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Scientometric Analysis of the Antimicrobial Properties of Copper (cu^{+}) Nanoparticles in the Postharvest Treatment of Agricultural Crops

Análisis Cienciométrico de las Propiedades Antimicrobianas de las Nanopartículas de Cobre (Cu^{+})en el Tratamiento Postcosecha de Cultivos Agrícolas

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Abstract

The loss of crops and postharvest products represents a global concern with direct implications for sustainable development and food security. Among the main contributing factors, phytopathogens stand out due to their persistent impact, posing a constant challenge to the agricultural sector. Although various products have been implemented to control their proliferation, conventional methods have shown significant negative impacts on ecosystem sustainability. In this context, the present study conducts a scientometric exploratory analysis using the Scopus and Web of Science (WoS) databases, to examine the potential of copper nanoparticles (Cu^{+}) in the postharvest treatment of agricultural products. The analysis focuses on their effectiveness as antimicrobial agents, their toxicity, and other applications. The results highlight the use of copper nanoparticles as a viable alternative to traditional agrochemicals, establishing them as highly effective control agents suitable for direct application in the field for the management of crop diseases.

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Keywords: copper nanoparticles, postharvest loss, antimicrobial control

Resumen

La pérdida de cultivos y productos postcosecha representa una preocupación global con implicaciones directas para el desarrollo sostenible y la seguridad alimentaria. Entre los principales factores contribuyentes, destacan los fitopatógenos debido a su impacto persistente, lo que representa un desafío constante para el sector agrícola. Aunque se han implementado diversos productos para controlar su proliferación, los métodos convencionales han mostrado impactos negativos significativos en la sostenibilidad del ecosistema. En este contexto, el presente estudio realiza un análisis cienciométrico exploratorio utilizando las bases de datos Scopus y Web of Science (WoS), con el fin de examinar el potencial de las nanopartículas de cobre (Cu^{+}) en el tratamiento postcosecha de productos agrícolas. El análisis se centra en su eficacia como agentes antimicrobianos, su toxicidad y otras aplicaciones. Los resultados destacan el uso de nanopartículas de cobre como una alternativa viable a los agroquímicos tradicionales, estableciéndolas como agentes de control altamente efectivos, adecuados para su aplicación directa en el campo en el manejo de enfermedades de los cultivos.

Palabras clave: nanopartículas de cobre, pérdidas poscosecha, control antimicrobiano

1. Introduction

Postharvest losses represent a critical challenge for global sustainable development, generating cascading effects that range from the loss of economic and environmental resources to impacts on food security. One of the main causes of this issue is phytopathogens—infectious organisms that affect plants—against which agrochemicals have traditionally been used, despite their adverse effects on the environment [1], [2]

In this context, monovalent copper nanoparticles (Cu^{+}) have emerged as a promising alternative to currently used biocides due to their highly effective antimicrobial properties. These nanoparticles have proven particularly useful in controlling pathogens in fruits and vegetables during storage and transportation. Among them, copper oxide nanoparticles (CuO NPs) stand out for their strong activity against a wide range of pathogenic microorganisms [3], [4], [5]. Their versatility in biomedical, industrial, and environmental applications has led to exponential growth in scientific research, making it necessary to understand how this field has evolved, both in terms of publication volume and thematic focus [6], [7].

Despite the growing interest in the antimicrobial mechanisms and agricultural applications of copper nanoparticles, there is still no comprehensive scientometric study that analyzes the main research trends in this field on a global scale. Recent studies have explored specific aspects such as mechanisms of action or particular applications [3], [8], [9], but they do not systematically address the global evolution of knowledge nor the networks of scientific

collaboration within this domain. This gap limits the identification of thematic voids, emerging regions in scientific production, and key disciplinary interactions [10], [11].

For instance, Chauhan et al. [3] highlights the potential of metallic nanoparticles in agriculture, although it discusses nanoparticle types in a general manner without focusing specifically on Cu^{+}. Meanwhile, Madeshwaran & Venkatachalam [12] analyzes the environmental applications of CuO NPs but does not delve into co-authorship or co-citation analyses. On the other hand, Balaji et al. [8] reports that copper oxide nanoparticles synthesized via eco-friendly methods using plant extracts exhibit remarkable antimicrobial activity, supporting their potential application in postharvest crop management as a sustainable alternative to conventional methods—yet it lacks a scientometric perspective. Collectively, these studies highlight the need for a cross-cutting review of the research landscape.

This article seeks to address these gaps through a scientometric analysis of the literature on the antimicrobial properties of copper nanoparticles, with particular emphasis on their applicability in postharvest treatment of agricultural products. The aim is to construct a global overview of trends in the field by identifying temporal patterns, key contributors, collaboration networks, and agricultural applications. In doing so, this work aspires to offer a useful reference framework to guide future research efforts.

2. Methodology

For the development of this article, two prestigious web-based content databases were used to facilitate the scientometric analysis of the potential of copper nanoparticles. The search was conducted through access provided by the National University of Colombia via its online library, using the Scopus and WoS databases, both recognized for their broad coverage of peer-reviewed scientific literature [13]. Articles containing key terms such as “Nanoparticles,” “Copper,” and “Antimicrobial” were selected. The time range considered extended from 2009 to April 10, 2025, resulting in a total of 381 articles from WoS and 402 from Scopus, which were downloaded and processed for analysis (see Table 1).

Table I. Search parameters used in Scopus and WoS databases.

Parameter	**WoS**	**Scopus**
Range	2009-2025	
Date	April 10, 2025	
Document Type	Articles	
Words	Title: Characterization antimicrobial copper oxide nanoparticles OR Title-Abstract-Keywords: (nanoparticles) AND (antimicrobial) AND (extract) AND (copper AND oxide)	
Results	381	402
Total (WoS + Scopus)	709	

The processing of the bibliometric data obtained from the databases was carried out in several stages (see Figure 1). Initially, 74 duplicate articles were identified and removed from the combined database, resulting in a refined dataset of 709 unique records. From these, the relevant data for the scientometric analysis were organized into 22 Excel sheets, which included information such as references, countries of origin, year of publication, number of citations, journal quartile, and co-authorship networks. Finally, interconnections among the analyzed publications were established, highlighting collaboration, citation, and co-authorship networks within the global scientific output related to the antimicrobial properties of copper nanoparticles, allowing for an assessment of their potential application in the field [14], [15], [16], [17].

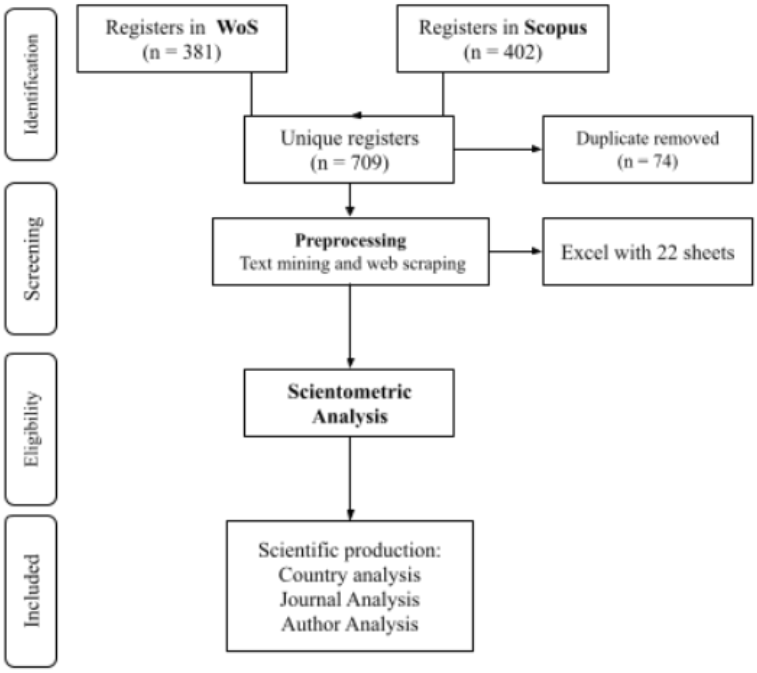

Figure 1. Detailed illustration of collected information.

3. Results

Scientific Annual Production

The analysis of annual scientific output is of great importance, as it reveals key moments in the evolution of the field, as well as its trends and advances. Figure 2 illustrates the production of scientific articles and the total number of citations related to the antimicrobial properties of copper nanoparticles over the period from 2009 to 2024.

In general terms, a gradual and continuous increase in total publications is observed in both databases starting in 2015. The annual growth rate between 2009 and 2024 was 40.72%, reaching its peak in 2024, which reflects an exponential growth in scientific interest in nanoscience and its antimicrobial applications.

In contrast, the behavior of total citations is more variable, peaking in 2021. From that year onward, a progressive decline is observed, which could be attributed to the time lag between article publication and the accumulation of citations. Three major periods can be distinguished that summarize the development of scientific production related to the use of copper nanoparticles as an antimicrobial agent (Figure 2).

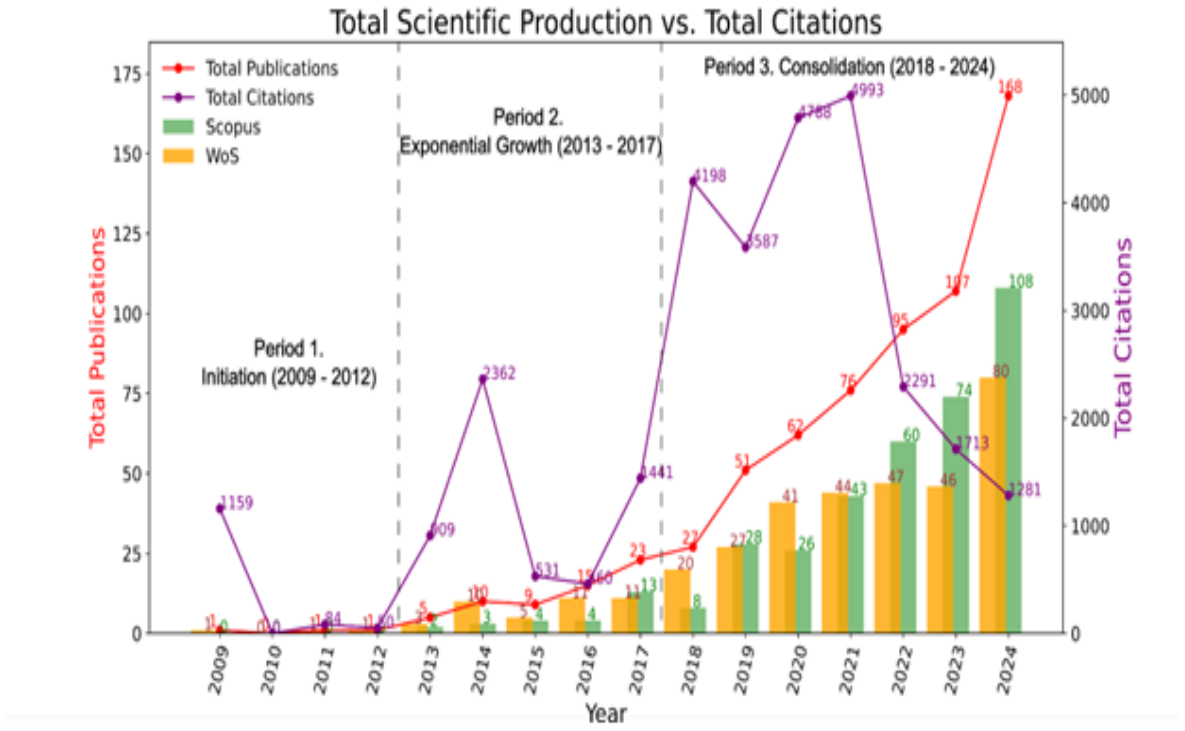

Figure 2. *Scientific Production vs. Total Citations over the time*

Period 1: Initiation (2009–2012)

This period marks the beginning of the development of the research line and is characterized by zero growth in scientific output (0.0%), representing the interval with the lowest number of recorded publications. During these years, a maximum of one publication per platform was reached, indicating a minimal yet foundational level of production for the emergence and consolidation of this derived topic. Despite the limited number of publications, the high number of citations stands out.

These initial contributions are notable for the impact of the published scientific content. In particular, the year 2009 suggests that the study on the antimicrobial properties of copper nanoparticles conducted by Ren et al. [18] was a key milestone in the emergence and structuring of new knowledge in the field, given that information on the topic was limited

during this period. Similarly, research providing fundamental information on the synthesis, characterization, and applications of copper nanoparticles was also published [19], [20].
Period 2: Exponential Growth (2013–2017)
With an annual growth rate of 46.45% over a four-year interval, this period marks the beginning of exponential growth in the field of study. While the number of publications in Scopus remained low and constant, WoS showed a significant increase, consolidating interest in the topic through a higher number of published works.

The large number of citations, concentrated in a small number of articles, suggests not only an expansion in scientific exploration but also the publication of key reference works that gained high visibility and impact within the research community. This pattern is clearly reflected in the citation peak recorded between 2013 and 2014, during which the first significant advances were disseminated regarding the antimicrobial properties of copper nanoparticles synthesized through green methods [21], [22], [23].

The study by Abboud et al. [24] in 2013 highlighted the scarcity of scientific literature on the synthesis of copper nanoparticles using microorganisms and algae, laying the foundational groundwork for this emerging field. Its contributions were such that it became a landmark study, reaching over 500 citations to date. In parallel, during this period of accelerated growth, the research by K. Giannous et al. [10] stands out as the first record found in both WoS and Scopus that evaluated the antimicrobial potential of copper nanoparticles as an input for postharvest crop treatment, offering an alternative to conventional agrochemicals.
Period 3: Consolidation (2018 – 2024)

Between 2018 and 2024, research in this field grew at an annual rate of 35.62%. Although this figure is lower than that of the previous period, these years recorded the highest number of publications and citations. This indicates that the topic reached unprecedented academic visibility and impact. Furthermore, its consolidation shows that it has become an established area of study with distinctive approaches.

During the first four years of this phase, there were citation peaks significantly higher than in previous periods. This growth reflects the increasing interest of the scientific community in the applications of the microbicidal properties of copper nanoparticles, particularly those biologically synthesized and their uses [7], [25].

Country Analysis

Table II presents a comparative analysis of the 10 countries with the highest scientific output, their impact in terms of citations, and the quality of their publications, which was determined according to the quartile classification provided by Scimago Journal. India tops the table with 29.37% of the total number of articles, followed by Saudi Arabia with 8.04% and Iran with 7.58%.
In terms of citations, India also leads (23.66%), although Iran (8.87%) and Egypt (8.20%) stand out significantly despite having lower publication output, suggesting high visibility or relevance of their research. Regarding the quality of publications, notable differences can be

observed: India ranks first with a high number of publications in Q1 (65) and Q2 (74) journals, followed by Iran and Saudi Arabia. In contrast, scientific output from Iraq is primarily concentrated in mid-tier journals (Q2 and Q3).

Table II. Scientific Production and Impact by Country

Country	Production		Citation		Quality			
	Count	%	Count	%	Q1	Q2	Q3	Q4
India	252	29.37	7813	23.66	65	74	44	17
Saudi Arabia	69	8.04	2660	8.06	31	28	3	1
Iran	65	7.58	2928	8.87	28	20	9	0
Egypt	59	6.88	2706	8.2	26	17	9	0
Pakistan	38	4.43	1729	5.24	13	12	6	5
China	33	3.85	988	2.99	16	12	2	0
Korea	23	2.68	599	1.81	14	6	0	0
Usa	22	2.56	435	1.32	11	4	3	0
Turkey	21	2.45	153	0.46	8	7	4	1
Iraq	20	2.33	57	0.17	3	7	4	1

In one of the most recent studies, published in India in 2025 and conducted by researchers from that country, bio-nanocomposite films were developed using Kodo millet starch (KMS), tragacanth gum (GT), and CuO. The results demonstrated that the combination of these three components significantly enhanced the films' mechanical, barrier, and especially antimicrobial properties. This study confirmed that such films represent a highly effective and sustainable alternative for postharvest applications, acting as natural coatings or protective layers that extend the shelf life of agricultural products, inhibit microbial growth, and reduce reliance on toxic components such as plastics and synthetic preservatives [5].
Meanwhile, a study published in Iran utilized Cu and CuO nanoparticles synthesized from Citrus aurantium extracts, which proved to be an eco-friendly, cost-effective, and efficient solution for wastewater decontamination [26].

In Saudi Arabia, a recent publication titled "Green synthesis and biological applications of Peganum harmala-mediated copper oxide nanoparticles" focused on the green synthesis of CuO nanoparticles using Peganum harmala (PH) plant extract, followed by characterization using FTIR, UV–Vis spectroscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD). The study highlighted the high biological potential and efficacy of these nanoparticles, particularly their strong antimicrobial activity against various pathogenic bacteria and a significant antidiabetic effect [27].

Additionally, a 2025 study from Pakistan reaffirmed the antimicrobial properties of biosynthesized CuO and Ag nanoparticles derived from cinnamon bark extract, identifying them as a promising solution to combat resistant microorganisms [28].

Figure 3 presents the international scientific collaboration network related to the use of CuO nanoparticles, especially in postharvest treatment of agricultural products. The network reveals six distinct communities, all of which have contributed to publications on this subject. The figure shows that communities 1 and 2 are the most dominant, with community 1 comprising 18 countries and community 2 including 14. Notably, all communities exhibit interconnected links among the countries within them. A particularly relevant observation is the leadership of Saudi Arabia in community 2 and India in community 3.

While the nodes and links show fluctuations over time, an overall upward trend is evident. In particular, the exponential growth of international links underscores the strengthening of global scientific collaboration in this area.

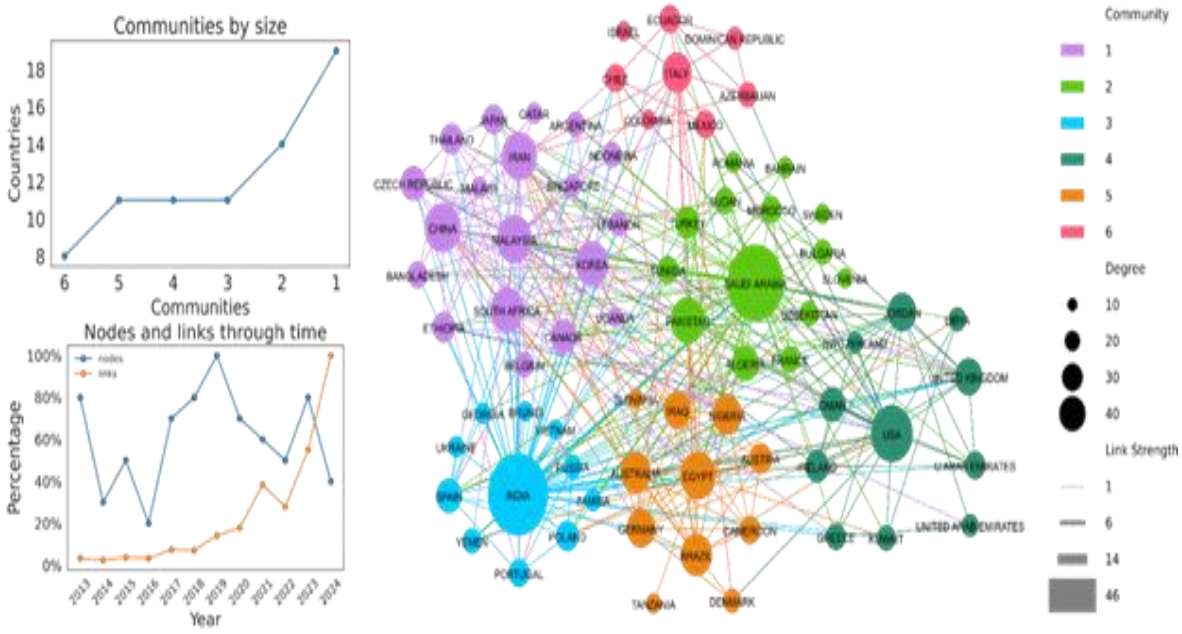

Figure 3. Global Collaboration Network

Journal Analysis

Table III presents the ten journals with the highest number of publications related to the antimicrobial properties of CuO nanoparticles (CuO NPs). It is noteworthy that five of these journals are ranked in the Q1 quartile, indicating high-quality scientific output, while the remaining titles fall within moderate impact categories (Q2 and Q3). Only one journal is not currently indexed within these quartile classifications. This distribution underscores the overall high quality and academic impact of the research being conducted in this area.

Among the Q1 journals, the International Journal of Biological Macromolecules stands out with the highest number of publications, a strong SCImago Journal Rank (SJR) of 1.285, and

an H-index of 219. Meanwhile, Scientific Reports holds the top position in terms of H-index (347), with an SJR of 0.874. An interesting observation is that Inorganic Chemistry Communications, Nanomaterials, and ChemistrySelect appear exclusively in the Web of Science (WoS) database, whereas Materials Today: Proceedings is indexed only in Scopus. Notably, this latter journal does not report quartile rankings, yet it shows acceptable metrics with eight publications indexed in Scopus and an H-index of 112.

On the other hand, Green Processing and Synthesis, ranked in Q2, exhibits the lowest values for both H-index (48) and SJR (0.600), which may suggest a comparatively lower impact within the field.

Table III. *Productivity and Impact of Leading Journals*

Journal	SN	Wos	Scopus	Total	SJR	H-INDEX	Quartile
International Journal Of Biological Macromolecules	01418130	9	6	15	1,285	219	Q1
Scientific Reports	20452322	8	6	12	0,874	347	Q1
Inorganic Chemistry Communications	13877003	8	0	11	0,758	86	Q1
Rsc Advances	20462069	7	4	11	0,777	230	Q1
Materials Today: Proceedings	22147853	0	8	8	0,585	112	-
Nanomaterials	20794991	6	0	8	0,811	151	Q1
Bionanoscience	21911630	3	7	8	0,488	52	Q3
Biomass Conversion And Biorefinery	21906815	1	7	7	0,702	56	Q2
Chemistryselect	23656549	5	0	7	0,366	70	Q3
Green Processing And Synthesis	21919542	3	4	7	0,600	48	Q2

The *International Journal of Biological Macromolecules* has recently published research on a nanocomposite with both antimicrobial properties and controlled drug release capabilities [4]. In this study, bimetallic gold-copper oxide (Au-CuO) nanoparticles were synthesized using plant extracts and subsequently incorporated into a matrix of chitosan and copolymers. The resulting material exhibited high antimicrobial efficacy.

On the other hand, *Scientific Reports*, which holds a higher impact with an H-index of 347, has also contributed notable research in this area. In a recent publication, the journal reported on an experiment involving silver and copper oxide nanoparticles coated with gum arabic (GA@Ag-CuO). These nanomaterials demonstrated strong protective capabilities, with pronounced antimicrobial and even anticancer properties. Specifically, they were effective against bacteria and fungi, and also showed cytotoxic activity against breast cancer cells.

These findings underscore the potential of such nanocomposites as alternative antibacterial agents, particularly against antibiotic-resistant bacteria, and point to promising avenues for the development of more effective and safer biomedical treatments [6].

Additionally, the same study presented the green synthesis of another bimetallic nanocomposite (GA@CuO–ZnO), composed of copper and zinc oxides stabilized with gum arabic. This compound exhibited favorable physicochemical properties and significant antimicrobial activity against a variety of bacterial and fungal strains [29].

Figure IV presents the citation network among journals, highlighting three distinct communities. The first is led by Microbial Pathogenesis, the second by the Arabian Journal of Chemistry, and the third by the International Journal of Nanomedicine. The node-link visualization over time illustrates a noticeable increase in the percentage of inter-journal connections after 2017, indicating a growing consolidation within the academic community focused on this field.

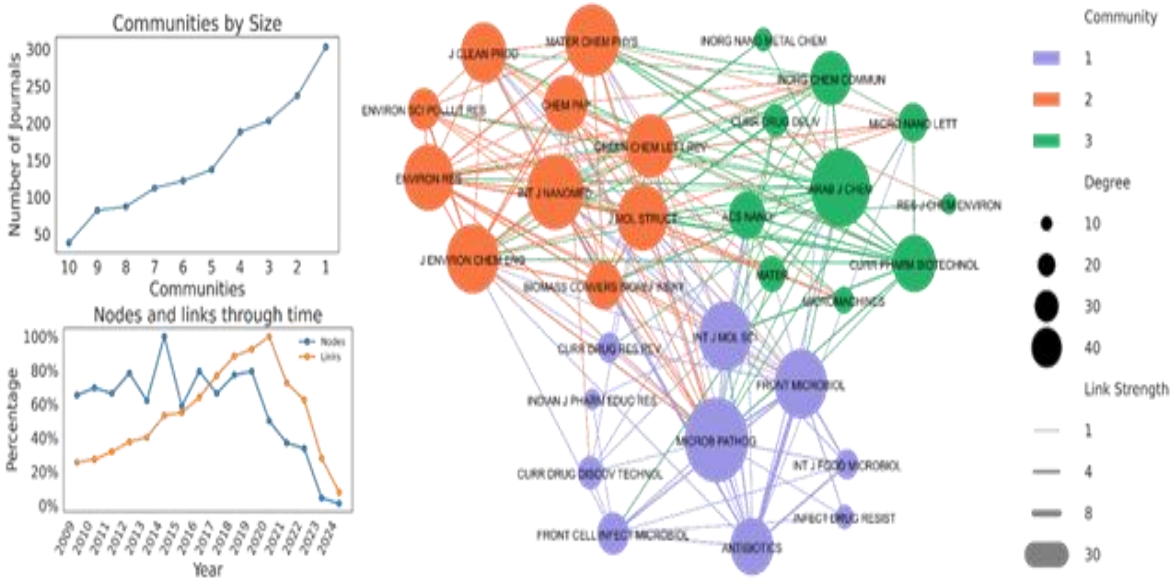

Figure 4. *Citation Network of Leading Journals*

Author Analysis

Table IV presents the ten most prolific authors in the field of antimicrobial properties of CuO NPs, including the number of publications, h-index, total citations, Effective Size, constraint, and the Collaboration Diversity Index (CDI). Among them, Anoar Ali Khan stands out as the most productive author on this topic, with an h-index of 5. In a recent study, he explored the green synthesis of copper oxide nanoparticles using Ricinus communis leaf extract, focusing on their photocatalytic applications for dye degradation and their antimicrobial potential. Techniques such as X-ray diffraction (XRD) were used to confirm the crystalline structure

of the nanoparticles, while FTIR spectroscopy was employed to identify plant-derived compounds acting as key agents in the synthesis process. Photocatalytic tests revealed a dye degradation efficiency of 96.37%, and antimicrobial assays demonstrated inhibitory effects against various bacterial strains, positioning this approach as a sustainable and cost-effective method for CuO NP production in environmental applications [9]. Another prominent researcher is Saurabh Kumar, who has the highest h-index (10) among the group and a total of eight publications. One of his studies focuses on 3D nanocomposites of β-TCP-H_3BO_3-Cu, which exhibit notable mechanical and biological properties. These composites have been engineered for applications in bone regeneration and antimicrobial activity [30].

Table IV. Leading Researchers in Antimicrobial Studies of Copper Oxide (CuO) Nanoparticles: top 10 Authors by Publication Count and Affiliation

Author	Papers Total	Total Citations	H-Index	Effective_Size	Constraint	CDI
Khan A	9	316	5	273.3	0.01	0.09
Ghotekar S	8	265	7	130.01	0.03	0.1
Khan M	8	558	6	294.17	0.01	0.1
Khan S	8	825	6	239.53	0.01	0.12
Kumar S	8	574	10	340.73	0.01	0.12
Rajeshkumar S	8	418	6	111.82	0.03	0.16
Ahmed S	7	57	3	143.47	0.02	0.15
Chauhan A	7	62	4	76.28	0.05	0.09
Hashem A	7	81	4	56.39	0.06	0.15
Kumari A	7	76	5	80.73	0.04	0.1

Regarding social network variables, the Effective Size metric reflects the level of collaborative diversity among authors. For example, Amr Hashem shows the lowest Effective Size value (56.39), indicating that he works primarily within a small, tightly connected group of collaborators who also publish with one another. This interpretation is supported by his high constraint value (0.06), which suggests a dense internal network within his co-authorship circle. In contrast, Shanmugam Rajeshkumar stands out with the highest CDI value (0.16), indicating broader collaborative diversity through interactions with a wider range of co-authors across publications.

Overall, this scientific network analysis reveals important relationships between publication output and the structural quality of the research community in this field. It enables the identification of diverse collaboration strategies employed by authors, while also highlighting their scientific relevance based on productivity and the impact of their publications.

Figure 5. The scientific collaboration network, represented by nodes corresponding to the principal researchers listed in Table IV, is structured around personal networks (ego networks). The analysis reveals the presence of a single dominant group or component within this network, exemplified by the collaboration of Suresh Ghotekar with Garima Rana, Vivek Kumar Dhiman, Syed Kashif Ali, Ankush Chauhan, and Majid Jabir [11]. Together, they

conducted a comprehensive literature review analyzing the synthesis of various metallic nanomaterials derived from plant extracts, emphasizing sustainable and efficient approaches. The review also presents characterization methods, optimal synthesis conditions, and the influence of particle shape and size. Furthermore, the study examines the reduction mechanisms of different plant species and their diverse applications, particularly in biomedicine, such as antimicrobial, anticancer, cytotoxic, and antidiabetic effects, as well as environmental uses, including photocatalytic applications. The potential of these nanoparticles in water treatment is also highlighted, encouraging further research into their role in addressing a range of environmental challenges.

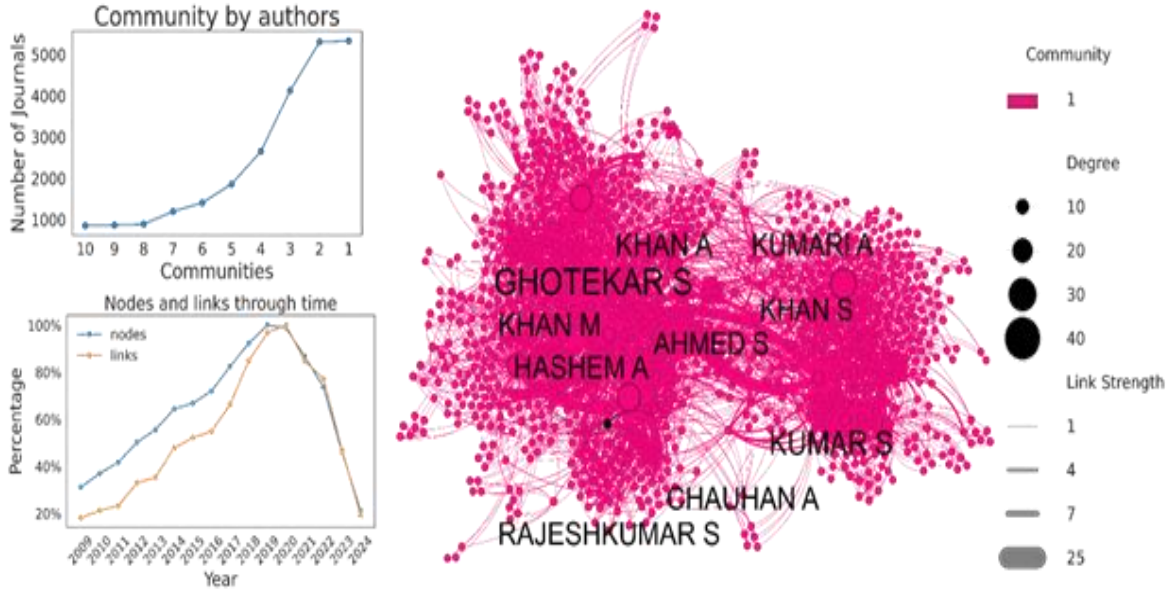

Figure 5. *Network Collaboration of the Most Productive Authors*

Conclusions

This scientometric analysis revealed a sustained growth in scientific production concerning the antimicrobial properties of Cu^{+} in postharvest applications for crops. Searches were conducted in two distinct databases—Web of Science and Scopus—which were integrated using advanced data mining and web scraping techniques. A total of 709 documents were retrieved and served as the foundation for this study. The findings demonstrate a significant evolution in this field of knowledge between 2009 and 2024, highlighting the growing interest of the scientific community in sustainable technological solutions as alternatives to conventional agricultural inputs. Most of the research has been published in high-impact journals, with countries such as Iran, Saudi Arabia, and India emerging as leading contributors, not only in terms of publication volume but also in citation frequency, positioning them as key reference points in this domain.

Moreover, the results indicate that CuO NPs, particularly those synthesized through green methods, offer a more effective and productive alternative for controlling phytopathogens. These nanoparticles show potential applications in areas such as biomedicine, water treatment, and notably, in extending the shelf life of agricultural inputs. This scientometric assessment also enabled the identification of collaborative research networks and thematic concentration among journals, underscoring the academic rigor and research quality within the field. However, despite the observed advancements, significant gaps remain in the practical implementation of this innovation, especially in postharvest treatment of crops in regions with limited scientific output. The lack of applied research and long-term environmental impact assessments poses a major barrier to translating theoretical advancements into practical applications.

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