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Global research dynamics in green urea: Emerging technologies, scientific networks, and sustainability pathways

Arlenson Lopez Vega[1], Wilmar Leonardo Rondon-Romero[1,2], Arly Dario Rincon-Quintero[1,*]
[1] Unidades Tecnológicas de Santander, Colombia
[2] Universidad a Distancia de Madrid, Spain

*Corresponding author E-mail: arincon@correo.uts.edu.co

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Abstract

This study presents a bibliometric analysis of research trends on renewable urea production and its uses between 2006 and 2025. Initially, a comprehensive search was conducted in the Web of Science database using keywords related to the topic of interest. Subsequently, a set of 1279 relevant scientific documents was selected and analyzed using VOSviewer and R-Bibliometrix to examine statistical patterns. In this context, it was identified that over the past 20 years, research has shifted from developing the fundamentals of urea use for improving nitrogen levels in the soil as a high-value fertilizer, to a new trend toward decarbonized production and carbon capture as a sustainability strategy, implementing catalytic and electrocatalytic technologies. Finally, in the development of the methodology and the results, different relevant aspects within the social structure of this scientific sector are presented, highlighting its main representatives, which allow the reader to orient themselves within this ecosystem vital for the sustainable development and food security of humanity.

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Keywords: Renewable urea, VOSviewer, R-bibliometrix, trend analysis, text mining, sustainability

1. Introduction

The rapid growth of the world's population and the intensification of the effects of climate change have placed global agricultural and energy systems under strain [1]. Consequently, humanity faces the dual challenge of ensuring food security while simultaneously drastically reducing greenhouse gas emissions [2]. In this context, the fertilizer industry, and urea production in particular, occupies a strategic position. Generally speaking, urea is the most widely used nitrogen fertilizer in the world, but its production has historically relied on fossil fuel-intensive processes. This has prevented it from being considered a negative emissions technology, despite its enormous potential for integrating CO_2 as a raw material.

However, the energy transition opens up an unprecedented opportunity. The implementation of technologies such as process electrification, the use of green hydrogen, and the development of catalytic and electrocatalytic routes for CO_2 conversion are redefining the technological landscape [3]. These aspects have been reflected by

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the International Energy Agency, which projects that by 2050, urea production could approach net-zero emissions through the integration of renewable energies and new carbon capture and utilization platforms [4], [5].

Given this scenario of profound transformation, the need arises to understand how scientific knowledge about renewable urea has evolved and what trends are guiding its development. Therefore, this study adopts a bibliometric approach to map global scientific output between 2006 and 2025, analyzing 1,279 documents selected using rigorous criteria.

Ultimately, this analysis allows us to visualize the transition from traditional urea uses focused on fertilization and nitrogen management in soils toward new technological frontiers such as CO_2 electroreduction, advanced catalysis, hydrogen production, and the synthesis of renewable materials. In this way, bibliometrics not only reveals the state of the art but also guides researchers toward emerging niches with the greatest potential to drive the production of green urea as a key component of a sustainable energy and agricultural future.

2. Research method

2.1. Data recovery

This study uses a bibliometric approach for the identification, representation, visualization, and analysis of data from scientific texts. In this context, they are used to identify trends and technological or conceptual developments in various scientific fields [6]–[10]. Consequently, bibliometric analysis and meta-analysis use quantitative methods to identify patterns in conceptual, social, and intellectual structures, while systematic literature reviews rely primarily on qualitative techniques and reader interpretations, which can be prone to bias or arbitrariness from scholars with diverse academic backgrounds [11].

Regarding current data sources, scientific databases such as Scopus, Web of Science (WoS), Dimensions, Cochrane Library, Lens, and PubMed stand out, each with specialized areas and different objectives and missions, but WoS and Scopus are the most widely used in most research fields. This study uses metadata extracted from Web of Science, which generates a manageable volume of data for addressing the topic of interest and metadata quality that optimizes information processing time. Accordingly, the search was conducted using the equation "(renewable urea OR green urea) AND production AND fertilizer," with the aim of focusing the results on the production of renewable urea for use as fertilizer. Finally, the documents were limited to those published between 2006 and 2025 to perform a comprehensive analysis of the behavior of this technology over the last 20 years, resulting in a set of 1333 scientific documents.

2.2. Data screening

This research includes original articles, review articles, books, book chapters, and conference proceedings. Using these sources, a comprehensive evaluation of the available data was conducted to identify research focused on the production of renewable or green urea as a topic of study. To ensure the quality of the data processing, only articles in English were selected. Redundant or duplicate articles were removed as a data cleaning mechanism. Finally, after applying these inclusion and exclusion mechanisms, a set of 1279 scientific documents was obtained. This data collection was downloaded in plain text format from the Web of Science database for processing using bibliometric data processing software.

2.3. Data analysis

The R-bibliometrix package (version R.4.4.3) was first installed and then loaded into R Studio. To run the program, the code "biblioshiny()" is entered in the R command line. Biblioshiny is a web application that facilitates access to the bibliometrix software in R. This platform includes a series of tools for comprehensive biometric analysis for academics [12]. Specifically, this statistical analysis tool allows for data mining to determine the probability of simultaneous occurrences of keywords in scientific works. Furthermore, the platform loads metadata downloaded from the Web of Science (WoS) database in a .txt file, and from this data, generates network graphs that enable the analysis of trends and behavior in the social, conceptual, and intellectual structure of renewable urea production. Additionally, VOSviewer (version 1.6.20) is used to

visualize large datasets. In other words, this program allows the generation of bibliometric networks with greater interpretation due to its graphic and exploratory strength, through the use of zoom, movement and search [13].

3. Results and discussion

3.1. Annual growth of publications and average citations

Figure 1 illustrates the progress in scientific publications on the production of renewable or green urea for use as fertilizer over the period from 2006 to 2025. This trend shows a growing interest from the scientific community in researching these types of products, especially after 2019, when an acceleration in scientific output was observed. On the other hand, regarding the citation trends for each year, a gradual decrease in citations is normal because more recent documents are less likely to be read and therefore referenced. However, three sudden drops in citations stand out in the years 2009, 2010, 2013, and 2017, which would suggest that the research conducted in those years had a lower impact within the scientific community compared to other years.

It is worth noting that in 2019 the XVI International Conference on Carbon Dioxide Utilization (ICCDU 2019) was held, which directly included the importance of urea production from captured CO_2 and renewable energies, thus promoting the development of a more sustainable society.

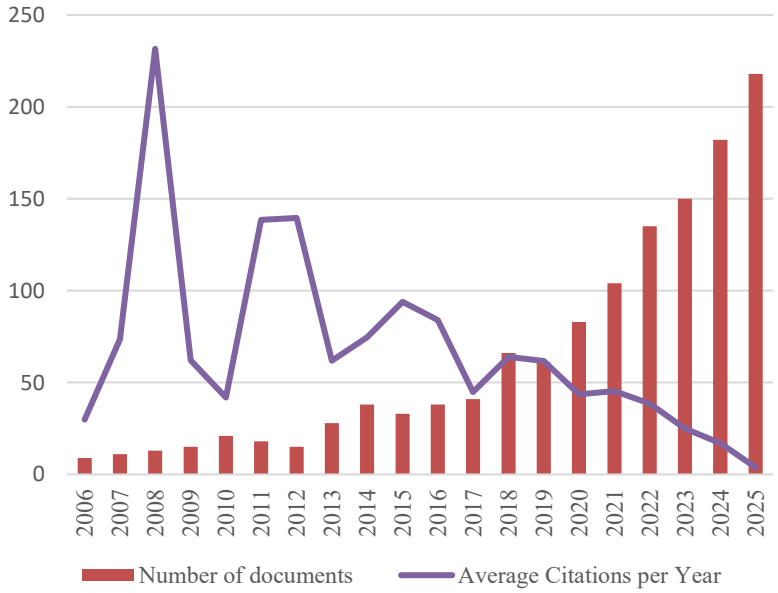


Figure 1. Annual growth of publications and average citations

3.2. The most relevant authors

Figure 2 reflects the social structure of the authors and their collaboration in developing renewable urea-producing technologies for use as fertilizer. In constructing this network, the requirement of having published at least two documents was applied as an exclusion criterion. Observing this network reveals a clique-like behavior, in which different working groups consistently generate scientific output with the same group of individuals. Furthermore, the citation size criterion was applied to the network nodes, highlighting those authors who have received the most citations. From this perspective, two networks or working groups stand out: the green group and the red group, led by Zhang, Lina and Li, Jianzhang, respectively. Subsequently, after identifying these working networks, a specific exploration of their scientific output was conducted, revealing that their work focuses on the use of urea for cellulose and hydrogen production processes, as exemplified by the following works [14]–[18].

Finally, this exercise identifies that the strongest working networks with the highest number of citations focus on topics related to the use of urea in renewable processes, identifying this field as a mature area of research.

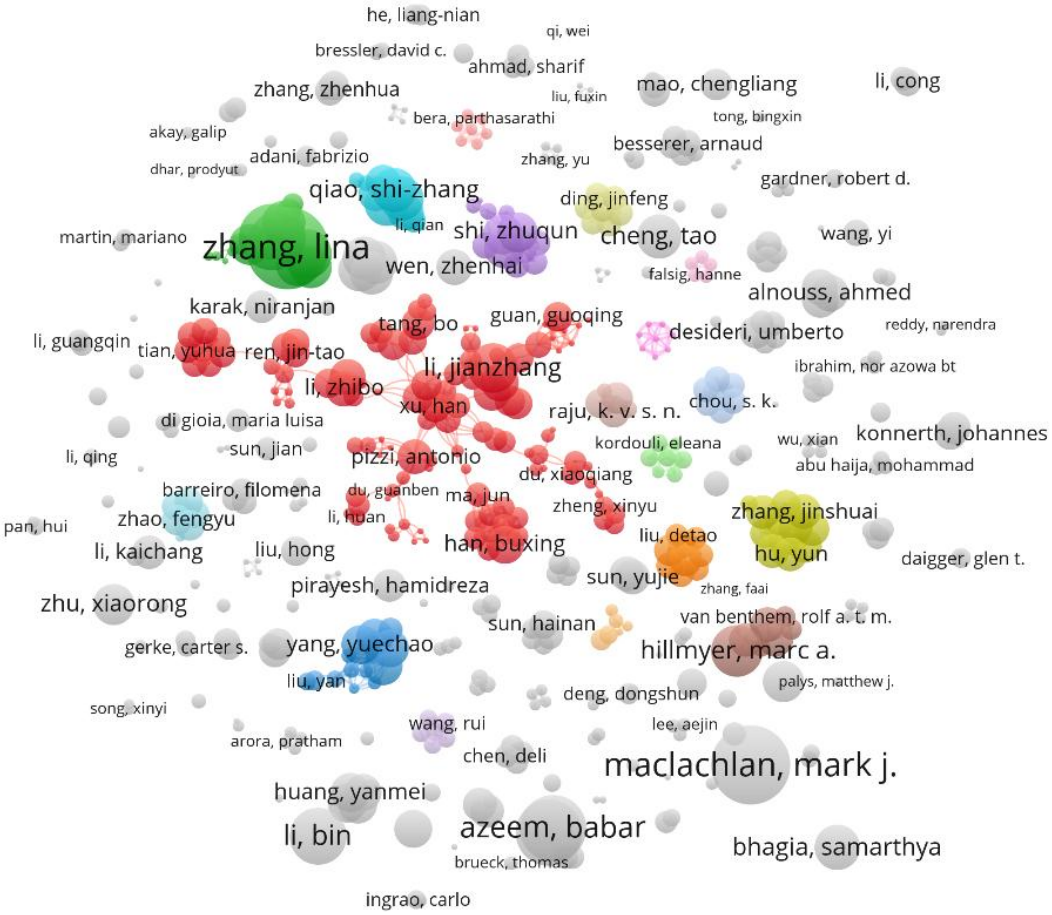


Figure 2. Author network (Generated using VOSviewer)

3.3. Journal with the highest production

Figure 3 highlights the top 10 scientific journals with the highest research output on green urea production and its uses. This list is led by two journals that share the same number of publications with 32 documents each: Chemical Engineering Journal [19]–[23] and Journal of Applied Polymer Science [24]–[28]. Following these, in descending order, are Industrial Crops and Products [29]–[33] with 30 documents, Journal of Cleaner Production [34]–[38] with 27, and ACS Sustainable Chemistry & Engineering [39]–[43] with 26. On the other hand, the number of publications is not always related to impact or H-index, because the journals with the highest ratio of citations to published documents are Industrial Crops and Products with an H-index of 19, followed by Chemical Engineering Journal with an H-index of 18, and Green Chemistry, also with an H-index of 18. These findings suggest that, while scientific output is increasing, academic impact depends more on the reputation of the journals, the scope of the research, and the influence of citations than on the volume itself.

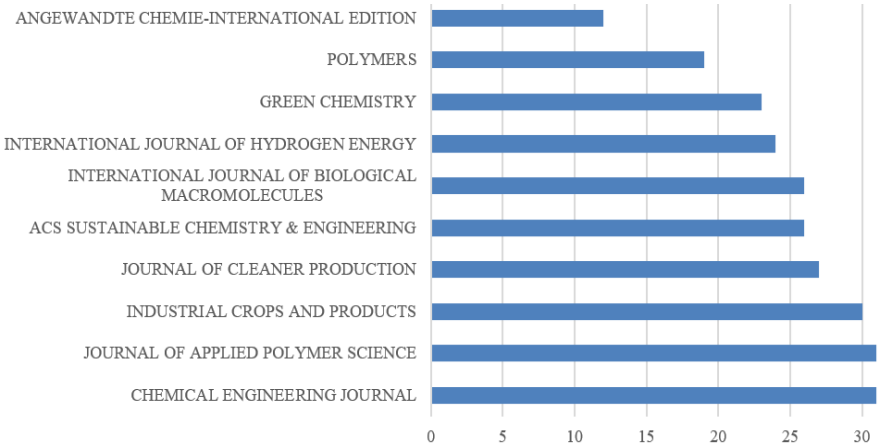


Figure 3. Journal with the highest production

3.4. The most relevant institutions

This study examines the scientific output of organizations or author affiliations involved in the production of renewable urea and its uses. As shown in *Figure 4*, the Chinese Academy of Sciences [44]–[48] has the highest output among all the organizations with 105 published documents, followed by the Egyptian Knowledge Bank (EKB) [49]–[53] with 31 documents, and in third place the Centre National de la Recherche Scientifique (CNRS) [54]–[58] with 25 documents. Following these, six organizations are tied for positions 4 through 9 with 22 documents each, and finally, the Indian Institute of Technology System (IIT SYSTEM) occupies the last position with 21 documents in this ranking of 10.

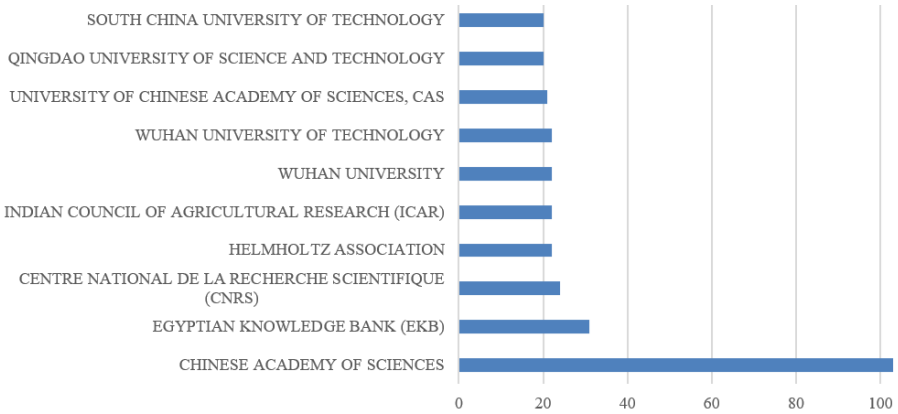


Figure 4. The most relevant institutions

3.5. Scientific output of the country

Figure 5 highlights the global contribution to research on the production and uses of green or renewable urea, with China leading the way with 504 documents (40% of total publications). Among these, its largest strategic partner in production is the United States, contributing 36 documents, followed by Australia and India with 13 and 10 documents, respectively, published in collaboration with China. In terms of the number of publications, the USA ranks second with 142 documents, followed by India with 135, Germany in fourth place with 55 documents, and Brazil in fifth place with 52 documents. China's dominance reflects the predominant authors in this set of documents and indicates a global trend of its dominance in various research fields.

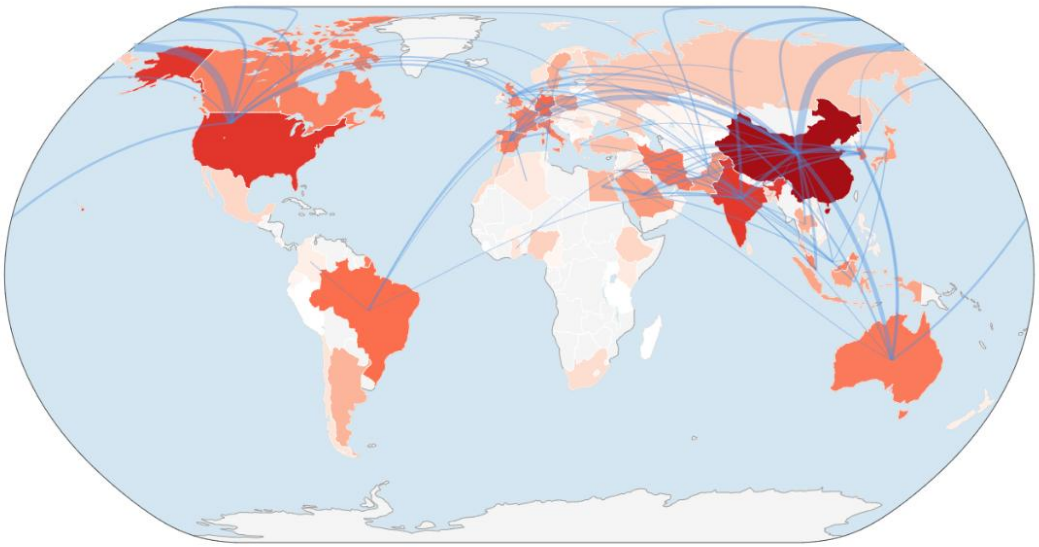


Figure 5. Scientific output of the country (generated using R bibliometrix)

3.6. Conceptual structure of renewable or green urea

Regarding the exploration of the conceptual structure of the analyzed dataset, a network of keywords was generated using the VOSviewer software, as shown in *Figure 6*. This network reveals three groups or thematic

areas related to renewable urea. First, the red group, led by the words Urea, Cellulose, Acid, Polymers, Wood, Lignin, and nanofibers, focuses on the chemistry of biomass-based materials, cellulose and lignin modification, polymers derived from renewable resources, and chemical processes where urea appears as a modifying reagent or resin precursor.

Second, the green group, represented by words such as Nitrogen, Soil, Growth, Emissions, Nitrate, and Agriculture, represents the agro-environmental dimension of urea use, addressing nitrogen management in soils, fertilization efficiency, N_2O emissions, impact on crop yield, and nitrate pollution. Finally, the blue group, led by words like Performance, Catalysts, Water, Carbon-dioxide, Reduction, and Nanoparticles, reflects how this field addresses CO_2 electroreduction methodologies, hydrogen production using water, advanced catalysis, and nanoparticles for energy conversion.

Additionally, it also identifies how urea production can be a strategy for developing CO_2 capture and utilization technologies, processes that could fuel the path to green or renewable urea and the implementation of renewable energy systems.

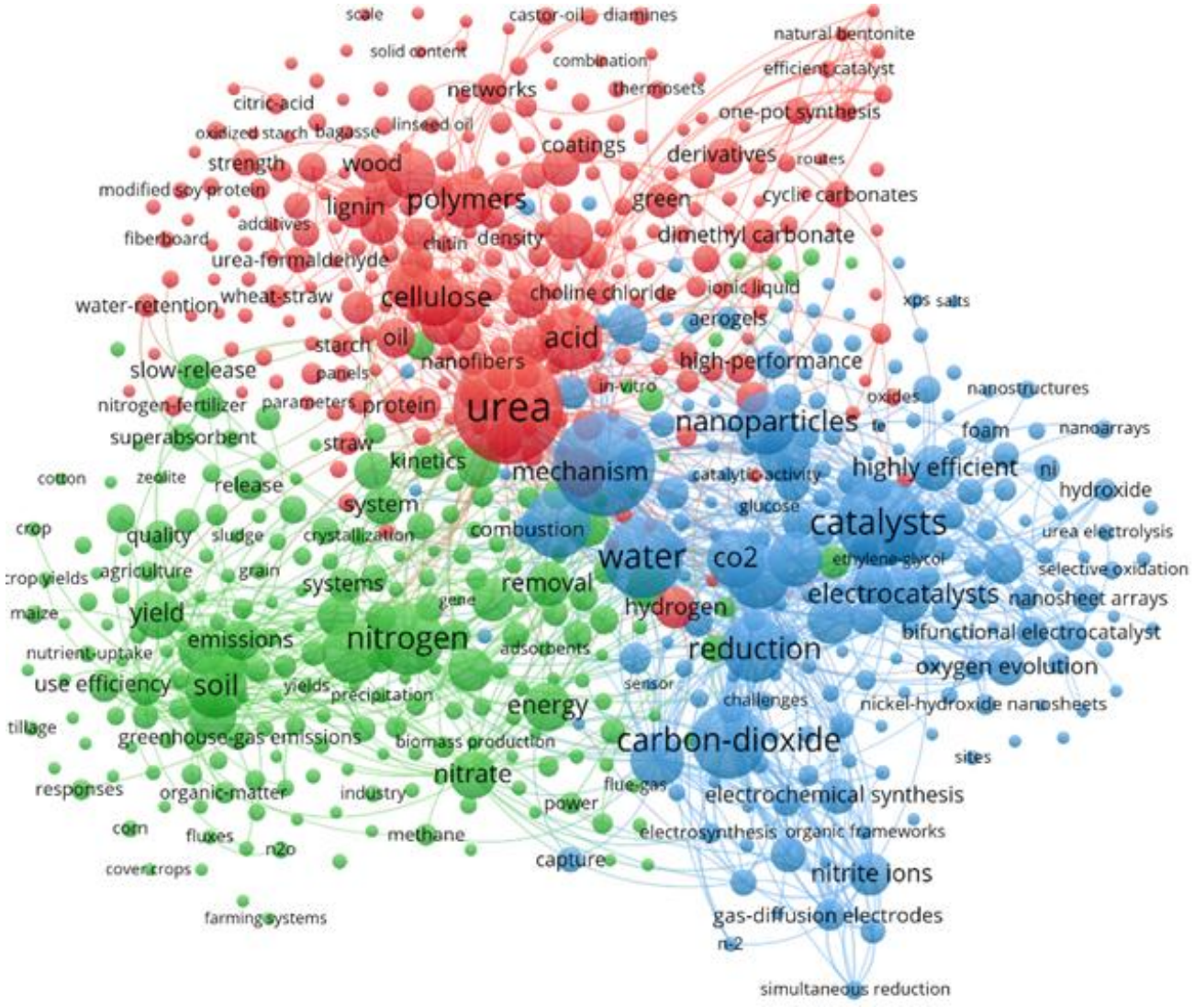


Figure 6. Keyword network (Generated using VOSviewer)

After clarifying the behavior of research areas within the renewable urea framework, a variation of the network is generated using a temporal overlay visualization, as shown in Figure 7. This reflects the use of keywords over time, showing how the blue group is mainly composed of words with more recent use, closer to the years after 2023, demonstrating that the new research trend focuses on CO_2 capture, green hydrogen production, catalysis, and electrocatalysis for urea production.

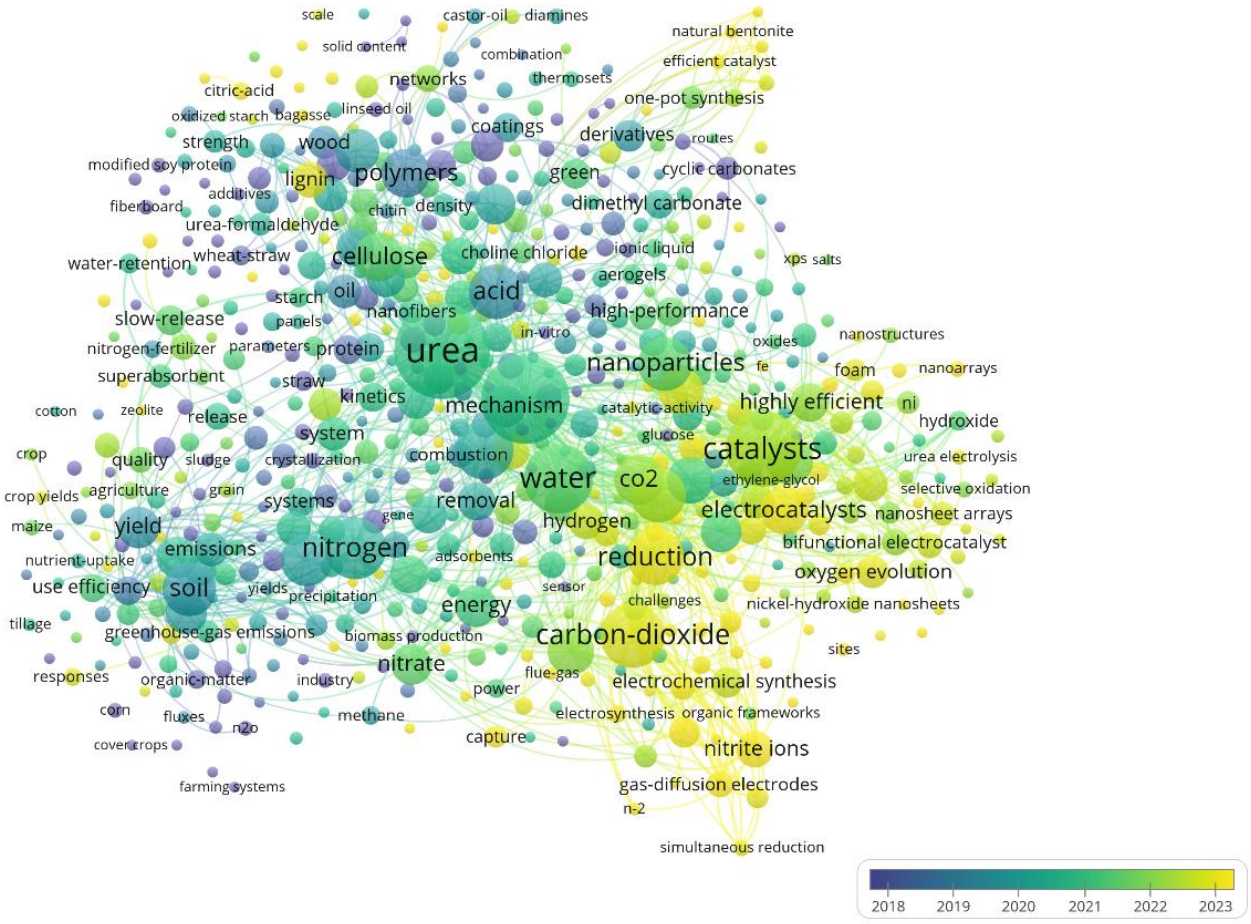


Figure 7. Keyword temporal network (Generated using VOSviewer)

Additionally, as a verification mechanism, a thematic evaluation analysis is performed using the R bibliometrix software, establishing two analysis periods: one between 2006 and 2016, and the other between 2017 and 2026, as shown in Figure 8. In this context, it is identified how the topics focused on Acid, Urea, Cellulose, and Oil evolve, concentrating on urea and other areas of research such as nitrogen, yield, and carbon dioxide.



Figure 8. Thematic evolution (generated using R bibliometrix)

Finally, to understand the behavior or trends in development and research, the thematic map for the period 2017-2026, shown in *Figure 9*, is analyzed in more detail. This map reflects how urea, acid, and cellulose have become driving themes with a high degree of density and centrality, conditions that indicate they are currently the main drivers of research in the field of green or renewable urea. In this sense, the map demonstrates how nitrogen, biomass, and soil sciences are fundamental. Also, the production of hydrogen using water and processes such as catalysis or electrocatalysis is identified as a highly relevant niche within the scientific community, reflecting its importance for the future of sustainable development.

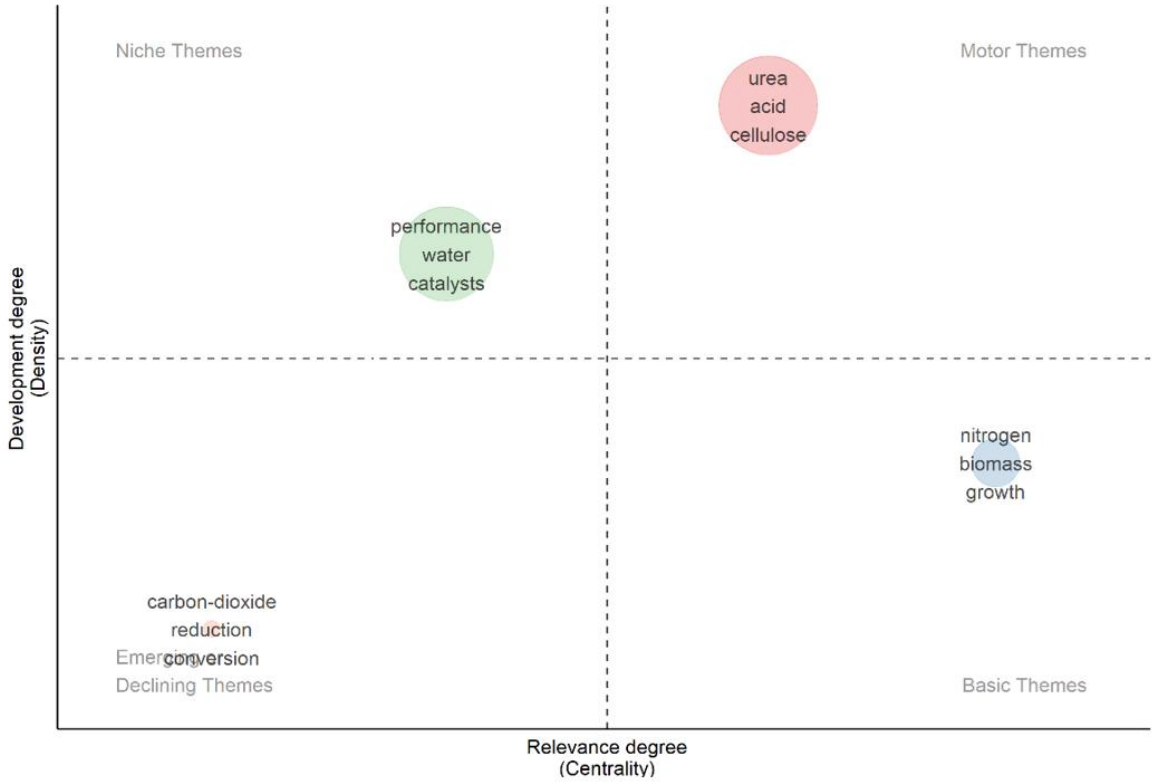


Figure 9. Thematic map (Generated using R bibliometrix)

4. Conclusions

This bibliometric analysis of research on green or renewable urea between 2006 and 2025 reveals key trends and evolving scientific priorities. Firstly, studies focused on the chemistry of biomass-based materials, cellulose and lignin modification, polymers derived from renewable resources, and chemical processes where urea appears as a modifying reagent or resin precursor. Secondly, a mature and robust body of knowledge was identified within the agro-environmental dimension of urea use, addressing nitrogen management in soils, fertilization efficiency, N_2O emissions, impact on crop yield, and nitrate pollution.

Finally, among the new research trends identified are CO_2 electroreduction methodologies, hydrogen production using water, advanced catalysis, and nanoparticles for energy conversion. Additionally, urea production is identified as a potential strategy for developing CO_2 capture and utilization technologies, processes that could fuel the path to green or renewable urea and the implementation of renewable energy systems.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Wilmar Leonardo Rondon-Romero, Arly Dario Rincon-Quintero, Arlenson Lopez Vega: study conception and design. Arlenson Lopez Vega: data collection. Wilmar Leonardo Rondon-Romero, Arly Dario Rincon-Quintero: analysis and interpretation of results. Arly Dario Rincon-Quintero: draft preparation. All authors approved the final version of the manuscript.

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