, and keyword co-occurrence networks. Each addresses a distinct analytical dimension. Co-authorship networks examined collaboration patterns among authors, institutions, and countries, revealing the social structure of the research community. Co-citation networks identified intellectual foundations by analyzing how frequently pairs of documents are cited together. Keyword co-occurrence networks captured the conceptual structure of the domain and identified dominant themes and emerging topics.

Network construction and analysis were performed using standardized procedures implemented in the Bibliometrix package. For each network, nodes represent bibliographic entities (authors, documents, or keywords), while edges represent relational links such as co-authorship, co-citation, or co-occurrence. Network metrics including degree centrality, link strength, and PageRank were computed to identify influential and highly connected nodes.

To enhance interpretability, network visualizations were generated using normalization and thresholding procedures to reduce noise while preserving significant relationships. Minimum frequency thresholds were applied to keywords and citation links, and community detection algorithms were used to identify clusters representing coherent research themes or collaboration groups. The outcomes of the science mapping analysis provided the basis for identifying collaboration structures, thematic organization, and evolutionary research patterns. These results also supported the application of the Tree of Science model, described in the following subsection.

Tree of Science (ToS) implementation

To further elucidate the intellectual structure and evolutionary dynamics of the research field, the Tree of Science (ToS) model was applied to the consolidated corpus. The ToS approach is a citation-based scientometric method designed to classify scientific documents according to their functional role within a research domain, particularly in emerging or rapidly evolving fields.

The ToS model is based on direct citation networks, where documents are represented as nodes and citation relationships as directed edges. Within this framework, publications are categorized into three conceptual groups according to their position and connectivity: roots, trunk, and leaves.

Root documents correspond to foundational works that provide the theoretical or methodological basis of the field and are characterized by high outdegree and low indegree values.

Trunk documents represent structural or bridging studies that connect foundational knowledge with more recent developments, typically exhibiting balanced indegree and outdegree centrality.

Leaf documents correspond to recent publications that build upon existing knowledge and reflect current research fronts, usually characterized by high indegree and low outdegree values.

In this study, the ToS classification was implemented using citation network data extracted from the bibliographic corpus and processed through the Bibliometrix package. Centrality measures derived from the directed citation network, including indegree and outdegree metrics, were used to assign documents to each category. This classification enabled a hierarchical organization of the literature, highlighting the progression from foundational studies to consolidated research streams and emerging thematic directions.

The ToS model complements traditional bibliometric indicators and science mapping techniques by capturing the intellectual lineage of the field. While performance indicators quantify productivity and impact, and network analyses reveal relational patterns, the ToS framework provides an evolutionary perspective that facilitates identification of scientific maturity, consolidation phases, and emerging research fronts. The results obtained from the ToS analysis supported the qualitative interpretation of foundational studies, core contributions, and recent advances, discussed in the Results and Discussion sections.

Software, parameters, and reproducibility

All stages of the bibliometric and scientometric analysis were conducted using the Bibliometrix package in R, which provides a standardized framework for data processing, performance analysis, and science mapping. The use of this open-source environment ensures methodological transparency and facilitates reproducibility. The bibliographic records retrieved from Web of Science and Scopus were imported, merged, and processed within the Bibliometrix workflow. Data preprocessing included harmonization of author names, affiliations, keywords, and source titles, as well as standardization of bibliographic fields to ensure consistency across databases. When applicable, synonymous keywords were consolidated to reduce fragmentation in thematic analyses.

Network analyses-including co-authorship, co-citation, and keyword co-occurrence-were constructed using normalization procedures implemented in Bibliometrix. Minimum frequency thresholds were applied to nodes and links to reduce network noise and improve interpretability while preserving significant relational structures. Threshold values were selected based on dataset size and network density to balance analytical robustness and visual clarity. Centrality measures such as degree centrality, indegree, outdegree, and PageRank were computed to identify influential documents, authors, and thematic elements. Community detection algorithms were applied to identify clusters representing cohesive collaboration groups or thematic structures.

The Tree of Science (ToS) classification was implemented using directed citation network data derived from the same standardized corpus, ensuring methodological consistency. All analytical steps-from data import and cleaning to indicator computation and network visualization-were executed within the same software environment to minimize variability and enhance reproducibility. Detailed information on data processing scripts, analytical parameters, and additional visualizations is provided in the Supplementary Materials, allowing independent researchers to replicate the study or adapt the workflow to related domains.

RESULTS

Annual scientific production

The temporal evolution of scientific production on copper-doped hydroxyapatite coatings is presented in Figure 1. The results show a sustained increase in publications over the analyzed period (2004-2025), with an overall annual growth rate of 7.64%.

During the early stage (2004-2012), the field exhibited low and irregular productivity, reflecting its exploratory nature. A gradual increase is observed between 2013 and 2019, indicating growing interest in the antibacterial and bioactive properties of doped hydroxyapatite systems. Notably, a marked acceleration occurs after 2020, suggesting consolidation of the field and expansion toward advanced coating technologies and multifunctional applications. These trends indicate a transition from isolated studies toward a more structured and continuously growing research field.

Country scientific production and collaboration

The geographical distribution of scientific production reveals disparities in research activity across countries. As shown in

Table 1: Search parameters used in both databases, Web of Science and Scopus.

Parameter	Web of Science	Scopus
Range	2004-2025	
Date	May 07, 2025	
Document Type	Paper, book, chapter, conference proceedings	
Words	TITLE-ABS-KEY ("coat*") OR TITLE-ABS-KEY ("recubrimient*") OR TITLE-ABS-KEY ("coating*") AND TITLE-ABS-KEY ("hydroxyapatite") OR TITLE-ABS-KEY ("hidroxiapatita") OR TITLE-ABS-KEY ("HA") AND TITLE-ABS-KEY ("copper") OR TITLE-ABS-KEY ("Cu") AND TITLE-ABS-KEY ("biocompatib*"))	
Results	122	136
Total (WoS+Scopus)	195	

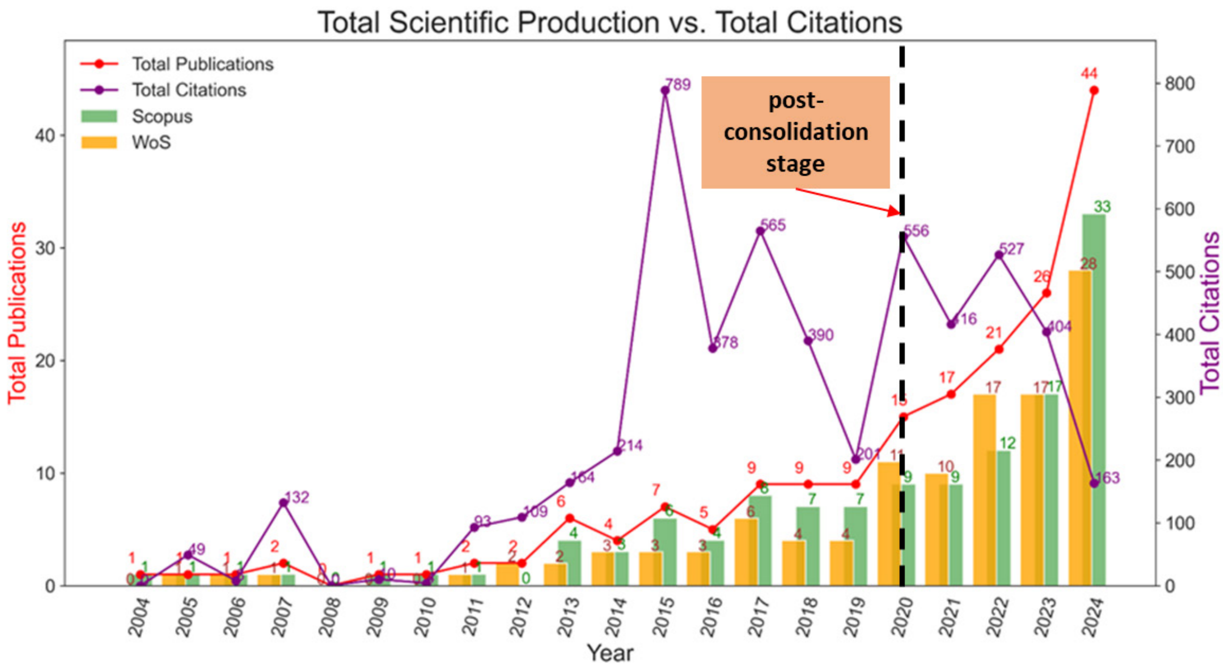

Figure 1: Annual scientific production of publications on copper-doped hydroxyapatite coatings indexed in Scopus, Web of Science, and the combined dataset (2004-2025).

Figure 2, China and India emerge as the leading contributors in terms of publication volume, reflecting strong activity in materials science and biomedical engineering. In contrast, the United States and Japan exhibit comparatively higher citation impact, indicating greater influence within the scientific community. European countries show moderate but consistent participation, often associated with collaborative research networks. The country collaboration network presented in Figure 2 highlights the progressive strengthening of international cooperation, particularly between Asian, European, and North American research groups. Central nodes suggest the existence of key countries acting as collaboration hubs, facilitating knowledge exchange and co-authorship across regions.

Source and journal analysis

The distribution of publications across scientific journals follows a concentration pattern consistent with Bradford's law. As illustrated in Figure 3, a limited number of core journals account for a significant proportion of publications, while a larger number of peripheral journals contribute fewer articles. The most productive journals are primarily focused on materials science, surface engineering, and biomaterials, reflecting the interdisciplinary nature of the field. High-impact journals tend to concentrate influential articles, indicating that research on HA-Cu coatings is increasingly disseminated through well-established outlets. This distribution confirms a defined publication structure, with specialized journals playing a central role in consolidating the research domain.

Author collaboration network

Figure 4 illustrates the co-authorship network, organized into several interconnected clusters. These clusters represent groups of authors who collaborate frequently and form cohesive research communities. The network structure is characterized by a limited number of highly connected authors acting as central nodes, while a larger number occupy peripheral positions with fewer collaborative links. The co-authorship network analysis reveals collaboration patterns among researchers in the field. The results indicate several research clusters, typically organized around leading authors and research groups. Although collaboration is evident, the network exhibits moderate fragmentation, with some clusters operating relatively independently. Nevertheless, interconnected nodes suggest increasing integration of research efforts over time. These patterns reflect a field evolving from localized research groups toward a more interconnected scientific community, although further consolidation of collaboration networks is still developing.

Tree of Science (ToS) analysis

The intellectual structure of the field was analyzed using the Tree of Science (ToS) model, which classifies documents based on their position within the citation network. Results are presented in Figure 5. The roots correspond to foundational studies that establish key concepts of hydroxyapatite bioactivity, ion substitution, and biocompatibility. These works provide the theoretical and experimental basis for subsequent developments. The trunk includes structurally central studies that connect foundational knowledge with more recent research. These publications are primarily focused on coating techniques, antibacterial mechanisms, and material optimization strategies, reflecting field consolidation. The leaves represent emerging research fronts characterized by recent publications. These studies are mainly associated with advanced surface engineering approaches, including Plasma Electrolytic Oxidation (PEO/MAO), biodegradable magnesium-based substrates, copper-based nanostructures, and multifunctional implant surfaces. This hierarchical organization reveals a clear progression from fundamental studies toward technologically advanced applications.

Keyword co-occurrence and thematic structure

The thematic organization of the field was examined through keyword co-occurrence analysis, as shown in Figure 6. Results indicate the presence of well-defined clusters associated with key research topics. Central keywords include "hydroxyapatite," "copper," "coatings," and "antibacterial activity," reflecting the core focus of the field. Additional clusters are associated with emerging themes such as "magnesium alloys," "nanostructures," and "surface modification," indicating diversification toward advanced materials and functional coatings. The thematic map reveals that certain topics are well developed and central, while others appear as emerging or niche areas. This distribution suggests an active and evolving research landscape, with expansion into new technological directions.

DISCUSSION

Research evolution and growth

The temporal evolution of scientific production reveals a field that has transitioned from an exploratory phase to sustained growth and consolidation. As shown in Section 3.1, annual publication output remained low and fragmented during the early years, followed by a progressive increase culminating in a marked acceleration after 2020. This growth pattern is characteristic of emerging technological domains in materials science, where conceptual studies evolve into application-oriented research.

The post-2020 inflection point in publication output coincides with a broader intensification of research in biomedical surface engineering and functional coatings. Experimental studies reflect increased interest in multifunctional implant surfaces, where hydroxyapatite-based coatings are modified through metal-ion incorporation to address bioactivity and antibacterial performance (Hong *et al*., 2025; kang *et al*., 2022; Valarmathi and Sumathi, 2024). This convergence of biological and materials-engineering objectives has likely contributed to the rapid expansion observed in recent years.

In parallel, advances in coating technologies and surface modification techniques have enabled more sophisticated material designs, supporting the transition from proof-of-concept studies to application-driven research. The growing number of publications addressing copper incorporation through plasma-based methods, electrodeposition, and hybrid strategies reflects maturation of experimental capabilities (David *et al*., 2020; Rarokar *et al*., 2024; Wang *et al*., 2022). These developments

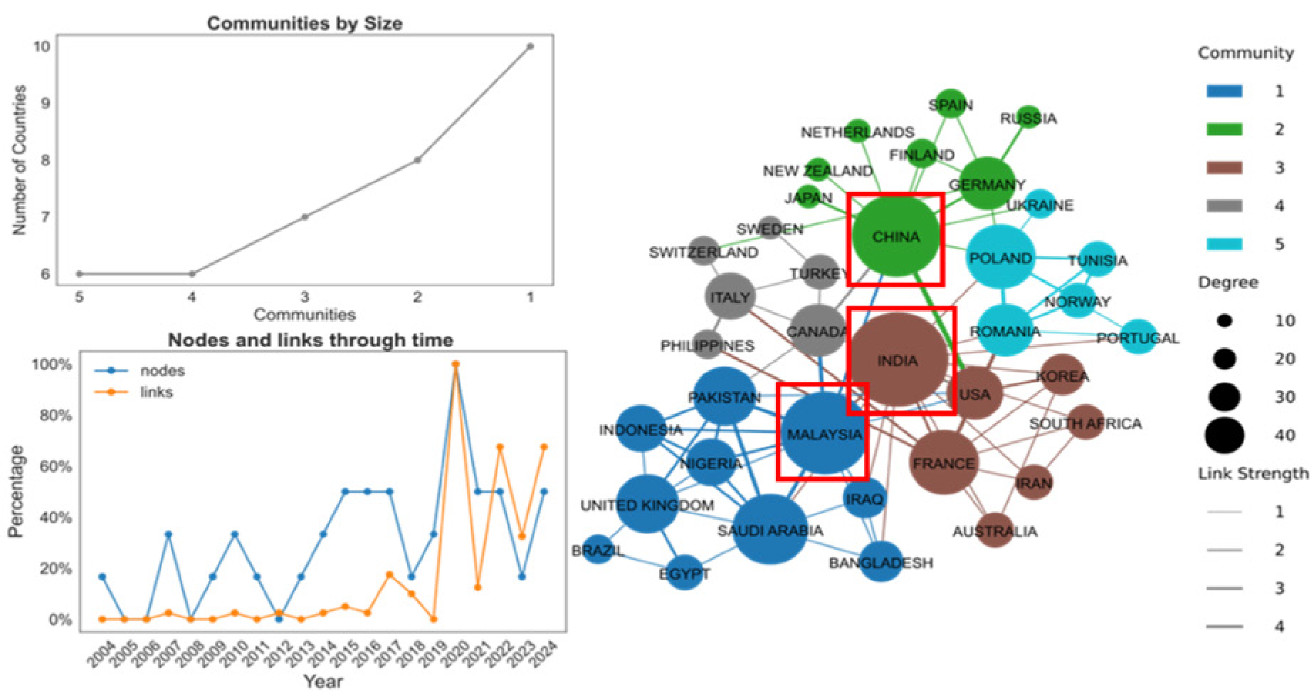

Figure 2: Country collaboration network based on co-authorship relationships in publications on copper-doped hydroxyapatite coatings.

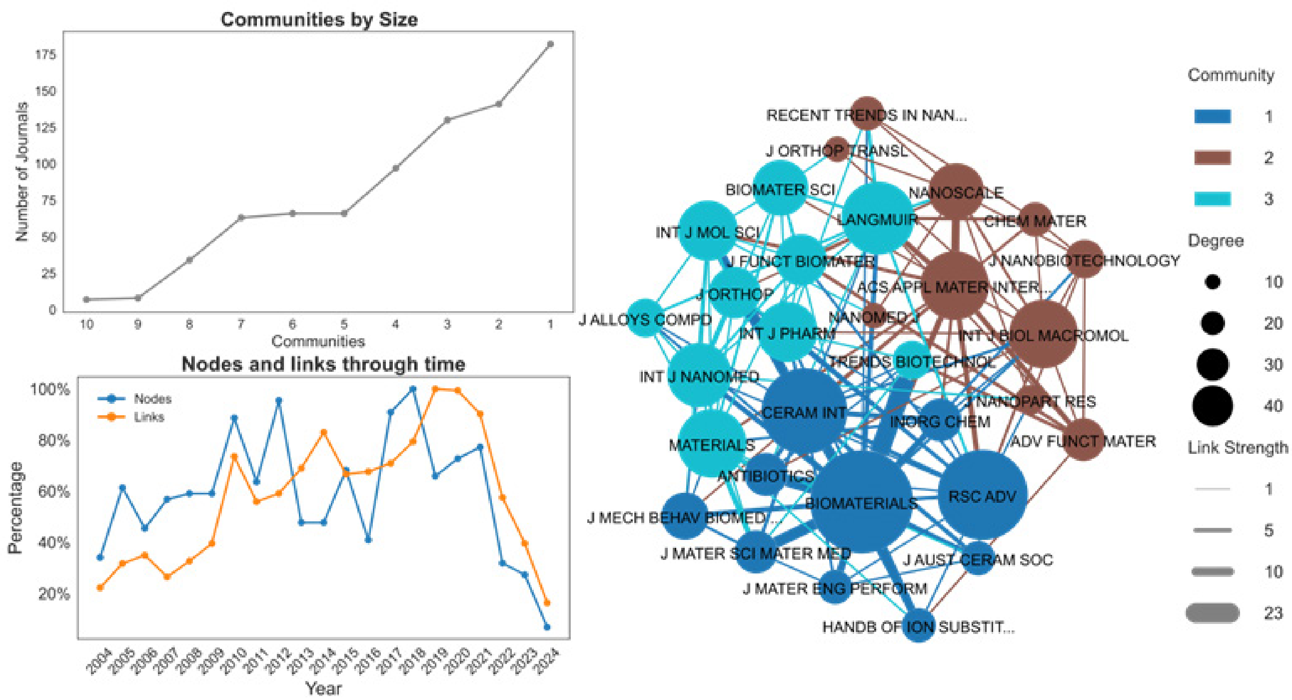

Figure 3: Journal co-citation network showing the citation structure of publication venues in the analyzed corpus.

align with increased publication volume and diversification of research topics captured in the scientometric analysis.

The sustained growth rate identified in the Results section is also consistent with the expanding clinical and industrial relevance of antimicrobial and biocompatible coatings. Concerns related to implant-associated infections, antibiotic resistance, and long-term performance have stimulated research into alternative antimicrobial strategies based on metallic ions and bioactive ceramics (Altınsoy *et al.*, 2024; Huang *et al.*, 2016; Marques *et al.*, 2017). As copper-doped hydroxyapatite systems offer a balance between antibacterial efficacy and biocompatibility, they have become an attractive focus of investigation.

Overall, the observed growth trajectory reflects a shift from isolated experimental efforts toward a more integrated research domain characterized by technological diversification, interdisciplinary collaboration, and increasing application relevance. This evolution provides the foundation for the collaboration patterns, thematic structures, and emerging research fronts discussed in the following sections.

Country leadership and collaboration dynamics

The country-level analysis reveals a heterogeneous distribution of scientific leadership, characterized by a distinction between research productivity and citation impact. As shown in Section 3.2, China and India dominate in publication volume, while countries such as the United States and Japan exhibit higher citation impact. This asymmetric pattern is common in materials science and biomedical engineering, where differences in funding strategies, infrastructure, and publication practices shape national research profiles.

The strong productivity of China and India can be interpreted in the context of sustained investment in biomaterials research and surface engineering technologies, particularly in implant coatings and antimicrobial materials. Recent experimental studies from these countries focus on copper-modified hydroxyapatite systems, advanced coating techniques, and biocompatibility assessment, contributing to the rapid expansion of the literature (Hong *et al.*, 2025; Kang *et al.*, 2022; Valarmathi and Sumathi, 2024). The high output reflects large research communities and institutional participation rather than a concentration of influence in landmark publications.

In contrast, the higher citation impact observed for the United States and Japan suggests a research strategy oriented toward high-impact contributions, often associated with interdisciplinary approaches and advanced characterization techniques. Studies from these countries frequently integrate materials science with biological evaluation and clinical relevance, increasing their visibility and citation potential (Rarokar *et al.*, 2024; Wang *et al.*, 2022). This pattern explains the divergence between publication volume and citation influence identified in the scientometric results.

The collaboration network analysis indicates that international cooperation has intensified in recent years, particularly after the increase in publication activity around 2020. China and India emerge as central hubs within the global network, connecting peripheral countries and facilitating knowledge exchange across regions. Such hub-and-spoke structures are typical of rapidly growing research fields, where leading countries act as anchors for collaborative expansion (David *et al.*, 2020).

The temporal evolution of collaboration patterns suggests that output consolidation preceded collaboration intensification. Early research efforts were conducted within nationally bounded groups, whereas later stages show increased cross-border co-authorship. This shift reflects the growing complexity of research on copper-doped hydroxyapatite coatings, which requires complementary expertise in materials synthesis, surface engineering, biological evaluation, and advanced characterization methods (Altınsoy *et al.*, 2024; Huang *et al.*, 2016; Marques *et al.*, 2017).

Overall, the observed country leadership and collaboration dynamics indicate a field that has progressed beyond isolated national efforts toward a more interconnected international landscape. The coexistence of high-volume and high-impact contributors highlights the complementary roles of different countries in shaping the evolution of research on copper-doped hydroxyapatite coatings and related biomedical surface technologies.

Thematic structure and emerging research fronts

The thematic structure revealed by keyword co-occurrence analysis (Section 3.6 and Figure 6) highlights a field organized around interconnected conceptual clusters, reflecting consolidation and diversification. Rather than forming isolated thematic islands, the clusters exhibit strong interconnections, indicating active knowledge exchange between material development, coating technologies, and biomedical applications. One dominant cluster is centered on hydroxyapatite-based materials and metal-ion modification, reflecting sustained interest in tailoring bioactive ceramics to overcome the limitations of pristine hydroxyapatite. Experimental studies show that copper incorporation enhances antibacterial performance while maintaining acceptable biocompatibility, positioning Cu-doped HA as a viable alternative to conventional antimicrobial strategies (Altınsoy *et al.*, 2024; Huang *et al.*, 2016; Kang *et al.*, 2022). The prominence of this cluster suggests that material composition remains a foundational axis supporting both fundamental and application-driven studies.

A second thematic grouping is associated with magnesium-based and biodegradable substrate systems, emerging as a distinct but strongly connected research front. The appearance of magnesium-related keywords reflects growing interest in resorbable implant platforms that better match the mechanical properties of natural bone while eliminating secondary removal surgeries. However, the high corrosion rate of magnesium in physiological environments has motivated research into protective and bioactive coating strategies, particularly hydroxyapatite- and copper-containing systems (Perumal *et al.*, 2020; Rahman *et al.*, 2020; Sarian *et al.*, 2022; Yin *et al.*, 2020). The integration of this cluster within the broader network indicates that magnesium substrates are treated as part of a coherent surface engineering strategy.

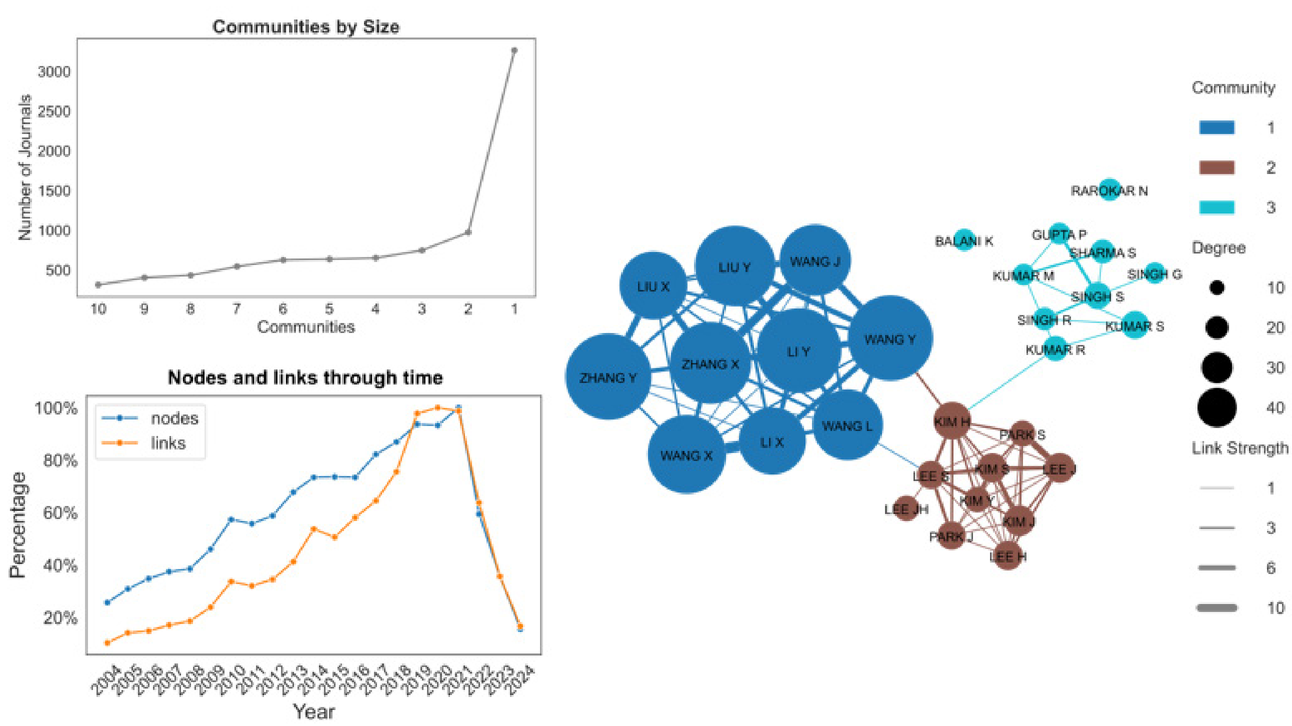

Figure 4: Author collaboration network based on co-authorship relationships within the consolidated corpus.

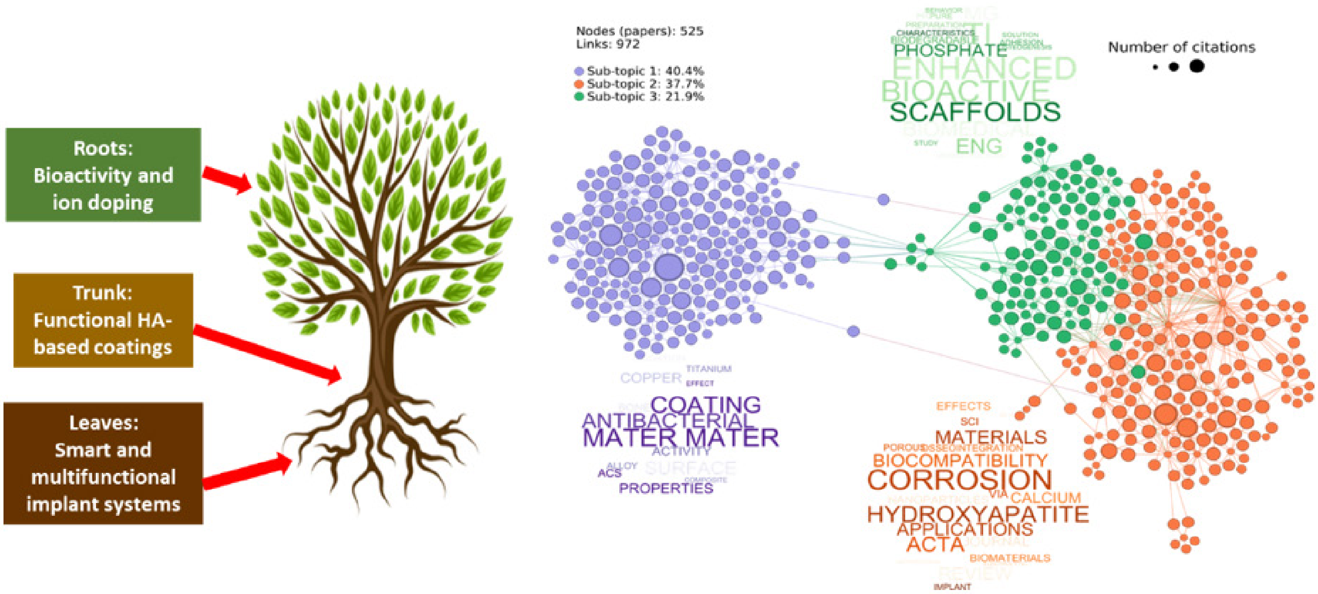

Figure 5: Tree of Science (ToS) representation of the citation network, classifying documents into root, trunk, and leaf categories.

The third cluster focuses on coating technologies and surface engineering methods, including Plasma Electrolytic Oxidation (PEO/MAO), electrodeposition, and hybrid or multilayer approaches. The increasing frequency and centrality of related keywords reflect their role as enabling technologies that allow controlled incorporation of copper and other bioactive ions (Durdu *et al.*, 2022; Van *et al.*, 2020; Wang *et al.*, 2022; Zhang *et al.*, 2022). This cluster acts as a methodological bridge between material design and functional performance.

The coexistence and interconnection of these clusters indicate a shift toward multifunctional design paradigms, where antibacterial activity, biocompatibility, corrosion resistance, and controlled degradation are addressed simultaneously. Recent studies explore synergistic strategies combining copper with other bioactive elements, nanostructures, or polymeric layers to fine-tune biological responses and material stability (Fattah-alhosseini *et al.*, 2022; Jacobs *et al.*, 2021; Mozafarnia *et al.*, 2022; Sayahi *et al.*, 2020). The presence of such approaches suggests maturation toward integrated system-level solutions.

Overall, the thematic organization identified through keyword co-occurrence analysis reveals a research landscape that is structurally coherent and dynamically evolving. The emergence of interconnected fronts related to material modification, biodegradable substrates, and advanced coating technologies reflects a transition from single-property optimization toward comprehensive surface engineering strategies. These trends provide a conceptual bridge between the intellectual structure captured by the Tree of Science analysis and the broader technological implications discussed in the following section.

Intellectual structure and scientific maturity of the field

The Tree of Science (ToS) analysis provides a structured perspective on the intellectual evolution and scientific maturity of research on copper-doped hydroxyapatite coatings. By distinguishing between root, trunk, and leaf documents, the ToS framework reveals how foundational concepts have been consolidated and expanded into current research fronts, offering insights beyond conventional bibliometric indicators.

The root documents correspond to early studies that established the fundamental principles governing biocompatibility evaluation, antibacterial surface modification, and ion-doped ceramic and metallic systems. These works laid the conceptual and methodological foundations by introducing standardized biological testing approaches and demonstrating the feasibility of metal-ion incorporation to impart antibacterial functionality (Heidenau *et al.*, 2005; Kokubo and Takadama, 2006; Stanić *et al.*, 2010; Witte *et al.*, 2008). Their position at the base of the citation structure reflects their enduring influence despite being temporally distant from current research.

The trunk documents represent a phase of knowledge consolidation, in which foundational concepts were translated into reproducible material systems and application-oriented research streams. Studies in this category focus on the development of copper- and multi-ion-substituted hydroxyapatite coatings, optimization of deposition techniques, and evaluation of biological and corrosion-related performance (Ghosh *et al.*, 2019; Huang *et al.*, 2016; Huang *et al.*, 2014; Martínez-Gracida *et al.*, 2020; Radovanović *et al.*, 2012; Sinulingga *et al.*, 2021). Their central position indicates that they function as reference

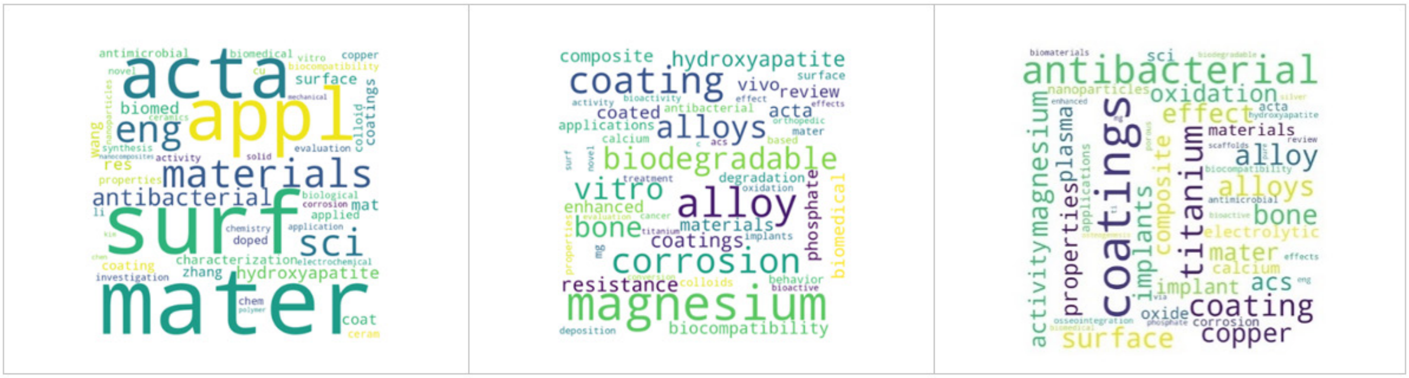

Figure 6: Keyword co-occurrence network illustrating the thematic structure of research on copper-doped hydroxyapatite coatings.

frameworks for both earlier and more recent studies, stabilizing the intellectual core.

The leaf documents capture the current momentum and diversification of research activity. These recent publications are characterized by exploration of advanced surface engineering strategies, multifunctional coating architectures, and novel substrate-coating combinations, including biodegradable magnesium alloys, nanostructured copper-containing phases, and hybrid organic-inorganic systems (Mozafarnia *et al*., 2022; Perumal *et al*., 2020; Van *et al*., 2020; Zhang *et al*., 2022). Their dependence on trunk literature reflects continuity rather than rupture, suggesting that innovation is largely incremental and integrative.

Taken together, the ToS structure indicates that research on copper-doped hydroxyapatite coatings has progressed beyond an exploratory stage and entered a phase of scientific maturity. The presence of a defined trunk and emerging leaf clusters suggests stable conceptual foundations with active diversification. This pattern is typical of applied materials research domains that have achieved methodological standardization while continuing to evolve in response to technological and clinical demands.

Importantly, the ToS analysis highlights the interdisciplinary nature of the field's intellectual structure. Foundational contributions originate primarily from materials science and biomaterials research, while trunk and leaf documents increasingly integrate surface engineering, corrosion science, microbiology, and biomedical evaluation. This convergence underscores the role of copper-doped hydroxyapatite coatings as a meeting point between fundamental materials design and application-driven biomedical research.

Overall, the intellectual structure revealed by the Tree of Science model complements the thematic patterns identified through keyword co-occurrence analysis and confirms that the field is both conceptually coherent and dynamically evolving. The transition from foundational studies to consolidated research streams and emerging multifunctional designs provides a framework for understanding current research priorities and anticipating future developments.

Implications, limitations, and future research directions

The scientometric findings presented in this study have scientific and strategic implications for researchers working at the intersection of materials science, surface engineering, and biomedical applications. By integrating bibliometric performance indicators, science mapping techniques, and the Tree of Science framework, this work provides a structured overview of how research on copper-doped hydroxyapatite coatings has evolved and diversified.

From a scientific perspective, the results indicate a transition from early proof-of-concept studies toward more integrated and multifunctional material systems. The convergence of thematic clusters related to material modification, biodegradable substrates, and advanced coating technologies suggests that current research efforts are increasingly oriented toward system-level design rather than isolated property optimization. This trend reflects broader shifts in biomaterials research, where antibacterial performance, biocompatibility, corrosion control, and controlled degradation are addressed simultaneously through coordinated surface engineering strategies (Altınsoy *et al*., 2024; Huang *et al*., 2016; Marques *et al*., 2017; Perumal *et al*., 2020; Van *et al*., 2020).

From a strategic standpoint, the identification of dominant countries, collaboration hubs, and core publication venues provides guidance for research planning and international cooperation. The coexistence of high-productivity and high-impact contributors highlights complementary national research strategies and underscores the importance of interdisciplinary and cross-border collaboration. For funding agencies and institutions, these patterns may inform decisions related to capacity building, collaborative project design, and long-term investment priorities.

Despite these strengths, several limitations should be acknowledged. First, the analysis is restricted to publications indexed in Web of Science and Scopus, potentially excluding relevant contributions from regional journals, non-indexed proceedings, patents, or grey literature. Second, reliance on specific search terms constrains the corpus to studies explicitly mentioning coatings, hydroxyapatite, copper, and biocompatibility, potentially underrepresenting related work using alternative terminology. Third, citation-based analyses are subject to biases such as citation delay, self-citation, and preferential accumulation of citations by well-established publications.

In terms of future research directions, the identified scientometric patterns point to promising avenues. One involves the need for long-term in vivo validation and standardized biological assessment protocols, as many studies remain focused on short-term in vitro evaluations. Another concerns the optimization of multifunctional and hybrid coating architectures, particularly those combining copper with other bioactive ions, nanostructures, or polymeric layers to achieve finely tuned biological responses. Additionally, the growing interest in biodegradable magnesium-based substrates highlights the need for deeper integration between corrosion science, surface engineering, and biomedical evaluation to address challenges related to degradation control and clinical reliability (Rahman *et al*., 2020; Sarian *et al*., 2022; Yin *et al*., 2020).

From a methodological perspective, future scientometric studies could expand this framework by incorporating patent analysis, funding data, or altmetric indicators to better capture translational and societal impact. The workflow presented here-combining bibliometric performance analysis, science mapping, and Tree of Science classification-offers a transferable approach applicable to other emerging domains in biomaterials and surface engineering.

Overall, this work clarifies the current state and evolution of research on copper-doped hydroxyapatite coatings and provides a structured basis for guiding future scientific inquiry and strategic decision-making.

CONCLUSION

This study provides a scientometric assessment of research on copper-doped hydroxyapatite coatings for biomedical applications, integrating bibliometric indicators, science mapping techniques, and the Tree of Science framework. The results show that this domain has evolved from an exploratory phase to a consolidated and expanding field within materials science and biomedical engineering. The analysis reveals sustained growth in scientific production, accompanied by increasing international collaboration and thematic diversification. The intellectual structure identified through the Tree of Science highlights a progression from foundational studies on hydroxyapatite bioactivity and ion substitution to more advanced research focused on coating technologies, antibacterial mechanisms, and multifunctional surface engineering. Emerging research fronts are associated with advanced coating processes, biodegradable magnesium-based substrates, copper-based nanostructures, and multifunctional implant systems. These trends indicate a shift toward integrated material design approaches addressing bioactivity, antibacterial performance, and long-term functionality. Despite these advances, important challenges remain, particularly regarding the translation of laboratory-scale developments into clinically viable applications. Future research should prioritize long-term performance evaluation, standardized biological testing, and interdisciplinary approaches that facilitate the transition from experimental studies to biomedical applications. Overall, this study provides a structured perspective on the evolution and current state of copper-doped hydroxyapatite coatings and offers a methodological framework applicable to other emerging domains in materials science and biomedical engineering.

ACKNOWLEDGEMENT

The authors acknowledge the Doctoral Program in Sciences of the Inter-University Agreement between Universidad Tecnológica de Pereira, Universidad de Caldas, and Universidad del Quindío for academic support, as well as the project "Recubrimientos de hidroxiapatita incorporando iones de cobre por sistemas PAPVD para posibles aplicaciones médicos" (Code 3247) for financial support. They also acknowledge Becas Bicentenario - second cohort - and the Universidad Nacional de Colombia for providing the infrastructure required for this research.

ABBREVIATIONS

HA: Hydroxyapatite; **HA–Cu:** Copper-doped hydroxyapatite; **WoS:** Web of Science; **ToS:** Tree of Science; **PRISMA:** Preferred Reporting Items for Systematic Reviews and Meta-Analyses; **DOI:** Digital Object Identifier; **SCP:** Single-country publications; **MCP:** Multiple-country publications; SJR: Scimago Journal Rank; **PEO/MAO:** Plasma electrolytic oxidation/micro-arc oxidation.

CONFLICT OF INTEREST

The authors declare that there is no conflict o of interest.

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Cite this article: Echeverry-Cardona LM, Moreno-Vargas JM, Gomez-Aristizaba MA, Santiago LB, Restrepo-Parra E. Scientometric Mapping of Copper-Doped Hydroxyapatite Coatings for Biomedical Applications: Knowledge Structure, Collaboration Patterns, and Emerging Research Fronts. Info Res Com. 2026;3(2):119-31.