RGe ISSN: 2177-3246

GLOBAL RESEARCH PATTERNS IN GREEN CHEMISTRY FOR BIOMATERIALS: INSIGHTS FROM A PRISMA-BASED META-ANALYSIS

PADRÕES GLOBAIS DE PESQUISA EM QUÍMICA VERDE PARA BIOMATERIAIS: INSIGHTS DE UMA META-ANÁLISE BASEADA EM PRISMA

PATRONES DE INVESTIGACIÓN GLOBALES EN QUÍMICA VERDE PARA BIOMATERIALES: PERSPECTIVAS DE UN METAANÁLISIS BASADO EN PRISMA

10.56238/revgeov17n6-097

Luana Costa de Souza[1], Ariene de Morais Alves[2], Boutros Sarrouh[3], Igor José Boggione Santos[4], Érika Cristina Cren[5], Renata Carolina Zanetti Lofrano[6]

ABSTRACT

This research presents a bibliometric analysis of the scientific landscape concerning the application of green methodologies for biomaterial production. Articles were retrieved from the Web of Science database, and parameters such as publication volume, citation count, H-index, and keyword co-occurrence were examined. The United States, China, and India emerged as leading contributors in publication output. The journals analyzed were classified into three groups: biomaterials and biopolymers, green chemistry and chemical engineering, and environmental technologies and bioeconomics. Among institutions, the National University of Singapore stood out with 75.2 citations per article. Edgar and Kevin were the most influential authors, achieving 23.04 citations. Keyword analysis highlighted 44 terms of major relevance, reflecting thematic diversity and research growth. Overall, findings confirm an increasing trend in biomaterial studies guided by sustainable approaches, with applications advancing in the food, pharmaceutical, and biomedical industries, consolidating green technology as a transformative scientific field.

Keywords: Biopolymer. Sustainable Materials. Eco-Friendly Processing. Green Innovation.

RESUMO

Esta pesquisa apresenta uma análise bibliométrica do panorama científico referente à aplicação de metodologias verdes na produção de biomateriais. Os artigos foram

[1] Federal University of São João del-Rei (UFSJ), Postgraduate Program in Chemical Engineering (PPGEQ) Orcid: 0000-0002-4199-7957
[2] Federal University of São João del-Rei (UFSJ) Postgraduate Program in Chemical Engineering (PPGEQ) Orcid: 0009-0005-1351-0709
[3] Federal University of São João del-Rei (UFSJ), Department of Chemistry, Biotechnology and Bioprocess Engineering (DQBIO). Orcid: 0000-0003-4476-2309
[4] Federal University of São João del-Rei (UFSJ), Department of Chemistry, Biotechnology and Bioprocess Engineering (DQBIO). Orcid: 0000-0003-1897-2804
[5] Federal University of Minas Gerais (UFMG), School of Engineering, Department of Chemical Engineering (DEQUI). Orcid: 0000-0003-0312-5872
[6] Federal University of São João del-Rei (UFSJ), Department of Chemical Engineering (DEQUI) E-mail: renataczlofrano@ufsj.edu.br. Orcid: 0000-0002-5688-3936

recuperados da base de dados Web of Science e parâmetros como volume de publicação, número de citações, índice H e coocorrência de palavras-chave foram examinados. Os Estados Unidos, a China e a Índia emergiram como os principais contribuintes em termos de produção científica. Os periódicos analisados foram classificados em três grupos: biomateriais e biopolímeros, química verde e engenharia química, e tecnologias ambientais e bioeconomia. Entre as instituições, a Universidade Nacional de Singapura destacou-se com 75,2 citações por artigo. Edgar e Kevin foram os autores mais influentes, com 23,04 citações cada. A análise de palavras-chave destacou 44 termos de grande relevância, refletindo a diversidade temática e o crescimento da pesquisa. De modo geral, os resultados confirmam uma tendência crescente nos estudos de biomateriais guiados por abordagens sustentáveis, com aplicações avançando nas indústrias alimentícia, farmacêutica e biomédica, consolidando a tecnologia verde como um campo científico transformador.

Palavras-chave: Biopolímero. Materiais Sustentáveis. Processamento Ecológico. Inovação Verde.

RESUMEN

Esta investigación presenta un análisis bibliométrico del panorama científico en relación con la aplicación de metodologías verdes para la producción de biomateriales. Se recuperaron artículos de la base de datos Web of Science y se examinaron parámetros como el volumen de publicaciones, el número de citas, el índice H y la coocurrencia de palabras clave. Estados Unidos, China e India se destacaron como principales contribuyentes en la producción científica. Las revistas analizadas se clasificaron en tres grupos: biomateriales y biopolímeros, química verde e ingeniería química, y tecnologías ambientales y bioeconomía. Entre las instituciones, la Universidad Nacional de Singapur sobresalió con 75,2 citas por artículo. Edgar y Kevin fueron los autores más influyentes, con 23,04 citas. El análisis de palabras clave resaltó 44 términos de gran relevancia, lo que refleja la diversidad temática y el crecimiento de la investigación. En general, los hallazgos confirman una tendencia creciente en los estudios de biomateriales guiados por enfoques sostenibles, con aplicaciones que avanzan en las industrias alimentaria, farmacéutica y biomédica, consolidando la tecnología verde como un campo científico transformador.

Palabras clave: Biopolímero. Materiales Sostenibles. Procesamiento Ecológico. Innovación Verde.

1 INTRODUCTION

Technological and industrial progress has brought countless benefits to modern society, but has also resulted in significant environmental challenges. Pollution resulting from production processes, the intensive exploitation of natural resources, and the generation of toxic waste have become central issues in the search for a more sustainable development model. In the biomaterials sector, this problem is even more critical, since many conventional synthesis methods use harmful organic solvents, require high energy consumption, and can generate by-products that are harmful to the environment and human health. In addition, large-scale production often involves inefficient processes, resulting in raw material waste and ecological impacts (Ganesh et al., 2021; Iravani et al., 2017).

As an alternative, green chemistry seeks to prevent pollution by developing products and processes designed to minimize or eliminate the use and generation of hazardous substances. This approach allows for a broader assessment, considering factors such as the choice of raw materials, the selection of solvents, the toxicity and risks of reagents, and the efficiency of reactions and waste management (Sheldon et al., 2022). For these principles to be adopted, it is essential that academic training emphasizes sustainable practices, ensuring that future generations of chemists develop and apply environmentally responsible methods in their undergraduate and postgraduate laboratories. Applying the 12 principles of green chemistry (Table 1) provides a solid basis for guiding these processes and ensuring that greener and safer practices are integrated into research and teaching (Anastas & Green, 1998). By incorporating these aspects, green chemistry contributes to a more detailed understanding of the sustainability of processes and their environmental impacts, helping to formulate more effective strategies for optimizing and reducing ecological damage.

Table 1

The 12 principles of green chemistry.

Principle	Description
Prevention	It is better to avoid generating waste than to treat or dispose of it after it has been formed.
Atomic Economy	Synthetic methods should maximize the incorporation of all the materials used in the final product.
Synthesis of Less Dangerous Chemicals	The chemical substances produced should be less toxic to humans and the environment whenever possible.
Safe Product Projects	Chemical products must be developed to preserve their effectiveness while minimizing their toxicity.
Safer Solvents and Auxiliaries	Using auxiliary substances (such as solvents and separation agents) should be minimized or replaced by less harmful alternatives.
Energy Efficiency	The environmental impacts of chemical processes must be reduced by efficient energy use, preferably renewable sources.
Use of Renewable Raw Materials	Whenever possible, raw materials should be renewable rather than nonrenewable.

Reduction of Derivatives	To reduce waste, unnecessary steps, such as temporary locks (functional group protectors), should be minimized.
Catalysis	Catalysts (preferably selective) should be used to make the processes more efficient and less energy intensive.
Degradation Projects	Chemical products should be designed to break down into harmless substances after use, avoiding environmental persistence.
Real-time Monitoring	Analytical methods must be developed to monitor processes in real time, reducing the formation of hazardous substances.
Inherently Safer Chemistry	Substances and processes must be designed to minimize the risk of accidents such as explosions, fires, and toxic emissions.

Source: (Adapted Anastas & Green, 1998).

Given this problem, this study aims to carry out a systematic review and meta-analysis on the application of green chemistry in the production of biomaterials, using the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure methodological rigor and transparency in the selection and analysis of scientific publications. The meta-analysis will make it possible to quantify the impacts of this approach, assessing its influence on parameters such as synthesis efficiency, waste reduction, energy costs, and the final performance of biomaterials. By consolidating and interpreting the available data, this work aims to provide a critical and comprehensive overview of the benefits, challenges, and prospects of green chemistry in this field, contributing to the advancement of science and the development of more sustainable solutions in biomaterials.

2 METHODOLOGY

The data used in this research were obtained from the Web of Science platform, using the descriptors “Green Chemistry” AND “Biomaterials Production”, “Eco-friendly Catalysts” OR “Sustainable Biomaterials” OR “Waste Reduction” AND “Biopolymer Efficiency” as the search terms. The bibliometric indicators used were the number of publications and citations, the leading institutions, and the h-index.

The documents found were refined according to their year of publication and type of production, with only the “Article” and “Review” types being considered. The bibliographic data was represented according to the graphic didactics of the VOSviewer software (https://www.vosviewer.com/).

3 RESULTS AND DISCUSSION

3.1 EVOLUTION OF PUBLICATIONS ON GREEN CHEMISTRY IN THE PRODUCTION OF BIOMATERIALS

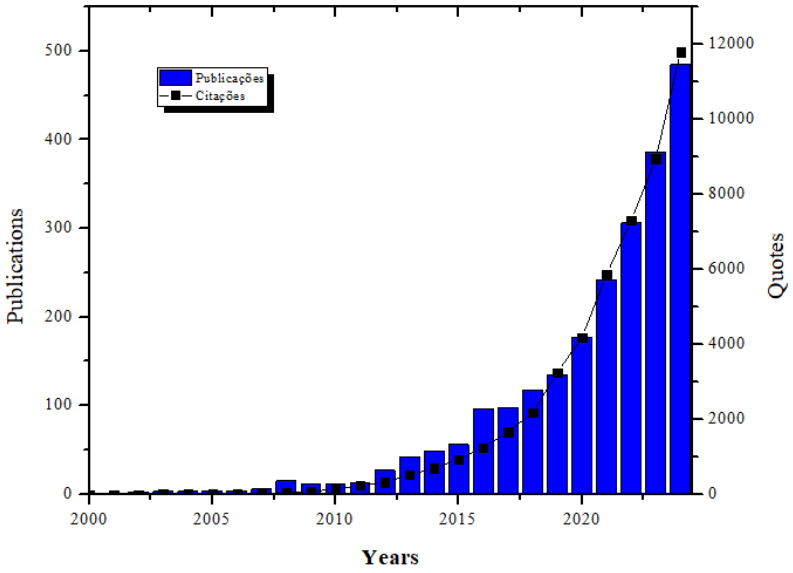
3.1.1 Number of articles over the years

Figure 1 shows a trend in publications over the years 2000 to 2024. This data was obtained from the Web of Science platform database. The search resulted in 2,191 research

articles and 37 review articles. The analysis concerns the intellectual interactions and structural connections between the constituents of the research (Donthu et al., 2021). According to the years surveyed, despite a slight drop in 2010, the number of articles published has continued to grow since 2015. This growth pattern can be seen more clearly from 2020 onwards, with more than 400 publications and close to the 12.000-citation mark. The subject's versatility can explain this favorable scenario as a highly innovative field of study encompassing engineering, biology, chemistry, and medicine (Todros; Bagno, 2021). Citations, as mentioned above, follow publications about the growth of articles over the years in the academic environment.

Figure 1

Publication trend



3.1.2 Main articles and authors

Table 2 shows the publications by article, authors, year of publication, and total citations. The years of publication from 2000 to 2024 were taken into account to generate the results. The data on total citations has been displayed to visually show that the number of citations decreases as the year progresses.

Table 2

List of the 10 most influential articles and authors.

Position	Article title	Authors	Year of publication	Full quote
1	Biodegradable polymer matrix nanocomposites for tissue engineering: A review	Armentano, I; Dottori, M; Kenny, JM.	2010	749

2	The role of biomass and bioenergy in a future bioeconomy: Policies and facts	Scarlat, N; Dallemand, JF; Nita, V.	2015	547
3	Comprehensive Evaluation of Deep Eutectic Solvents in Extraction of Bioactive Natural Products	Duan, L; Dou, LL; Liu, EH.	2016	377
4	Sustainable materials for electrochemical capacitors	Fic, K; Platek, A; Frackowiak, E.	2018	263
5	Applications of chitin and chitosan nanofibers in bone regenerative engineering	Tao, FH; Cheng, YX; Deng, HB.	2020	237
6	Engineered and Laser-Processed Chitosan Biopolymers for Sustainable and Biodegradable Triboelectric Power Generation	Wang, RX; Gao, SJ; Wu, W.	2018	234
7	A sustainable route from biomass cotton to construct lightweight and high-performance microwave absorbers	Zhao, HQ; Cheng, Y; Du, YW.	2018	230
8	Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites	Appels, FVW; Camere, S; Wösten, HAB.	2019	224
9	4-Hydroxyproline-Derived Sustainable Polythioesters: Controlled Ring-Opening Polymerization, Complete Recyclability, and Facile Functionalization	Yuan, JS; Xiong, W; Lu, H.	2019	221
10	Recent progress in biodegradable polymers and nanocomposite-based packaging materials for a sustainable environment	Wróblewska-Krepsztul, J; Rydzkowski, T; Thakur, VK.	2018	207

The grouping of the 10 main articles allows us to identify the biggest citations of this research in the academic community. Armentano et al. (2010) point out that their article on biodegradable polymer nanocomposites is used for tissue regeneration. The article's hypothesis discusses mechanical properties, biocompatibility, and applications in biomedical engineering, and it has 749 citations.

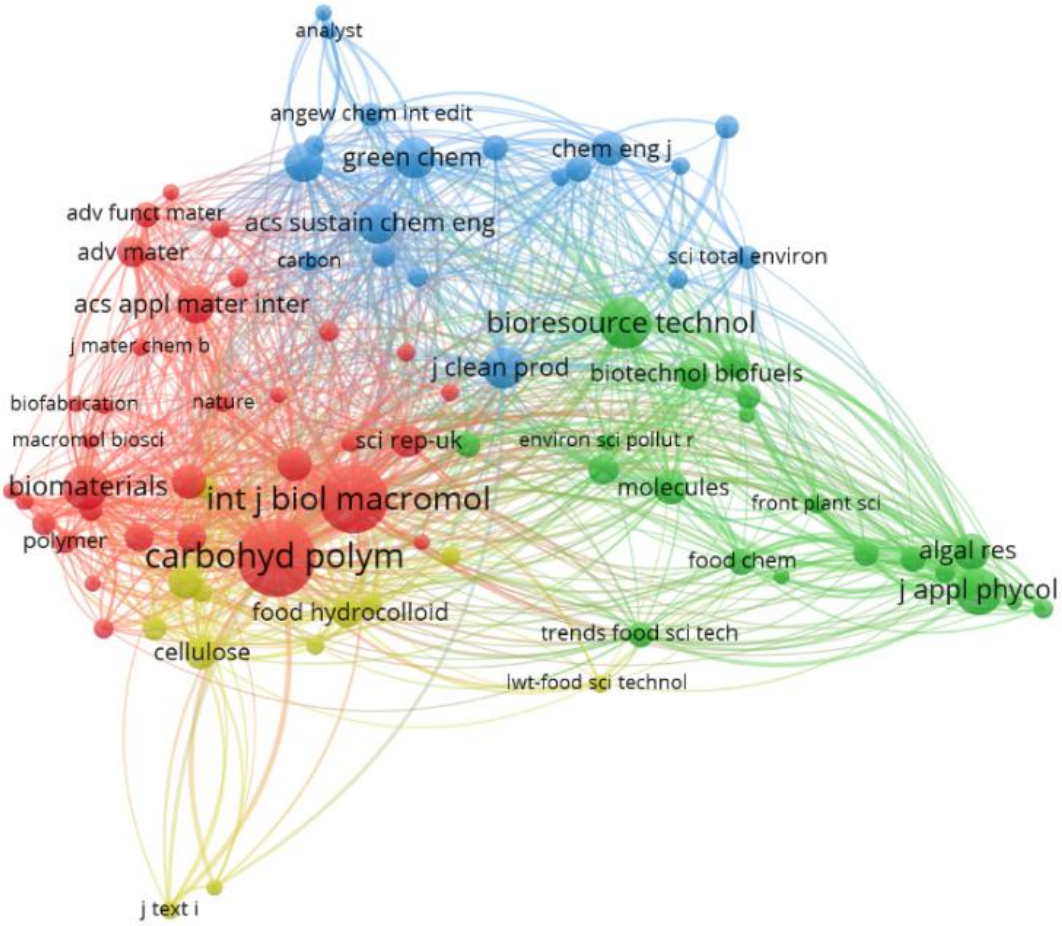
Another critical article was published by Scarlat et al. (2015), which described the analysis of global policies for a sustainable bioeconomy, highlighting the potential of biomass as a renewable energy source and substitute for fossil fuels. Its results include 547 total citations. The third article in the table, published by Duan et al. (2016), developed a study on using deep eutectic solvents as green alternatives for extracting bioactive compounds, with advantages such as low toxicity and recyclability. The other articles present the same scenario of using biomaterials in their research.

3.1.3 Main journals, institutions, and countries involved

The mapping carried out by the VOSviewer software (Figure 2) shows how scientific publications are organized into thematic clusters, reflecting the interaction between different areas of knowledge.

Figure 2

Scientific publications.



The co-citation network shows three main clusters of journals. The first cluster, represented by red, covers studies on biomaterials and biopolymers, with high-impact journals such as International Journal of Biological Macromolecules, Carbohydrate Polymers, and Biomaterials. This network region is strongly associated with the production and efficiency of biopolymers, exploring strategies to make materials more sustainable and functional.

The blue cluster includes journals focused on green chemistry and chemical engineering, such as Green Chemistry, Chemical Engineering Journal, and ACS Sustainable Chemistry & Engineering. This group investigates innovative approaches to using green catalysts and sustainable chemical processes, promoting solutions that reduce the environmental impact in producing biomaterials (Sheldon, 2016). The green cluster is related to environmental technologies and the bioeconomy. Journals such as Bioresource Technology, Journal of Cleaner Production, and Algal Research are present in this category, reflecting a strong interest in waste reduction strategies and developing sustainable biomaterials from renewable sources. This interaction suggests a growing interest in the

circular bioeconomy and the integration of sustainability principles in the materials industry (Clark; Luque, 2010).

Thus, the interconnectivity between the clusters indicates a strong interdisciplinarity between green chemistry, biomaterials' production, and biopolymers' efficiency. The relationship between journals from different clusters shows that advances in sustainable chemical processes directly impact the formulation of more efficient and environmentally friendly biomaterials (Anastas; Eghbali, 2010).

Table 3 combines the central institutions highlighted in this analysis, showing the performance of 10 research centers in the study of green methodology applied to producing biomaterials. The following indicators were considered to assess their relevance: number of publications, H index, and citations per item.

Table 3

Main institutions.

University	Publications	H-Index	Citation by item
Massachusetts Institute of Technology School of Engineering	13	8	33
King Saud University College of Science	13	6	11
Aalto University School of Chemical Engineering	13	10	31
National University of Singapore College of Design and Engineering	15	9	75
Peking University Shenzhen Hospital Department of Bone and Joint Surgery	16	8	13
Peking University Shenzhen Hospital	17	8	14
Peking University Health Science Center	19	9	19
Virginia Polytechnic Institute and State University Department of Chemistry	21	13	16
Nanyang Technological University College of Engineering	21	9	30
Virginia Polytechnic Institute and State University College of Science	22	13	17

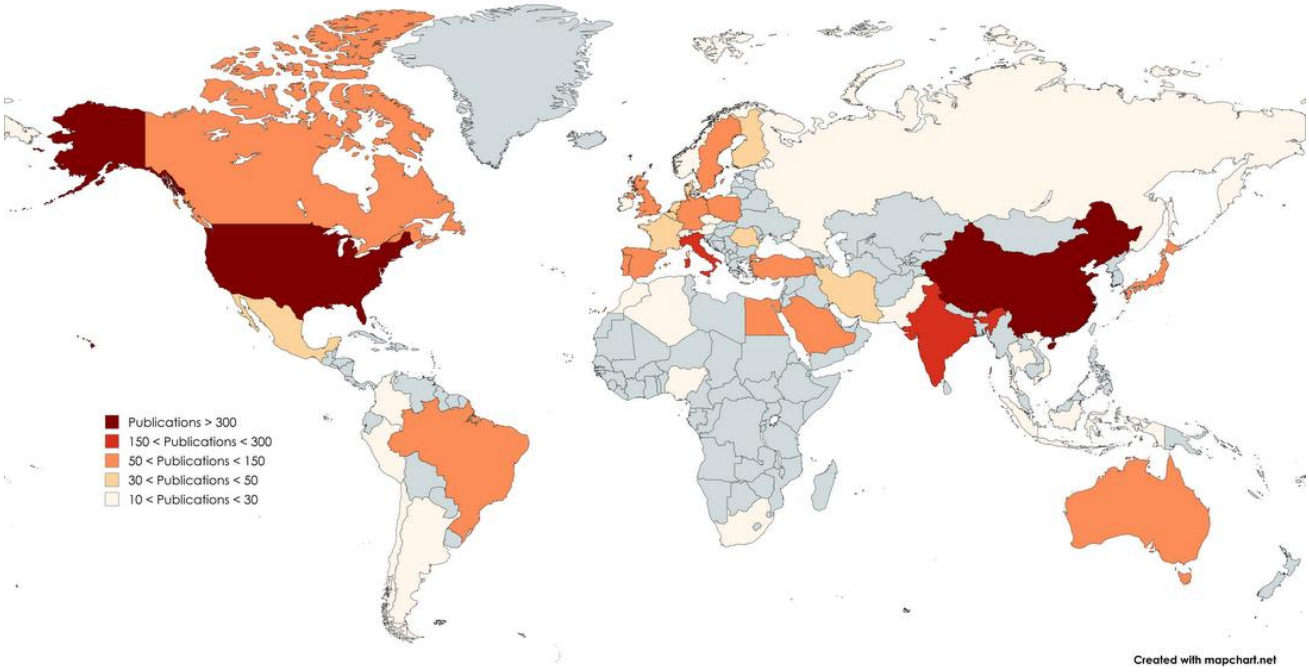
The institution with the most significant influence on publications on the subject is the National University of Singapore, with an average of 75.2 citations per article, which shows the relevance and impact of its scientific contributions, making it a reference in the area. Virginia Polytechnic Institute and State University and Nanyang Technological University also stand out, especially for the high number of publications, with around 21 articles each, as well as having higher H-indexes and average citations per item compared to the other institutions, indicating consistency and quality in their productions. The Massachusetts Institute of Technology (MIT) and the Aalto University School of Chemical Engineering stand out in terms of the impact of citations per item, with averages of 32.69 and 31.08, respectively, which demonstrates the substantial impact of their work, even with a smaller number of publications.

The other institutions analyzed have more modest values in the indicators used, having less influence in the specific scientific scenario of this study.

The map shown in Figure 3 reveals a geographical distribution of the concentration of scientific production related to green methodology in the production of biomaterials. The countries that have demonstrated significant influence are part of North America, Europe, Asia, and Oceania. According to the legend, each color intensity represents the different ranges of publication volume, i.e., the stronger the hue, the greater the number of articles published.

Figure 3

Global distribution of publications.



The countries that stand out with the highest volume of publications (>300) are the United States, China, and India, which are marked in dark red. They have a high rate of publications because they invest substantially in research and development in this field (Zhang and Liu, 2022). Italy appears in an intermediate position with values ranging from 150 to 300 publications, highlighted in medium red. Brazil, Japan, Germany, Iran, Turkey, Australia, the United Kingdom, Canada, France, Spain, and South Korea are in the 50 to 150 publication range (orange). This demonstrates the influence of this research in national and international terms. The countries that appear more modest in terms of the number of publications in the 30 to 50 range are Egypt, Argentina, Poland, the Netherlands, and Thailand, represented by the color beige. The white or light gray countries represent the

regions with fewer than 30 publications, with less contribution to the field (Zhang, Li, Liu, 2022).

3.2 APPLICATIONS OF BIOMATERIALS PRODUCED WITH GREEN METHODOLOGY IN THE FOOD, PHARMACEUTICAL, AND BIOMEDICAL INDUSTRIES

The production of biomaterials through green methodology has made a name for itself in academic research. Table 4 summarizes the main applications of biomaterials in different industries, highlighting how each sector uses these materials produced using green methodology. These materials are environmentally friendly and offer significant benefits for sustainability, and they are considered a growing field in the scientific community (Dutta et al., 2020).

Table 4

Applications of biomaterials produced using green methods.

Industry	Applications	References
Food	- Biodegradable packaging (e.g., chitosan and cellulose films) to extend food shelf life. - Natural additives (e.g., curcumin nanoparticles) as antioxidants. - Edible coatings for fruit/vegetables (e.g., alginate).	Sharma et al. (2021); Oun et al. (2020)
Pharmacist	- Controlled drug release systems (e.g., alginate microspheres). - Antimicrobial biomaterials (e.g., green silver nanoparticles). - Sustainable excipients (e.g., modified starch).	Kaur et al. (2022); Makvandi et al. (2021)
Biomedical	- Scaffolds for tissue engineering (e.g., bacterial cellulose hydrogels). - Dressings with healing properties (e.g., fibroin membranes). - Resorbable implants (e.g., lactic acid polymers derived from renewable sources).	Torres et al. (2020); Ahmed et al. (2021)

In the food industry, biomaterials are used to increase product shelf life, ensure greater food safety, and reduce the environmental impact of packaging that damages the environment. Biodegradable packaging stands out among these applications, such as chitosan and cellulose films, which offer natural barriers against moisture and microorganisms, prolonging the shelf life of food (Sharma et al., 2021; Qun et al., 2020).

In the pharmaceutical industry, biomaterials contribute to the development of new drug release systems and the replacement of some synthetic substances with biodegradable alternatives. Examples include alginate microspheres in controlled release systems, which allow the gradual and localized release of drugs in the body (Kaur et al., 2022; Mukwaya et al., 2021).

Biomaterials are used in tissue engineering, wound healing, and implant production in the biomedical sector. Scaffolds made from bacterial cellulose hydrogels act as three-

dimensional supports for tissue regeneration, enabling greater cell adhesion and uniform growth. Healing dressings, such as fibroin-based membranes, have shown good biocompatibility and accelerated the regeneration process of epithelial tissues (Torres et al., 2020; Ahmed et al., 2021).

3.3 BIBLIOMETRIC ANALYSIS AND CITATION NETWORKS

3.3.1 Main authors and institutions

The bibliometric analysis revealed that of the 1058 authors identified, only 10 stood out for publishing at least 10 documents from 2000 to 2024 (Table 5).

Table 5

Analysis of the principal authors and institutions.

Position	Author	Registration	Full quote	H-Index
1	Edgar, Kevin	27	23,04	16
2	Numata, Keiji	19	18	11
3	Reis, Rui L.	17	27,82	11
4	Kaplan, David L	16	35,94	11
5	Alves, Nuno	15	18,2	8
6	Zeng, Hui	14	14,43	8
7	AL-Oqla, Faris	12	23,58	7
8	Da Silva, Tiago Henriques	10	23,4	7
9	Chen, Yingqi	10	17,8	7
10	Jameel, Hasan	10	30,4	8

Among these researchers, Kevin Edgar is the author with the highest number of records (27), followed by Keiji Numata (19) and Rui L. Reis (17). However, the number of publications does not necessarily directly reflect the academic impact of the work, and it is also essential to analyze the total citations and the H-index.

When comparing the average number of citations per year, David L. Kaplan has the highest value (35.94) despite only having 16 publications. This indicates that his works are highly cited and influential. Similarly, with 10 publications, Hasan Jameel has an average of 30.4 citations, surpassing Keiji Numata (18) and Rui L. Reis (27.82), who have more publications.

Another relevant aspect is the H-index, which measures research productivity and impact. Kevin Edgar, the leader in the number of publications, has an H-index of 16, the highest among the authors analyzed. Rui L. Reis and David L. Kaplan have H indexes 11, similar to Keiji Numata. Despite having fewer publications, these authors demonstrate a significant impact, reinforcing that the quality and influence of research are just as important as the number of articles published.

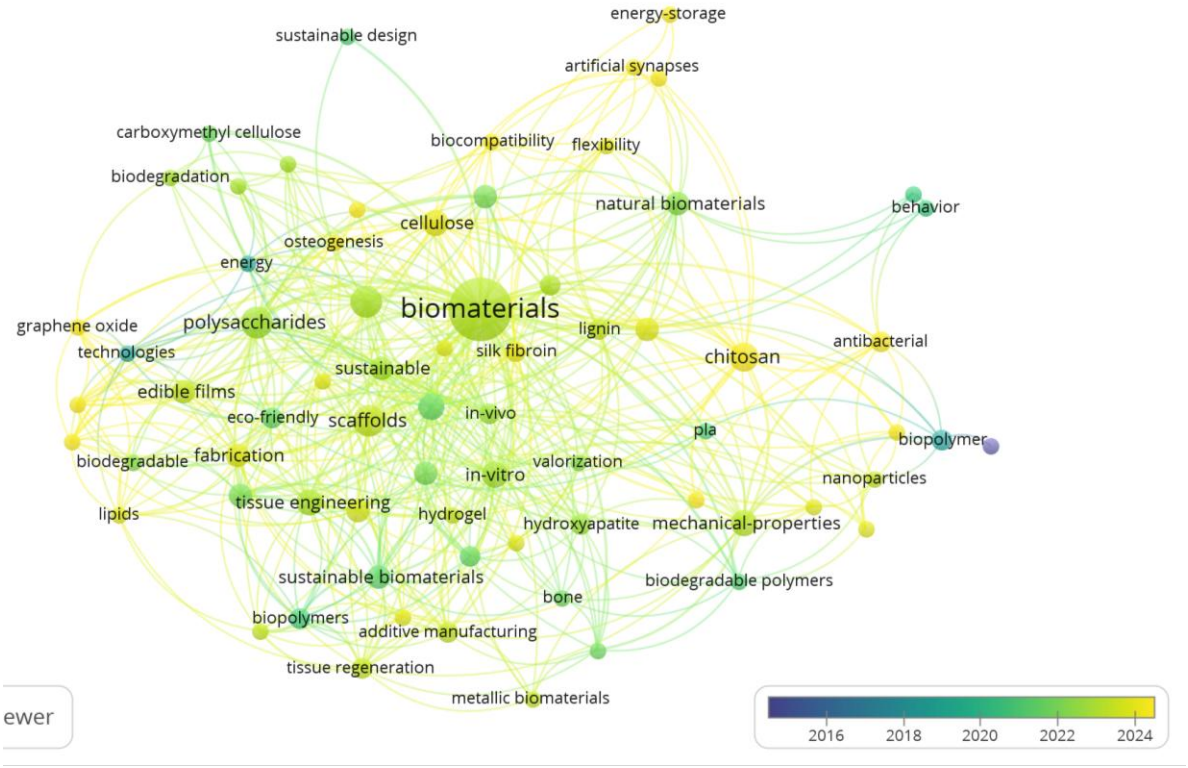
It is interesting to note the geographical and interdisciplinary diversity of the researchers, indicating that the production of sustainable biomaterials and their relationship with green chemistry have attracted scholars from different regions and academic backgrounds. Their research addresses the use of ecological catalysts, the efficiency of biopolymers, and waste reduction strategies, which align with the principles of green chemistry (Li, Chen, and Zhao, 2021).

3.3.2 Most relevant keywords

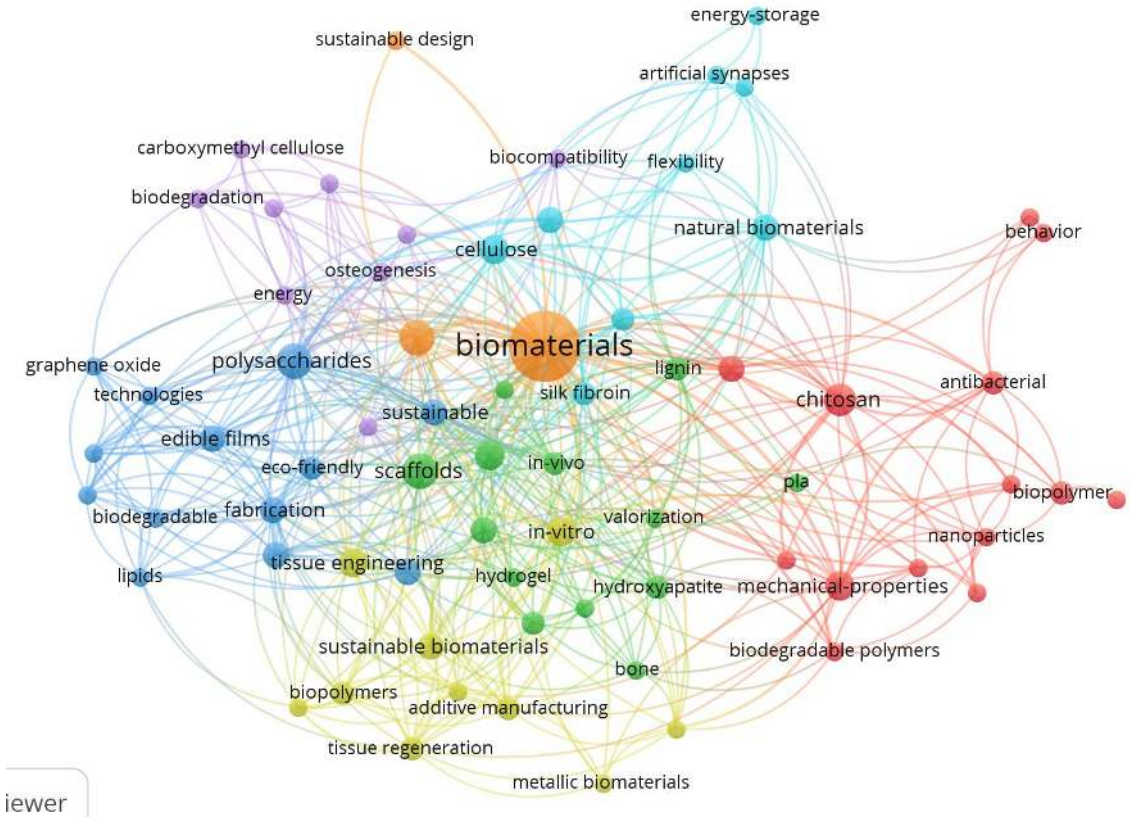
The VOSviewer program was used to obtain specific information for the analysis. Documents from 2000 to 2024 were refined, making it possible to circle the correlation between the keywords used. The co-occurrence map helps to understand current research trends by connecting them to the bigger picture. The cluster size is proportional to the strength of the word in the documents found, and the network linking them suggests that they are directly interconnected (Sahu and Pramanik, 2022).

Figure 4

Keywords analysis.



a)



b)

Keyword analysis is one of the most popular techniques to be used for data analysis. In this study, the keywords used were “Green Chemistry”, “Biomaterials Production”, “Eco-friendly Catalysts”, “Sustainable Biomaterials”, “Waste Reduction”, and “Biopolymer Efficiency”. This analysis makes it possible to identify the interconnection between occurrence, citation, coupling, and citation in the context of detailed bibliometric analysis to understand the research content as a leading indicator of information (Sahu and Pramanik, 2022). Figure 4a-b brings together 44 keywords, highlighting the prominent authors in the field.

3.4 ENVIRONMENTAL AND ECONOMIC IMPACT

The production of biomaterials using the green methodology represents an environmentally and economically viable alternative with strong potential for technological innovation. From an ecological point of view, replacing fossil raw materials with renewable sources such as biomass and waste significantly reduces the production processes' environmental footprint, promoting a more effective circular economy. Methods known as “benign by design” seek to minimize the use of toxic substances and the generation of hazardous waste. In addition, the specific applications of biomaterials further extend their positive impacts on the environment and society (Zhao, Cornish, & Vodovotz, 2020).

The application of green methodology in developing biomaterials has generated significant economic advances for scientific research. Using low-cost waste, such as agricultural waste and algae, as a raw material helps reduce costs. It adds value to previously discarded by-products, turning them into promising materials for producing nanocomposites and emerging technologies (Azevedo et al., 2020). In addition, simplified and less energy-intensive processes reduce operating costs, increasing the industrial viability of these solutions. Using these biomaterials in innovation sectors also creates new market opportunities, strengthening the link between sustainability and technological development (Patil, Dandge, and Jadhav, 2021).

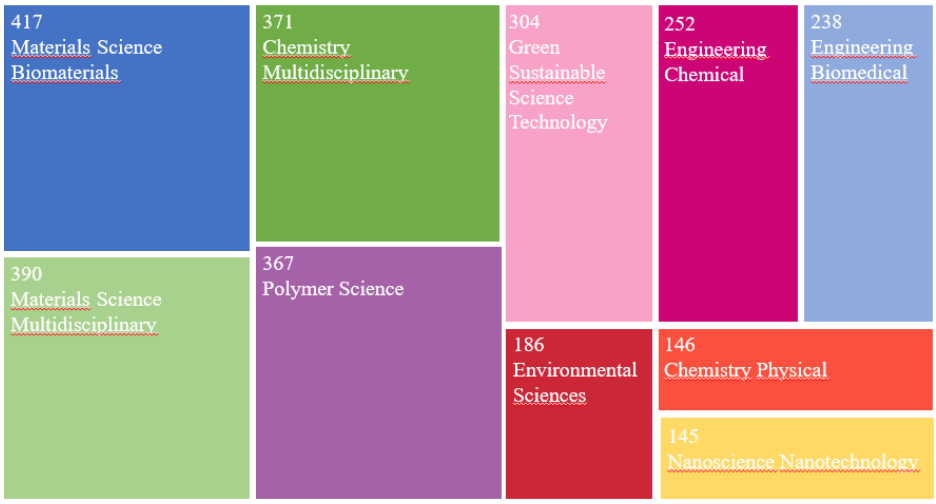
Although there are still challenges to be overcome, the continuous advances of research and the growing mastery of natural raw materials point to promising solutions in the future. The evolution of green methodologies strengthens their strategic role in building a more sustainable and economically viable production model, making them essential for a more balanced and conscious future (Niaounakis, 2019).

3.4.1 Main thematic areas

For this analysis, the treemap graphic method was used, a type of graphic that uses rectangles of sizes proportional to the number of publications to visually illustrate their production in different scientific areas linked to the biomaterial's scenario. In this case, Figure 5, investigates the relationship between various scientific fields that know conventional processes and processes based on green methodology for the development of biomaterials (Cobo et al., 2011).

Figure 5

Main thematic areas based on the green methodology.



The "Materials Science Biomaterials" area stands out, with 417 publications. This indicates that this is the main research category, despite the approach used. Next is the area of "Chemistry Multidisciplinary," which, with 371 publications, has a strong presence in this field. Chemical interdisciplinarity is an essential part of formulating and developing biomaterials.

The "Materials Science Multidisciplinary" area has 309 publications and demonstrates the breadth of knowledge in the field of materials, involving physical, chemical, and even environmental aspects. Clear evidence of the significant growth of green chemistry approaches in biomaterials research is the presence of the "Green Sustainable Science Technology" area, which with only 304 publications, shows that although conventional techniques still dominate in quantitative terms, sustainable strategies already occupy a specific position of prominence and represent a promising trend in the scientific field.

The field of "Polymer Science," with 267 publications, highlights the importance of polymers, which are an indispensable basis for developing biomaterials. Equally important, engineering is also well represented with 252 publications in chemical engineering and 238

publications in biomedical engineering, demonstrating that biomaterials have practical applications both on an industrial scale and in the health sector. The presence of areas such as “Environmental Sciences” with 186 publications, “Chemistry Physical” with 146 publications, and “Nanoscience Nanotechnology” with 145 publications demonstrates the growing concern with environmental impacts and the use of emerging technologies to make biomaterials more efficient and sustainable.

4 CONCLUSION

This bibliometric review, conducted using the PRISMA protocol, revealed that the application of Green Methodology principles has had positive impacts on reducing environmental damage and improving the economic viability of production processes. In addition to preventing waste generation, this approach values using renewable raw materials and promotes greater energy efficiency.

The analysis showed significant growth in scientific publications between 2000 and 2024, emphasizing institutions such as the National University of Singapore and researchers such as Kevin Edgar and David L. Kaplan, whose work had a high academic impact. The correlation between areas such as Materials Science, Green Chemistry, and Engineering highlights the interdisciplinary potential of this field of research, driving innovation in crucial sectors such as biodegradable food packaging, controlled-release pharmaceutical systems, and resorbable biomedical implants.

ACKNOWLEDGMENTS

The authors would like to thank the Federal University of São João Del-Rei/UFSJ, the National Council for Scientific and Technological Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the National Institute of Science and Technology for Research and Knowledge of Excellence in the Western(Eastern) Amazon (INCT-CONEXÃO) for their financial and infrastructure support.

DECLARATIONS

Author contributions: Conceptualization, R.C.Z.L.; methodology, L.C. de S. and A. de M.A.; data curation, L.C. de S.; A. de M.A. and R.C.Z.L. investigation, L.C. de S. and A.de M.A.; validation, L.C. de S. and A. de M.A.; formal analysis, L.C. de S. and A. de M.A.; supervision, R.C.Z.L.; visualization, R.C.Z.L.; B.S.; I.J.B.S. and E.C.C.; project administration, R.C.Z.L.;

writing—original draft, L.C. de S.; A. de M.A.; R.C.Z.L.; B.S.; I.J.B.S. and E.C.C.; writing—review & editing, R.C.Z.L.; B.S.; I.J.B.S. and E.C.C.; All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials: Data available on request from the authors.

Conflict of Interests: The authors declare no conflict of interest.

Funding: No funding was received for this study.

Ethics approval and consent to participate: Not applicable.

Consent for publication: All authors agree to the publication of this article.

REFERENCES

Agboola MO, Bekun FV, Joshua U. 2021. "Pathway to environmental sustainability: Nexus between economic growth, energy consumption, CO_2 emission, oil rent and total natural resources rent in Saudi Arabia." *Resources Policy* 74:102380. https://doi.org/10.1016/j.resourpol.2021.102380.

Ahmed S, Ikram S, Yaqoob M. 2021. "Applications of natural polymers in the biomedical field." *International Journal of Biological Macromolecules* 168:1–19. https://doi.org/10.1016/j.ijbiomac.2020.12.205.

Azevedo S, Costa-Pinto AR, Martins A, Neves NM. 2020. "Agricultural and food waste valorization into biomaterials: Recent trends and perspectives." *Biomaterials Advances* 106–107:100758. https://doi.org/10.1016/j.bioadv.2020.100758.

Clark JH, Luque R. 2010. "Catalysis for converting biomass to fuels and chemicals: The role of green chemistry." *Catalysis Today* 157(1–4):2–6. https://doi.org/10.1016/j.cattod.2010.02.048.

Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F. 2011. "Science mapping software tools: Review, analysis, and cooperative study among tools." *Journal of the American Society for Information Science and Technology* 62(7):1382–1402. https://doi.org/10.1002/asi.21525.

Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. 2021. "How to conduct a bibliometric analysis: An overview and guidelines." *Journal of Business Research* 133:285–296. https://doi.org/10.1016/j.jbusres.2021.04.070.

Dutta SD, Patil TV, Lim KT, Lee YS. 2020. "Sustainable biopolymer-based biomaterials: Processing, properties and applications." *International Journal of Biological Macromolecules* 154:304–315. https://doi.org/10.1016/j.ijbiomac.2020.03.120.

Kaur R, Kaur J, Arora S. 2022. "Green-synthesized nanoparticles in drug delivery and antimicrobial applications." *Journal of Drug Delivery Science and Technology* 68:103112. https://doi.org/10.1016/j.jddst.2021.103112.

Li J, Chen Y, Zhao X. 2021. "Sustainable biomaterials: Advances in green chemistry approaches." *Progress in Materials Science* 119:100795. https://doi.org/10.1016/j.pmatsci.2020.100795.

Makvandi P, Wang CY, Zare EN, Borzacchiello A, Niu LN, Tay FR. 2021. "Antimicrobial green nanomaterials." *ACS Applied Materials & Interfaces* 13(8):10121–10134. https://doi.org/10.1021/acsami.0c23074.

Mukwaya R, Ajambo H, Kiguli C. 2021. “Sustainable excipients and drug delivery systems: A review of biomaterial advances.” *Pharmaceutical Research* 38(3):479–490. https://doi.org/10.1007/s11095-021-03008-w.

Niaounakis M. 2019. *“Biopolymers: Applications and trends.”* Elsevier. https://doi.org/10.1016/C2017-0-00769-6.

Oun AA, Rhim JW, Abdellatief MH. 2020. “Alginate-based nanocomposites for food packaging.” *Carbohydrate Polymers* 240:116420. https://doi.org/10.1016/j.carbpol.2020.116420.

Patil P, Dandge PB, Jadhav JP. 2021. “Green synthesis of biocomposites and their industrial applications.” *Materials Today: Proceedings* 47(Part 11):3693–3700. https://doi.org/10.1016/j.matpr.2021.04.019.

Qun G, Zhang Z, Sun T. 2020. “Chitosan-based films and coatings for food packaging applications.” *Food Hydrocolloids* 100:105433. https://doi.org/10.1016/j.foodhyd.2019.105433.

Sharma S, Kumar S, Singh A. 2021. “Biodegradable packaging materials from renewable sources: A review.” *Environmental Chemistry Letters* 19:2345–2360. https://doi.org/10.1007/s10311-020-01133-w.

Sheldon RA. 2016. “Green and sustainable manufacture of chemicals from biomass: State of the art.” *Green Chemistry* 18(12):3180–3183. https://doi.org/10.1039/C6GC01301G.

Todros S, Bagno A. 2021. “Biomaterials and their biomedical applications: From replacement to regeneration.” *Processes* 9:1949. https://doi.org/10.3390/pr9111949.

Torres FG, Troncoso OP, Díaz DA. 2020. “Bacterial cellulose nanocomposites for wound healing applications.” *Materials Science and Engineering: C* 110:110740. https://doi.org/10.1016/j.msec.2020.110740.

Zhang L, Liu W. 2022. “Scientific research in biomaterials: A bibliometric analysis.” *Materials Science and Engineering: C* 134:112586. https://doi.org/10.1016/j.msec.2021.112586.

Zhang L, Li J, Liu W. 2022. “Global trends in biomaterials research: A bibliometric analysis.” *Materials Science and Engineering: C* 133:112655. https://doi.org/10.1016/j.msec.2021.112655.

Zhao X, Cornish K, Vodovotz Y. 2020. “Narrowing the gap for bioplastics: Biopolymers and biodegradable plastics.” *Food Packaging and Shelf Life* 26:100454. https://doi.org/10.1016/j.fpsl.2020.100454.