Rev. Colomb. Cienc. Quím. Farm., **54**(2), 546–560 (2025)

Review article

Bacterial immobilization matrices: a scientometric review

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Received: May 1, 2025
Corrected: May 26, 2025
Accepted: May 29, 2025

https://doi.org/10.15446/rcciquifa.v54n2.121162

SUMMARY

Introduction: This study analyzes the evolution of research on bacterial immobilization matrices using a scientometric approach, identifying trends in scientific production, materials used, characterization methodologies and emerging biotechnological applications. **Methodology:** To this end, a scientometric review based on PRISMA was carried out, with the search of articles in Scopus and PubMed using terms such as “cell immobilization”, “bacterial” and “matrix”, combined with “AND”. A total of 1,232 publications were identified, of which 94 were selected for analysis after applying filters of relevance and originality. Bibliometric tools were used to assess annual production, international collaboration, and key terms in publications. **Results:** The results show that scientific output experienced fluctuations between 2019 and 2024, with a drop in 2023, followed by a rebound in 2024. China, India and the United States lead research in this field. Biopolymers such as alginate, chitosan and polyvinyl alcohol are the most researched materials, while lignocellulosic waste is emerging as more sustainable alternatives. In terms of methodologies, the most commonly used include scanning electron microscopy (SEM) and infrared spectroscopy (FTIR). **Conclusions:** Bacterial immobilization continues to expand, with promising applications in bioremediation and biocatalysis. Diversification in materials and methodologies suggests that multidisciplinary approaches will be critical in the future, so it is recommended to strengthen international collaboration and increase funding in biotechnology to maximize the impact of these technologies.

Keywords: Bacterial immobilization; matrices for immobilization; scientometrics.

RESUMEN

Matrices de inmovilización bacteriana: una revisión cienciométrica

Introducción: Este estudio analiza la evolución de la investigación sobre matrices de inmovilización bacteriana mediante un enfoque cienciométrico, identificando tendencias en producción científica, materiales utilizados, metodologías de caracterización y aplicaciones biotecnológicas emergentes. **Metodología:** Para ello, se llevó a cabo una revisión cienciométrica basada en la metodología PRISMA, con la búsqueda de artículos en Scopus y PubMed usando términos como “cell immobilization”, “bacterial” y “matrix”, combinados con “AND”. Se identificaron 1,232 publicaciones, de las cuales 94 fueron seleccionadas para el análisis tras aplicar filtros de pertinencia y originalidad. Se utilizaron herramientas bibliométricas para evaluar la producción anual, la colaboración internacional y los términos clave en las publicaciones. **Resultados:** Los resultados muestran que la producción científica experimentó fluctuaciones entre 2019 y 2024, con una caída en 2023, seguida de un repunte en 2024. China, India y EE.UU. lideran las investigaciones en este campo. Los biopolímeros como alginato, quitosano y polivinil alcohol son los materiales más investigados, mientras que los residuos lignocelulósicos están emergiendo como alternativas más sostenibles. En cuanto a las técnicas, las más utilizadas incluyen microscopía electrónica de barrido (SEM) y espectroscopía infrarroja (FTIR). **Conclusiones:** La inmovilización bacteriana sigue en expansión, con aplicaciones prometedoras en bioremediación y biocatálisis. La diversificación en materiales y metodologías sugiere que los enfoques multidisciplinarios serán fundamentales en el futuro, por lo que se recomienda fortalecer la colaboración internacional y aumentar el financiamiento en biotecnología para maximizar el impacto de estas tecnologías.

Palabras clave: Inmovilización bacteriana, matrices para inmovilización; cienciometría.

RESUMO

Matrizes de imobilização bacteriana: uma revisão cienciométrica

Introdução: Este estudo analisa a evolução das pesquisas sobre matrizes de imobilização bacteriana utilizando uma abordagem cienciométrica, identificando tendências na produção científica, materiais utilizados, metodologias de caracterização e aplicações biotecnológicas emergentes. **Metodologia:** Para tanto, foi realizada uma revisão cienciométrica baseada no PRISMA, com a busca de artigos na Scopus e PubMed utilizando termos como “imobilização celular”, “bacteriana” e “matriz”, combinados com "AND". Foram identificadas 1.232 publicações, das quais 94 foram selecionadas para análise após aplicação de filtros de pertinência e originalidade. Ferramentas bibliométricas foram utilizadas para avaliar a produção anual, a colaboração internacional e os termos-chave nas publicações. **Resultados:** Os resultados mostram que a produção científica experimentou flutuações entre 2019 e 2024, com queda em 2023, seguida de recuperação em 2024. China, Índia e Estados Unidos lideram pesquisas neste campo. Biopolímeros como alginato, quitosana e álcool polivinílico são os materiais mais pesquisados, enquanto os resíduos lignocelulósicos estão surgindo como alternativas mais sustentáveis. Em termos de metodologias, as mais comumente utilizadas incluem microscopia eletrônica de varredura (MEV) e espectroscopia de infravermelho (FTIR). **Conclusão**: A imobilização bacteriana continua a se expandir, com aplicações promissoras em biorremediação e biocatálise. A diversificação de materiais e metodologias sugere que abordagens multidisciplinares serão críticas no futuro, por isso é recomendável fortalecer a colaboração internacional e aumentar o financiamento em biotecnologia para maximizar o impacto dessas tecnologias.

Palavras-chave: Imobilização bacteriana; matrizes para imobilização, cienciometria.

1. INTRODUCTION

Cell immobilization consists of the confinement of intact cells within a material or device known as a matrix or support, with the aim of maintaining their biological functionality. This process can be carried out by various methods, such as physical adsorption, encapsulation, entrapment, or self-aggregation [1]

The matrix, as a key component in these systems, acts as a three-dimensional support that provides a suitable structural and functional environment for the fixation of living cells, enzymes or other bioactive elements. In addition to providing physical stability, these matrices protect the immobilized components against adverse conditions, allowing them to maintain their viability and functionality for prolonged periods in different biological and chemical processes [2]. This ability to preserve the integrity and biological activity of cells or enzymes has been essential to maintain their viability, maximize the efficiency of biotechnological processes and guarantee their reproducibility [3].

These technologies have proven to be highly versatile and applicable in various fields, including medicine, where they are used in tissue regeneration, controlled drug release, and the production of therapeutic compounds [4]. In the agricultural field, its implementation has allowed the development of sustainable solutions such as bioinoculants, biofertilizers, and biopesticides, optimizing crop growth and reducing environmental impact [5]. Likewise, in the food industry, these technologies improve fermentation and enzymatic processes, while in the environmental sector they contribute to bioremediation and waste treatment [6-8].

The wide range of matrices used in cell immobilization encompasses both inorganic and organic materials. Among the most commonly used inorganic matrices are clays, silicates, crystals, ceramics, diatomaceous earth, polyurethane foam and porous volcanic stones, as well as systems based on the sol-gel technique. These matrices have been widely studied due to their high chemical and thermal stability, as well as their specific properties that favor the efficient immobilization of microorganisms. Recent research has validated its application in various biotechnological and industrial processes [9-15].

Among the most commonly used organic matrices are polymers such as polyacrylamide, agarose, polyvinyl alcohol and alginates, which provide adequate structural support and preserve the biological functionality of the immobilized bacteria. In addition, natural materials such as nylon fiber, cellulose, agar, κ-carrageenan, chitin and collagen have been used, which stand out for their biocompatibility and favorable mechanical properties [16, 17].

Agricultural by-products and lignocellulosic waste have emerged as innovative alternatives in cell immobilization, aligning with circular economy principles. Materials such as sugarcane bagasse, green coffee residues, sugarcane leaves, fibers *Opuntia* spp. y *Agave* spp., biochar and micronized plant residues of coffee have proven to be economical and effective for the immobilization of microorganisms. Other innovative options include the *Luffa cylindrica*, coconut fibers and biological layers of straw, peat and soil, which offer sustainable solutions with specific applications in bioremediation and industrial biotechnology [18-27].

To understand the impact and evolution of matrices used in bacterial immobilization, it is essential to analyze scientific production in this field. Bibliometrics and scientometrics allow us to evaluate trends, identify patterns of collaboration and highlight the technological advances that have driven the development of new cell immobilization strategies. In this context, the present research employs a scientometric approach to examine the scientific literature on bacterial immobilization matrices, providing a comprehensive view of its application in different sectors.

2. METHODOLOGY

This review was developed under a scientometric approach, following the guidelines of the PRISMA 2020 protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [28]. The objective was to identify, analyze, and synthesize scientific publications focused on bacterial immobilization matrices, with emphasis on the types of materials used, characterization methodologies, and their applications in environmental and industrial biotechnology.

2.1. Search Strategy

The bibliographic search was conducted in December 2024 in two scientific databases of high coverage and relevance: Scopus and PubMed. The search terms used were:

"cell immobilization" AND "bacterial" AND "matrix"

The results were limited to articles written in English, without restrictions by year of publication, in order to ensure broad temporal coverage. A total of 1,232 records were retrieved: 662 from Scopus and 570 from PubMed.

Before the screening process, the following were removed:

- Records older than five years: 491 from Scopus and 468 from PubMed.
- Duplicate records between both databases: 53 records eliminated using Mendeley.

After this initial filtering, 220 records were retained for evaluation.

2.2. Inclusion and Exclusion Criteria

The following inclusion criteria were applied:

- Original research articles (reviews, editorials, and conference abstracts were excluded).
- Studies specifically focused on bacterial cell immobilization using natural, synthetic, or composite matrices.
- Studies describing practical biotechnological applications, such as biocatalysis, biofertilization, or bioremediation.

During the evaluation process, the following were excluded:

- 28 records that were not original research articles (mainly reviews or short communications).
- 29 articles that were not available in full text.
- 69 articles that did not meet the thematic eligibility criteria, categorized as follows:
    - Not related to cell immobilization (*n = 25*): studies on general microbial processes or enzyme immobilization without bacterial involvement.
    - Focused on chemical matrices without biological interaction (*n = 29*).
    - Lacking relevance to biotechnology (*n = 15*): purely physical or theoretical studies without direct application.

Ultimately, 94 articles were selected that met all the established criteria.

The full process of identification, screening, exclusion, and eligibility is summarized in Figure 1 (PRISMA flow diagram).

2.3. Data Processing and Analysis

From each of the 94 selected articles, the following information was systematically extracted:

- Bibliographic data: title, authors, year of publication, country of affiliation, journal, and citation count.
- Technical content: type of matrix (biopolymers, lignocellulosic materials, inorganic materials), immobilization technique, bacterial strains used, characterization methods (SEM, FTIR), and biotechnological application.
- Keywords: for co-occurrence analysis and thematic trend evaluation.

The data were organized in Excel spreadsheets and categorized by type of matrix, method, application, and analytical technique. The analysis was performed using the following tools:

- Bibliometrix (in RStudio): to assess publication trends, keyword co-occurrence, and scientific output by country.
- Power BI: to generate the word cloud (Figure 6), based on the frequency of the most used terms.
- Python was used to create: Figure 2: annual scientific production graph (2019–2024). Figure 5: hierarchical clustering of terms.

- LaTeX was used to design the collaborative network diagrams (Figures 3a and 3b), distinguishing studies indexed in Scopus and PubMed.
- Excel was used to construct the geographic distribution map of scientific production (Figure 4) and to generate complementary statistical charts.
- To analyze thematic trends in the field of bacterial immobilization matrices, a hierarchical clustering analysis was performed using co-occurring author keywords extracted from the Scopus database. The most frequent terms were selected and processed applying Euclidean distance as the similarity measure and Ward's method for agglomerative linkage.

This methodological framework enabled a detailed and reproducible characterization of current trends, predominant topics, and knowledge gaps in the scientific literature on bacterial immobilization matrices.

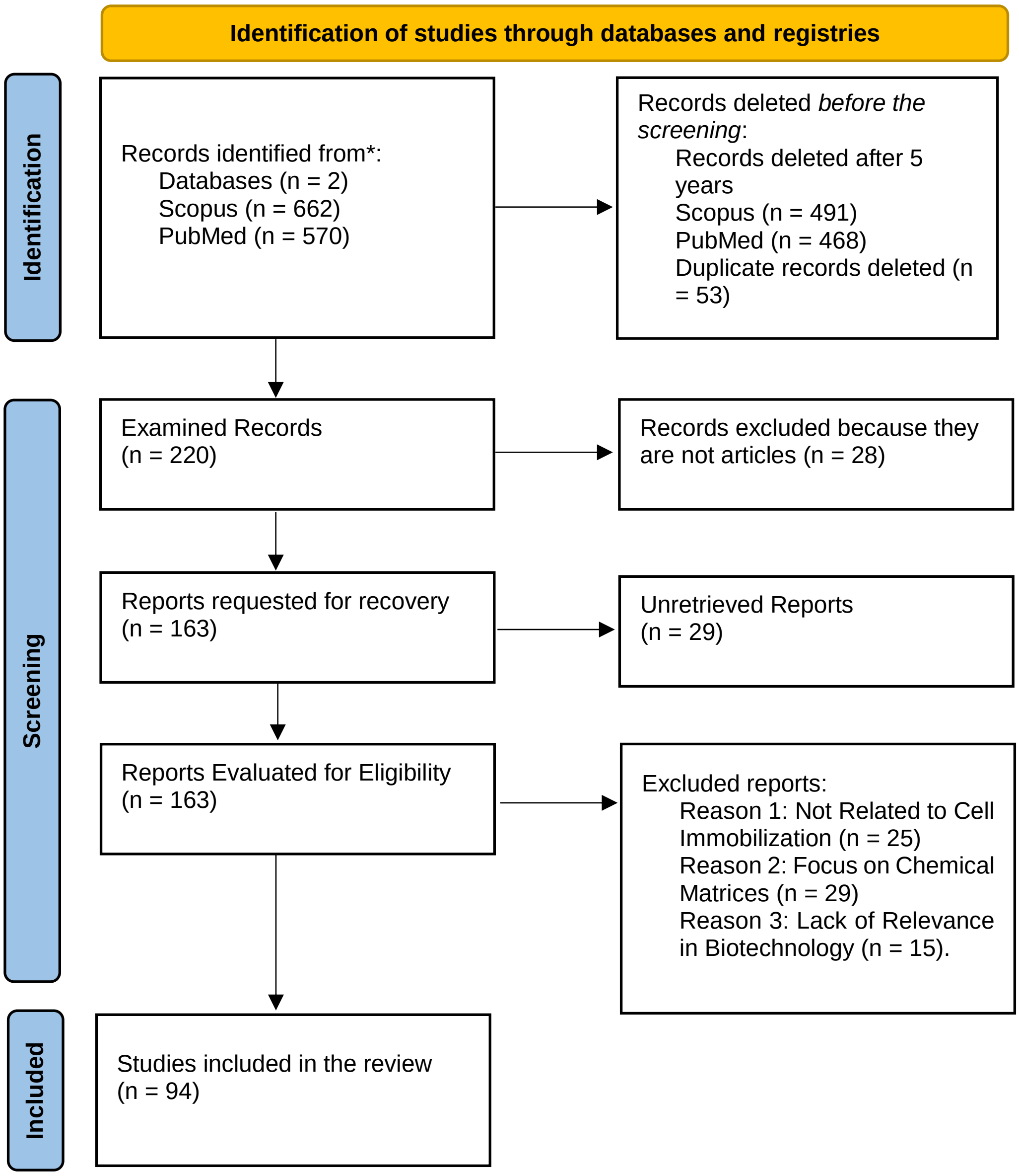

Figure 1. Prism diagram of the systematic review and reference selection process.

3. RESULTS

3.1. Annual Scientific Production

The analysis of the annual scientific production on cell immobilization matrices reveals a fluctuating trend in the number of publications throughout the period 2019-2024. A progressive decrease in the number of articles published from 2019 (19 articles) to 2023 (12 articles) is observed, suggesting a decrease in interest in or funding for research in this area during that period. However, in 2024, there is a rebound in production with a total of 19 publications, indicating a possible reactivation of the field or an increase in the relevance of research related to bacterial immobilization in biotechnology.

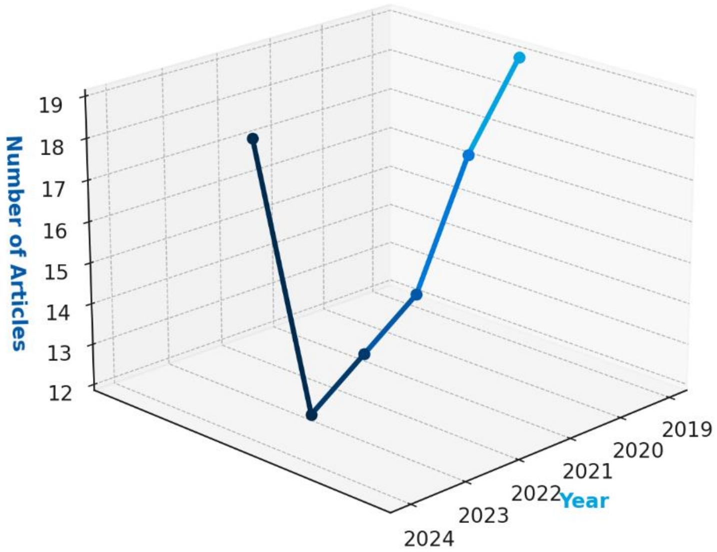

Figure 2. Annual scientific production.

The pattern of scientific production suggests that research on cell immobilization arrays has experienced periods of stabilization and decline, possibly due to changes in scientific priorities, the availability of resources, or the consolidation of previous knowledge. The low recorded in 2023 (12 articles) could be related to transitions in research strategies or the emergence of new areas of application that have diversified the focus of biotechnology studies. However, the increase in 2024 could be associated with advances in immobilization methodologies, new applications in industrial bioprocesses, and greater integration of these systems into emerging sectors such as bioremediation and environmental biotechnology.

These results highlight the importance of continuing to monitor scientific production in this field, as they reflect the impact and evolution of cell immobilization strategies in biotechnology. The upturn observed in 2024 suggests a possible consolidation of new lines of research or greater interdisciplinary collaboration in the development of innovative materials for the immobilization of microorganisms. This underscores the need to strengthen scientific collaboration networks and funding strategies to ensure sustained growth in this area of study.

3.2. Collaborative network

The analysis of the collaboration network in scientific production related to bacterial immobilization matrices (Figures 3a and 3b) reveals the structure and intensity of co-authorships within this field. The visualizations, generated from Scopus data, highlight the presence of different well-defined research groups, each led by central authors with a large volume of publications and collaborative links.

In Figure 3a, a dense group of authors, such as Tarasov Se, Arlyapov Va, and Machulin Av, exhibits strong internal connectivity, suggesting the existence of a consolidated research group working intensively on bacterial immobilization technologies. The pattern observed in this network points to an institutional or regional concentration, with limited external links to other groups. On the other hand, Figure 3b illustrates a more diversified and internationally distributed network, with prominent nodes including Muñoz B, Chen W and Andres A. These authors appear to act as bridges between different groups, fostering transnational and multidisciplinary collaboration

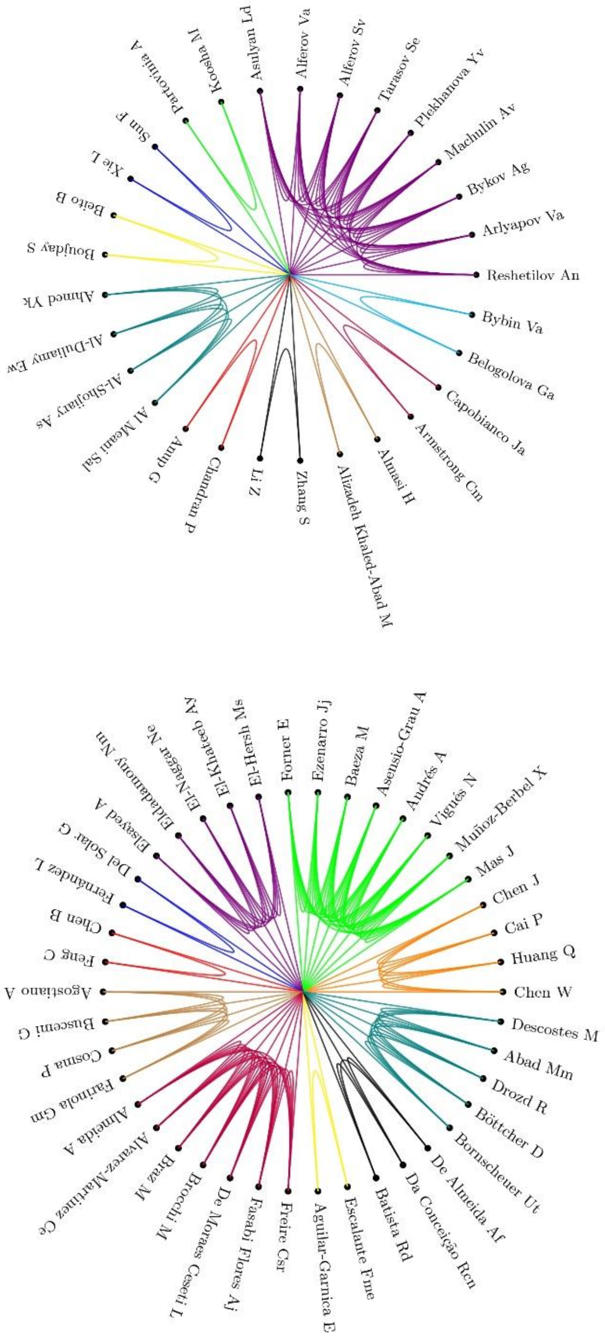

Figure 3a (*Scopus*) 3b (*PubMed*). Collaboration network between authors in research on bacterial immobilization matrices.

In Figure 3a, a dense group of authors, such as Tarasov Se, Arlyapov Va, and Machulin Av, exhibits strong internal connectivity, suggesting the existence of a consolidated research group working intensively on bacterial immobilization technologies. The pattern observed in this network points to an institutional or regional concentration, with limited external links to other groups. On the other hand, Figure 3b illustrates a more diversified and internationally distributed network, with prominent nodes including Muñoz B, Chen W and Andres A. These authors appear to act as bridges between different groups, fostering transnational and multidisciplinary collaboration.

Both networks show a significant presence of recurring authors, reflecting consistent academic contributions and the development of long-term lines of research. The connections observed between multiple institutions indicate a growing trend towards cooperative strategies and the integration of knowledge to address the complex challenges involved in microbial immobilization systems. This highlights not only the scientific maturity of the field but also the potential for greater global collaboration and innovation

3.3. Production by country

The analysis of scientific production by country in the field of bacterial immobilization, based on the Scopus and PubMed databases, Figure 1 reveals a heterogeneous geographical distribution with a strong concentration of publications in certain regions. China leads production with 26% of total publications, consolidating itself as the main contributor in this area. India, with 8.2%, and the United States, with 5.7%, also stand out as key actors in the generation of knowledge on the subject. These countries have extensive collaboration networks and a high impact on research applied to biotechnology and microbiology.

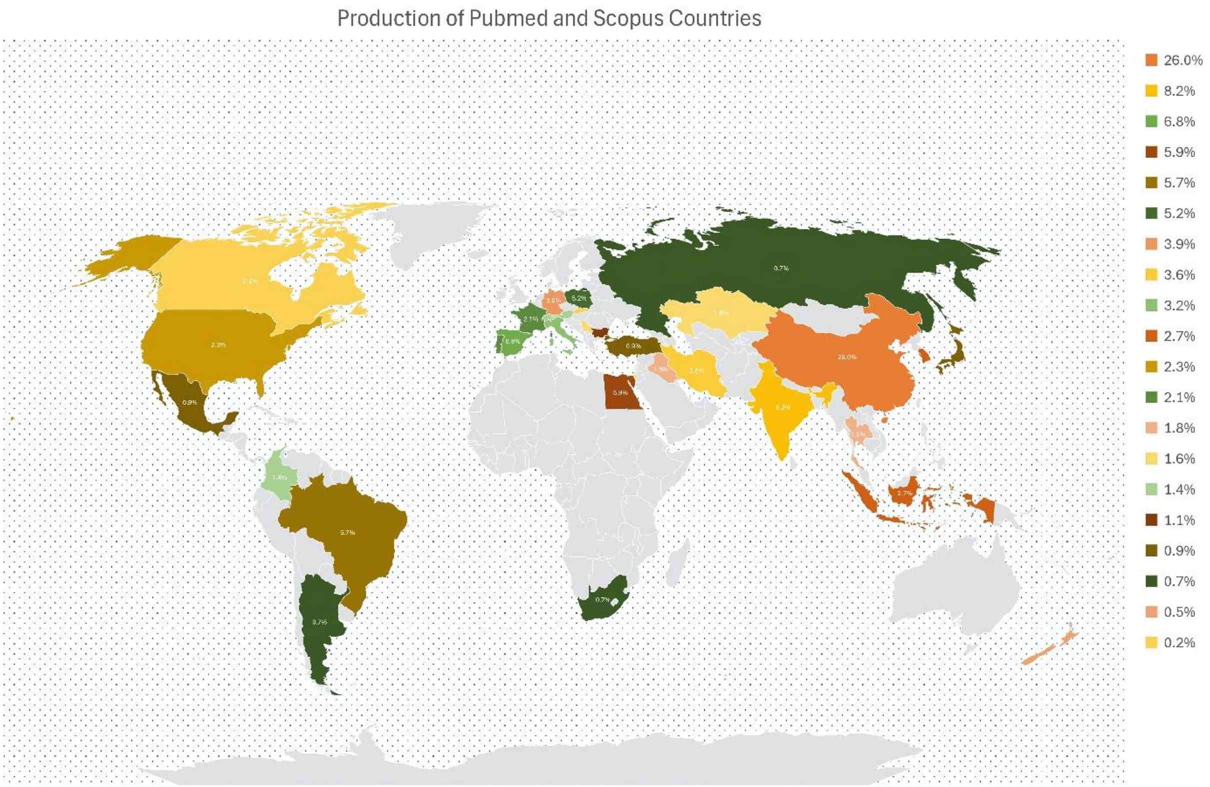

Figure 4. Geographical distribution of scientific production on bacterial immobilization matrices

In Latin America, Brazil is the country with the highest scientific production in this field, with 5.7% of total publications, followed by Argentina (0.7%) and Mexico (1.4%), reflecting a growth in biotechnology research in the region. In Europe, Germany (2.3%) and Italy (3.6%) appear as leaders in scientific contributions, followed by countries with lower production such as Spain and France. On the other hand, in the Middle East and Central Asia, Turkey (5.9%) and Russia (0.7%) have a relevant participation, while other nations show a lower representation in the development of research on bacterial immobilization matrices.

These results show a correlation between investment in biotechnology and scientific production, with highly industrialized countries and research funding policies leading the field. However, the presence of emerging countries on the list indicates an expansion of interest in bacterial cell immobilization in regions with biotechnological development potential. International cooperation and access to research infrastructures influence scientific production capacity, highlighting the importance of strengthening global collaboration networks to advance the biotechnological application of these technologies

3.4. Hierarchical grouping of terms in research on cell immobilization matrices

Hierarchical clustering analysis applied to the most relevant terms in cell immobilization matrix research (Figure 5) reveals interconnectivity and thematic trends in the field. The dendrogram shows the relationship between keywords, establishing groups based on Euclidean distance. It is observed that terms related to matrix types, such as *chitosan*, *sodium alginate,* and *polyvinyl alcohol*, are grouped into specific clusters, indicating their frequent use and their importance in scientific literature. These polymers have been extensively studied for their ability to provide an optimal environment for bacterial immobilization, reinforcing their relevance in biotechnology.

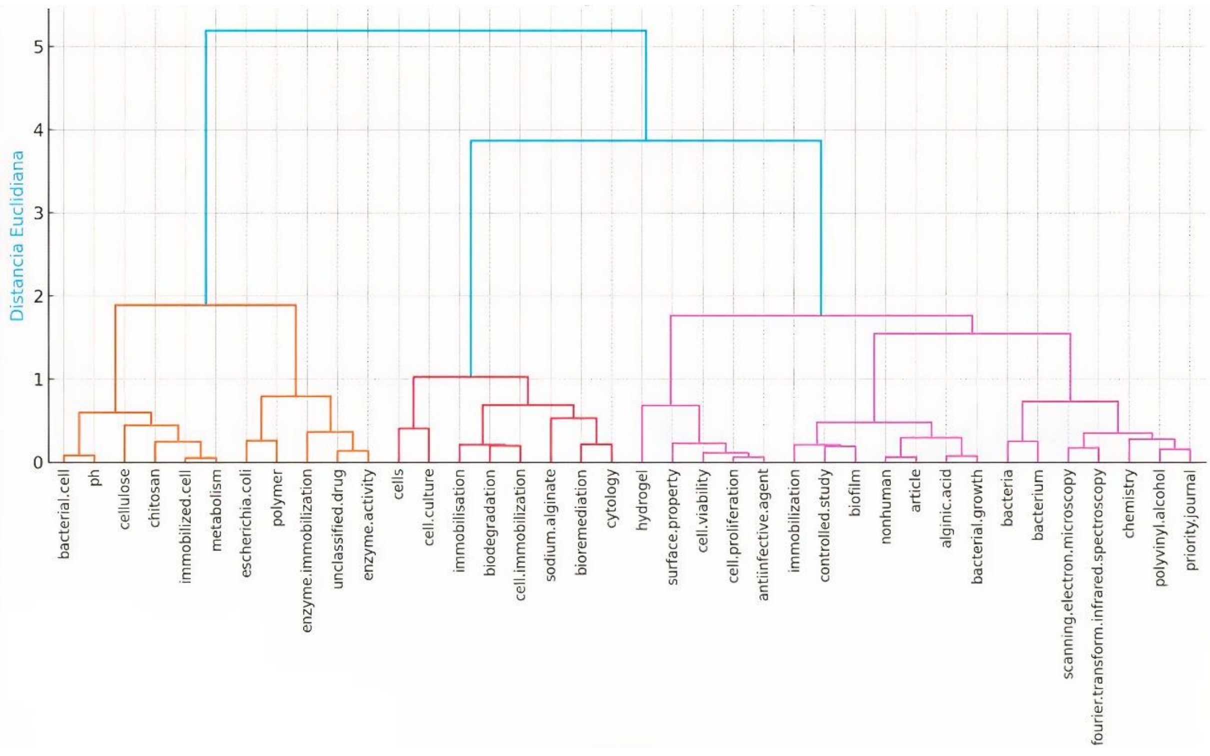

Figure 5. Analysis of hierarchical grouping of terms in research on cell immobilization matrices.

Another significant group of terms relates to the functionality and applications of immobilization matrices. Concepts such as *bioremediation*, *enzyme activity*, *bacterial growth* and *biofilm* appear in groupings that reflect the applied approach of research in this field. The strong relationship between cell immobilization and biocatalysis, evidenced by the proximity of terms such as *enzyme immobilization* and *metabolism*, suggests a continued interest in the use of immobilized systems to optimize enzymatic reactions and improve the efficiency of biotechnological processes.

Likewise, the dendrogram highlights the link between methodological and characterization terms, such as *scanning electron microscopy* and *Fourier transform infrared spectroscopy*, suggesting that these analytical methods are essential for the structural and functional evaluation of immobilization matrices. The presence of these terms in a separate group indicates that their application is transversal to different approaches within the study of cell immobilization, from the physicochemical characterization of supports to the evaluation of cell viability in immobilized systems.

In general, the clustering analysis suggests that research in cell immobilization is segmented into three main areas: the materials used, biotechnological applications and characterization methods. This classification allows for a structured visualization of trends in scientific production and suggests the need to continue exploring new combinations of matrices and methodologies to improve the efficiency of biotechnological processes that depend on cell immobilization.

3.5. Word Cloud

Figure 5 reveals that the most frequent term is immobilization, indicating that research in this field focuses on the use of methods to fix microorganisms in various matrices in order to improve their stability and efficiency. Along with this term, controlled study and bioremediation appear, suggesting that a large number of studies in this area are developed under controlled conditions and are aimed at environmental applications, such as the remediation of contaminated soils and waters.

Figure 6. Word cloud based on a scientometric approach to trends in bacterial immobilization research.

In addition, the prominent presence of terms such as biodegradation, adsorption, and cellulose, indicates that the degradation of compounds by microbial processes is a key focus in the literature analyzed. The inclusion of Escherichia coli, Staphylococcus aureus, and "Pseudomonas", along with words related to bacterium and bacterial cell, demonstrates that multiple bacterial genera have been studied in these investigations, due to their ability to produce biopolymers or degrade toxic compounds.

The appearance of terms such as polyvinyl alcohol, alginate, chitosan, and bentonite, suggests that the materials used for immobilization include natural and synthetic polymers. This reflects a trend towards the use of biopolymers and materials with adsorption and retention properties, which is crucial to improve the effectiveness of microorganisms in biotechnological and environmental applications

4. DISCUSSION

The scientometric analysis carried out on bacterial immobilization matrices has allowed the identification of key trends in research in this field, as well as the main associated biotechnological applications. The results reflect a constant development in this area, with variations in annual scientific production that may be influenced by the focus of research [29]. The identification of the most commonly used materials, emerging applications, and most commonly employed methodological approaches provides a comprehensive view of the state of the art in bacterial immobilization [30].

Bacterial immobilization has proven to be a versatile strategy in various biotechnology sectors, including bioremediation, biomolecule production, and biocatalysis [31]. The high frequency of terms such as immobilization, bioremediation and biodegradation in word cloud analysis suggests that the main efforts in this field are aimed at the application of immobilized microorganisms for the degradation of polluting compounds and wastewater treatment [32]. The consolidation of these approaches has been supported by the growing evidence that cell immobilization not only improves the stability and viability of microorganisms, but also increases the efficiency of biotechnological processes by providing a controlled microenvironment that favors their metabolic activity [33].

Analysis of the matrices used in bacterial immobilization shows that natural and synthetic polymers play a central role in this technology. Materials such as alginates, chitosan and polyvinyl alcohol have been widely used due to their biocompatible properties, their ability to form structured gels and their chemical stability [34]. The prominent presence of terms such as polyvinyl alcohol, alginate and chitosan in scientometric analysis reinforces the relevance of these materials in scientific literature and their potential for industrial and environmental applications [35]. In addition, the use of lignocellulosic residues and agricultural by-products as support for bacterial immobilization aligns with the principles of the circular economy, providing sustainable and low-cost alternatives that have shown promising results in bioremediation processes and bioproduct production [36].

From a methodological point of view, the characterization of matrices and immobilized bacteria has evolved significantly in recent years. The hierarchical grouping of terms has shown that analytical techniques such as scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) are fundamental tools for assessing the morphology and chemical composition of immobilized systems [37]. The importance of these methods in the literature suggests that the structural and functional characterization of the supports is a key aspect to optimize their performance in biotechnological applications [38].

On the other hand, the geographical distribution of scientific output in this field indicates that China, India, and the United States are leading research on bacterial immobilization matrices, which can be attributed to their investment in biotechnology and the number of research institutions specializing in microbiology and materials science [39]. In Latin America, Brazil is positioned as the country with the highest production in this area, reflecting a growth in the development of biotechnological technologies with applications in agriculture and the environment [40]. However, the lower participation of other countries in this area suggests the need to strengthen international cooperation and investment in research infrastructure to consolidate innovation in immobilization bacterial.

The analysis of collaborative networks reveals that studies in this area tend to be grouped around certain authors and institutions with a strong interconnection in Scopus, while in PubMed a lower density of interactions is observed. This may indicate differences in the focus of the publications indexed in each database, with Scopus being more inclined towards applied and multidisciplinary studies, while PubMed contains research with a more biomedical focus [41]. The presence of well-established collaborative networks in the literature suggests that bacterial immobilization is a field that benefits from interdisciplinary cooperation, integrating knowledge from microbiology, materials science, chemistry, and biotechnology [42].

5. CONCLUSION

The scientometric analysis carried out in this study has made it possible to identify the key trends in research on bacterial immobilization matrices, highlighting their relevance in various biotechnological applications, such as bioremediation, biodegradation and biocatalysis. The assessment of scientific output suggests that while there have been fluctuations in the number of publications in recent years, the growing interest in innovative materials and advanced immobilization techniques could drive new research in the field. The strong presence of natural and synthetic polymers such as alginates, chitosan and polyvinyl alcohol in the reviewed literature highlights the importance of these materials in the development of efficient systems for the stabilization and control of microbial activity in industrial and environmental environments. Likewise, the analysis of collaboration networks and geographical distribution of scientific production shows that research in this field is highly cooperative and dominated by countries with a strong investment in biotechnology, which underlines the need to strengthen global cooperation networks in this area.

The results of this study also show the increasing diversification of methodologies used to evaluate the efficacy of immobilization matrices, including electron microscopy techniques, infrared spectroscopy, and biocompatibility analysis. This trend suggests that the integration of multidisciplinary approaches will be key to the optimization of these systems in the future. Given the potential of bacterial immobilization in emerging applications, such as bioenergy and biomaterials production, it is critical to continue monitoring the development of new strategies and assessing their long-term impact on industrial and environmental biotechnology. Finally, it is recommended to promote greater collaboration between research groups from different countries and disciplines, as well as to strengthen financing policies in biotechnology, in order to promote innovation and maximize the benefits of these technologies in different productive sectors.

CONFLICT OF INTEREST

The authors do not declare a conflict of interest.

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HOW TO CITE THIS ARTICLE

J.J. Agredo-Collazos, D.R. Delgado, L.D. Ortega-Martínez, V.R. Soria, E. Girgis-El Kassis, L. Contreras-Mioni & I. Mendoza-Flores. Bacterial immobilization matrices: a scientometric review. *Rev. Colomb. Cienc. Quim. Farm.*, **54**(2), 546–560 (2025). Doi: https://doi.org/10.15446/rcciquifa.v54n2.121162