Bibliometric Analysis of Research on the Use of Nanostructures in Artificial Substrates and Their Evaluation by Root Parameters in Latin America and the World (2015–2025)

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Abstract

This paper presents the results of a descriptive bibliometric study aimed at mapping the course, evolution, and main trends of scientific research on the use of nanostructures in the development of artificial substrates and their evaluation by root parameters in Latin America and worldwide between 2015 and 2025. The Scopus and Web of Science databases were used, yielding 93 and 167 documents related to the topic of interest for Latin America and the world, respectively. The results reveal a steady rate of scientific production on the topic of interest in both research contexts, with Brazil and China as the leading contributors. Research in Latin America has focused on substrate optimization for agricultural production and on addressing the region's water scarcity problems. In contrast, global research has been analytical, exploratory, and innovative in nature, centering on the integration of nanotechnology in substrate development, the study of plant physiological and biophysical processes, and the environmental impact of these technologies. In both investigations, approximately one-quarter of the documents feature international co-authorship, suggesting that the topic is developed on a global scale.

Keywords: substrate, growing medium, nanotechnology, nanoparticles, root activity, Latin America, bibliometric study, bibliometrics.

Introduction

In a global context of climate change and limited agricultural resources, some of the main challenges facing agriculture include soil degradation, water stress, environmental sustainability, and the optimization of input use (FAO, 2021), which calls for the implementation of more adaptive, efficient, and sustainable production systems. In this regard, as a potential solution to these problems, the development of artificial substrates based on hydrogels, superabsorbent polymers, and nanostructures has been promoted—promising tools for improving water retention, strengthening root development, and enhancing plant growth across different cultivation systems (Oladosu et al., 2022; Malik et al., 2023). Latin America faces these challenges particularly acutely, as it is a region with a significant share of net global food exports (FAO, 2023) and holds 30% of the world's arable land (IAASTD, 2025).

With the aim of identifying the efforts and advances of Latin America and the world in this regard over the past 10 years, a detailed description of the corresponding scientific production is provided below, in order to map the course of scientific development around this topic by identifying the main research trends; the leading countries, sources, and institutions in terms of their production volume; the level of regional and international collaboration; and compliance with the main laws of scientific production. This is achieved through the use of bibliometrics, the field of science that studies scientific literature and its properties through quantitative models (Glänzel, 2003).

2. Methodology

This study employs a set of quantitative methods within a bibliometric approach to describe the scientific production on the topic of *the use of nanostructures in the development of artificial substrates and their evaluation by root parameters* in Latin America and the world for the period 2015–2025, identifying the main research trends. The analyses were carried out following the guide by Rojas Medina and Muñoz Callejas (2024), which provides a detailed foundation for this type of study.

The documents used for the analysis come from the *Scopus* and *Web of Science* databases. Given the specificity of the topic, two search equations (Appendix) were used to capture as many related documents as possible. The first equation targets only those documents related to the use of nanostructures in the development of artificial substrates and their evaluation by root parameters, while the second equation relaxes this evaluation criterion to capture documents related to this research line in which the agricultural application has not been extensively studied. After removing documents unrelated to the topic, 69 documents corresponding to Latin America and 133 corresponding to the global context were obtained with the first equation, while the respective figures for the second equation were 24 and 34. Both searches were conducted in the title, abstract, and keyword fields. To distinguish Latin American from global scientific production, the search filter for country or region, available in both databases, was used. The search cutoff date was December 13, 2025.

The statistical software *R* was used, specifically the *bibliometrix* package (Aria & Cuccurullo, 2017), for the analysis.

To avoid inconsistencies in the analysis, publication identifiers, document types, keywords, and the names of academic institutions were corrected and normalized.

Regarding scientific production, the most productive journals and countries are identified; the evolution of the cumulative number of publications per year is presented; and compliance with the main bibliometric laws is evaluated: Lotka's law (distribution of author counts by scientific production) and Bradford's law (distribution of source counts by scientific production).

For the identification of the main research trends, the *Field by Year* tool was used, which identifies the terms that appear most frequently in the keywords of the documents and the time at which they have had the greatest relevance in research; and the *Conceptual Structure* tool, which detects term clusters and explores their conceptual relationships through co-occurrence analysis of the keywords. The *Thematic Map* tool was also used, which classifies themes into four categories: motor themes, basic themes, niche themes, and emerging or declining themes.

Regarding scientific collaboration, it was evaluated between academic institutions and countries.

3. Results

3.1 Scientific Production

Some descriptive measures of the scientific production on the topic of interest in Latin America and the world are presented in Tables 1 and 2, showing the total number of documents and sources, the publication period, the annual growth rate, the age and average citations of the documents, the number of co-authors per document, and the percentage of international co-authorship. Although scientific production was higher in the global context, Latin America exhibits a higher annual growth rate, indicating a growing interest in the topic. In both research contexts, the documents are relatively recent and show moderate-to-high citation rates and international co-authorship.

Table 1. Bibliometric summary — Latin America

Indicator	Value
Period	2015–2025
Sources (Journals, Books, etc.)	67
Documents	93
Annual growth rate (%)	20.58
Average document age (years)	3.45
Average citations per document	12.34
Co-authors per document	7.11
International co-authorship (%)	21.51

Table 2. Bibliometric summary — World

Indicator	Value
Period	2015–2025
Sources (Journals, Books, etc.)	114
Documents	167
Annual growth rate (%)	16.86
Average document age (years)	3.94
Average citations per document	19.31
Co-authors per document	6.01
International co-authorship (%)	27.54

Tables 3 and 4 show the distribution of documents by type.

Table 3. Document types — Latin America

Type	Count
Article	90
Book chapter	2
Review	1

Table 4. Document types — World

Type	Count
Article	159
Book chapter	4
Review	2
Conference paper	2

In both investigations, the vast majority of documents are journal articles.

The cumulative annual evolution of the volume of scientific production on the topic of interest for Latin America and the world between 2015 and 2025 is shown in Figure 1. A steady level of production is evident in both cases.

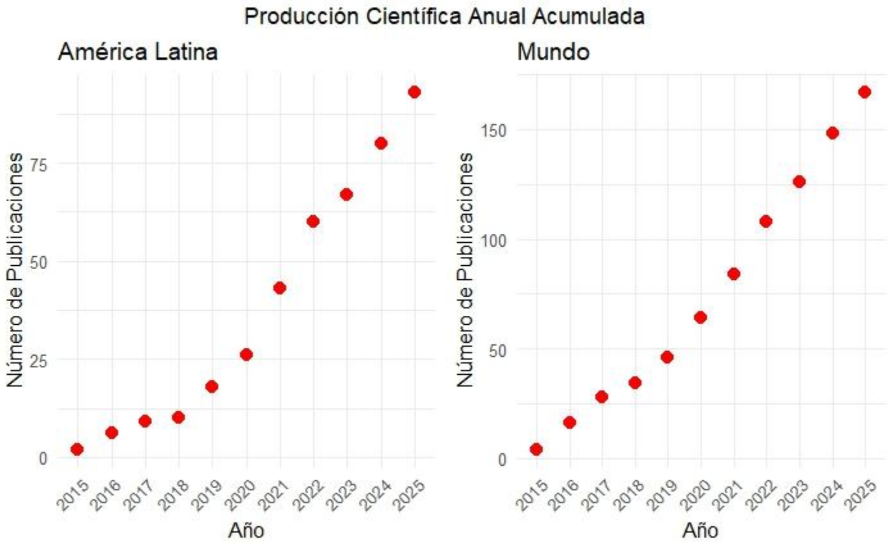

Figure 1. Cumulative annual scientific production.

Figure 2 shows the countries with the highest scientific production in Latin America and the world. Brazil and Mexico account for the majority of Latin American publications (73%), while in the global context, China stands out with the largest share (23%).

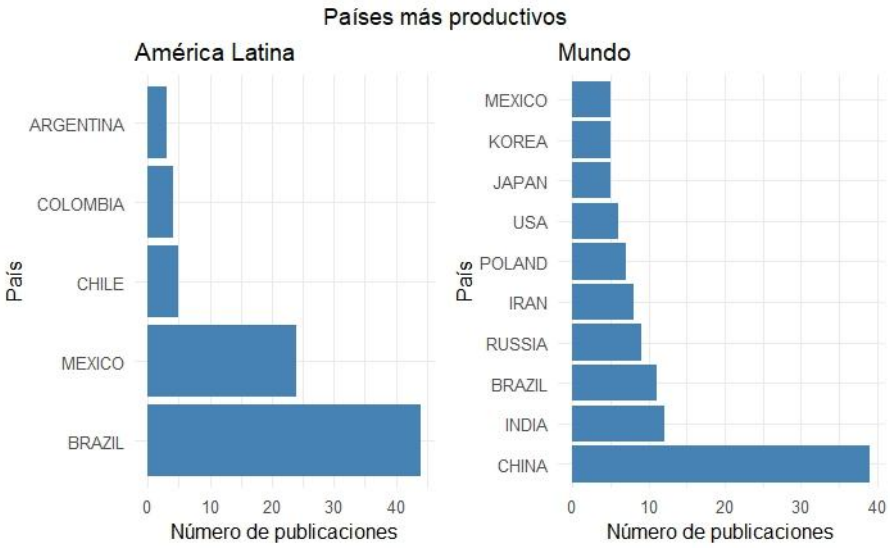

Figure 2. Most productive countries.

The analysis of the scientific production across diverse research fields has revealed the presence of certain patterns related to the distribution of authors and journals or sources by their number of publications. This is the case of Lotka's and Bradford's patterns, described in Lotka (1926) and Bradford (1934).

Lotka's law establishes that the distribution of author productivity is not symmetric. That is, the majority of researchers are responsible for a small fraction of total publications, while a small group of researchers is responsible for the vast majority of publications.

The mathematical model that describes this relationship is:

$$f(n) = C / n^{\beta}$$

where $f(n)$ represents the number of authors with n publications, C is a normalization constant, and β is a parameter indicating how quickly the number of authors decreases as the number of publications increases.

Tables 5 and 6 present the distribution of authors by number of publications for Latin America and the world, respectively.

Table 5. Author frequency by number of publications — Latin America

No. Publications	No. Authors	Frequency
1	554	0.92
2	41	0.07
3	4	0.01
4	2	0.00
5	1	0.00

Table 6. Author frequency by number of publications — World

No. Publications	No. Authors	Frequency
1	851	0.93
2	55	0.06
3	11	0.01
4	1	0.00
6	1	0.00

In both contexts, the number of authors decreases rapidly as the number of publications increases. That is, the results presented in the tables are consistent with Lotka's law. However, the model fit is performed for each case.

For the Latin American research, the fit is given by: $f(n) = 0.90 / n^{4.05}$

For the global research, the fit is given by: $f(n) = 0.87 / n^{4.07}$

Figures 3 and 4 show the theoretical author productivity model superimposed on the fitted model, along with the goodness-of-fit measure R^2, for each context. High goodness-of-fit percentages (98.8% and 95.4%) are observed, indicating that the scientific production on the topic of interest in Latin America and the world between 2015 and 2025 conforms to Lotka's law.

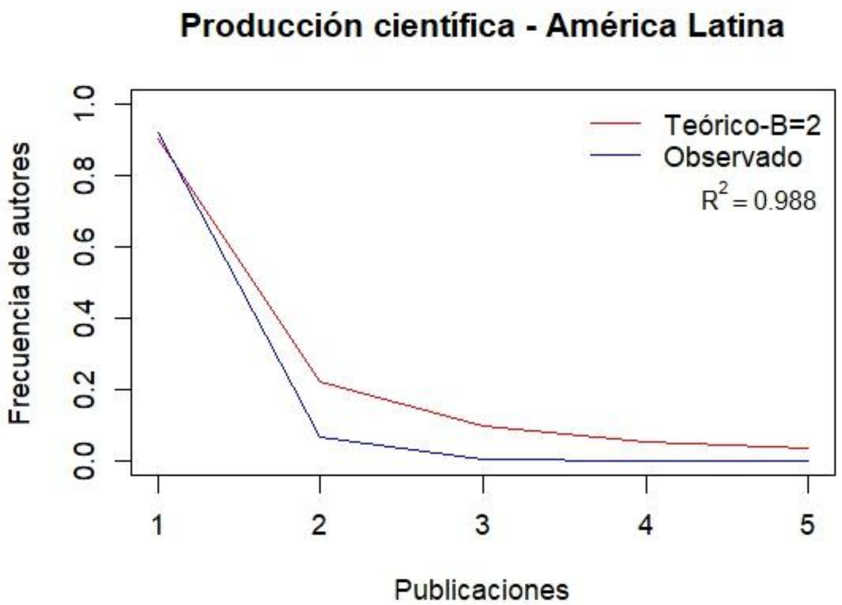

Figure 3. Lotka's scientific production model — Latin America.

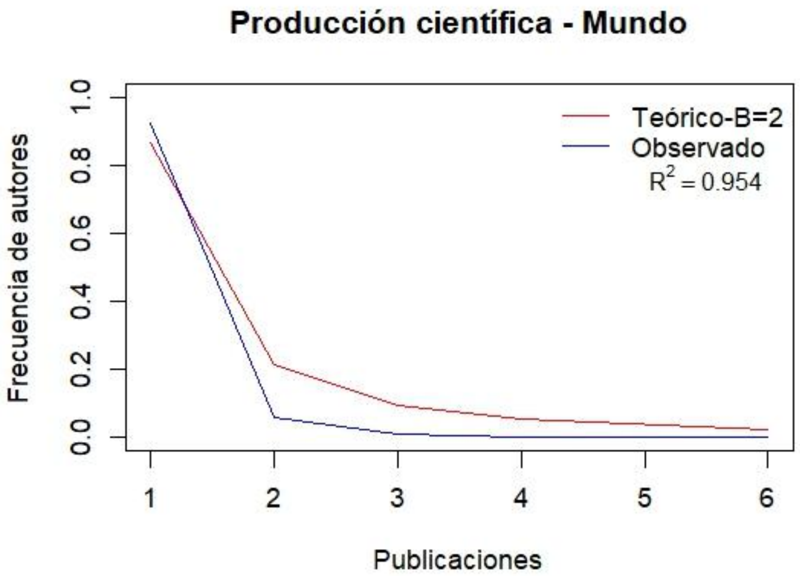

Figure 4. Lotka's scientific production model — World.

Bradford's law establishes that only a small group of sources publishes the majority of relevant documents on a research topic. This group is called the *core sources*.

Tables 7 and 8 present the leading sources associated with publications on the topic of interest in Latin America and the world, out of a total of 67 and 114 sources, respectively.

Table 7. Top sources — Latin America

Source	Publications	Cumul. %
Ciência Florestal	3	0.04
Notulae Botanicae Horti Agrobotanici Cluj-Napoca	3	0.09
Plants-Basel	3	0.13
Revista Brasileira de Engenharia Agrícola e Ambiental	3	0.18
Semina-Ciências Agrárias	3	0.22
3 Biotech	2	0.25
Environmental and Experimental Botany	2	0.28
Environmental Science and Pollution Research	2	0.31

Table 8. Top sources — World

Source	Publications	Cumul. %
Frontiers in Plant Science	6	0.05
Journal of Experimental Botany	6	0.11
Agronomy-Basel	5	0.15
Science of the Total Environment	4	0.18
Scientia Horticulturae	4	0.22
Agriculture-Basel	3	0.25
Ecotoxicology and Environmental Safety	3	0.27
Plant Physiology and Biochemistry	3	0.30

For the Latin American publications, the top eight sources account for 31% of total publications but represent only 12% of total sources. For the global publications, the top eight sources account for 30% of total publications but represent only 7% of total sources. That is, a small group of sources publishes a large proportion of the total documents in both contexts.

3.2 Conceptual Analysis

Figure 5 shows the time period during which some of the main terms have been most frequent or relevant in research on the topic of interest in Latin America (left) and the world (right) between 2015 and 2025. The position of each node represents the moment when each term gained the greatest importance, while the area of the node represents the frequency of the term at that time.

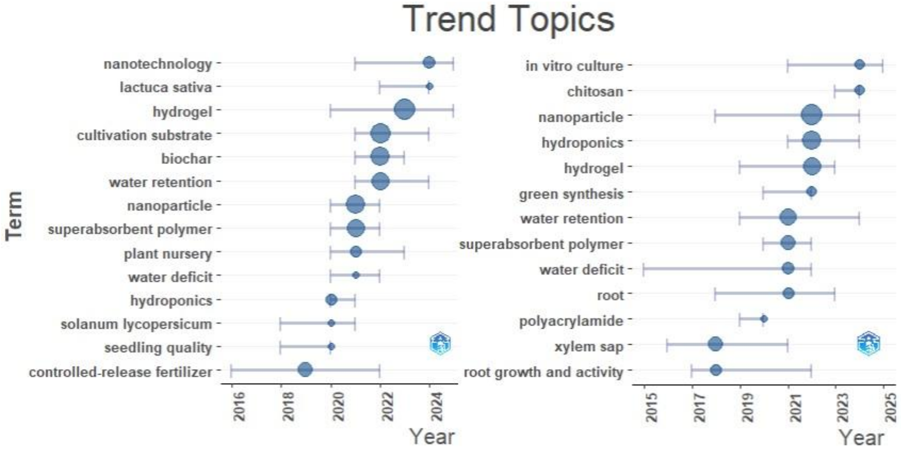

Figure 5. Relevant terms — Latin America (left) and World (right).

In Latin America, the initial phase of the research focused on optimal crop nutrition (**controlled-release fertilizer**) and on improving **seedling quality** particularly in species related to high-value commercial crops such as tomato (*Solanum lycopersicum*) (Bergougnoux, 2014). The intermediate phase focused on the application of technologies based on **hydrogels** and **superabsorbent polymers** for **water management** in agricultural systems. The recent phase has centered on the use of **hydroponics**, **nanotechnology**, and **biochar** in the production of crops such as lettuce (*Lactuca sativa*), a fast-growth model crop (Moon et al., 2023).

On the other hand, the initial phase of global research studied the impact of model materials, such as **polyacrylamide**, on the plant **root system** through the study of **xylem sap**. The intermediate phase focused on the **nano**-structuring of **hydrogels** and their implementation in controlled cultivation systems (**hydroponics**), aiming to maximize **water retention** in the growing medium. The most recent phase has examined the sustainable approach to nanoparticle production through **green synthesis**, using functional and eco-friendly biopolymers such as **chitosan** (Rinaudo, 2006; Wang & Zhuang, 2022) in ***in vitro*** systems.

Comparatively, research in Latin America has focused on the application of technologies and materials aimed at solving agronomic and environmental problems of the region, such as seedling quality, agricultural production, and water deficit. In contrast, global research has adopted a more analytical and materials-development approach, focusing on the underlying physiological and biophysical processes. The most recent phases of both research lines show a common interest in the sustainable dimension of this high-technology agriculture.

Figure 6 shows the conceptual structure of the publications on the topic of interest in Latin America, obtained from the co-occurrence analysis of document keywords, specifically through the multiple correspondence analysis methodology. This factorial plane captures approximately 80% of the variability associated with the keyword co-occurrence structure.

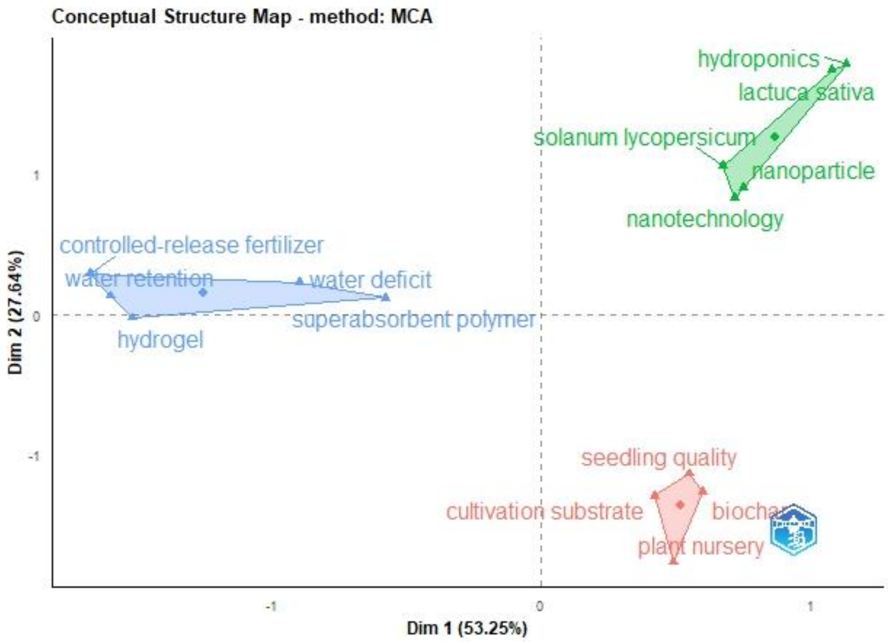

Figure 6. Conceptual structure — Latin America.

The research in Latin America can be classified into three main thematic families:

Blue cluster: Addressing water stress through the use of controlled-release fertilizers, hydrogels, and superabsorbent polymers, aimed at improving the water retention capacity of the substrate.

Red cluster: Use of biochar in substrate development for the nursery stage of agricultural production, seeking to produce high-quality seedlings.

Green cluster: Use of nanoparticles in hydroponic cultivation systems, particularly for tomato and lettuce crops.

Figure 7 shows the conceptual structure of the publications on the topic of interest worldwide. This factorial plane captures approximately 85% of the variability associated with the keyword co-occurrence structure.

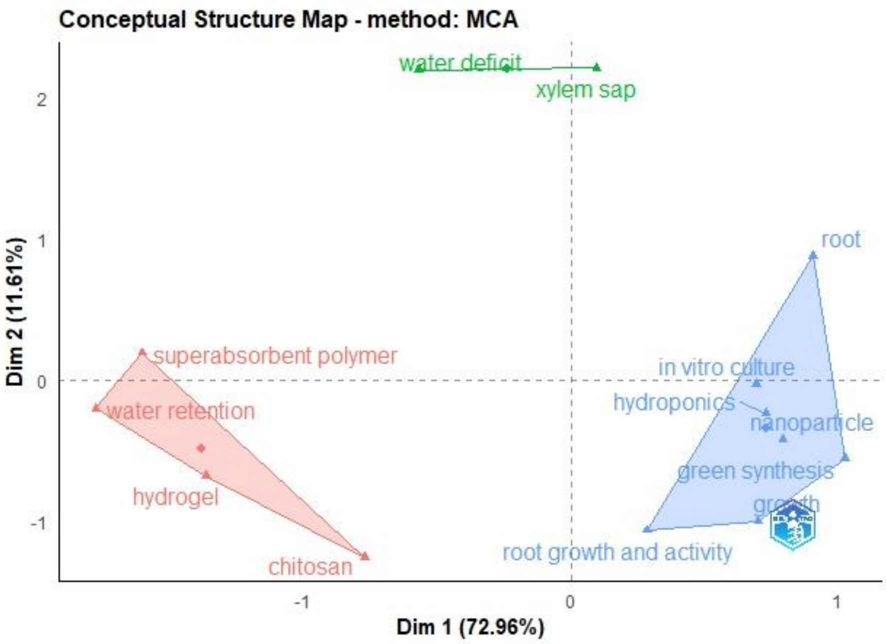

Figure 7. Conceptual structure — World.

The global research can be classified mainly into three thematic families:

Green cluster: Effect of water deficit stress stimulus on the internal transport of plant substances (xylem sap).

Red cluster: Use of superabsorbent polymers, chitosan, and hydrogels in substrates to improve their water retention capacity.

Blue cluster: Development of sustainable advanced materials (nanoparticles) and their impact on the plant, particularly on its roots and overall growth.

To complement the conceptual structure described above, a thematic classification of the main terms associated with both research lines is also presented. The criteria used for this classification are:

Centrality: Indicates the importance of a theme within the research field. It measures how much the theme connects with other themes.

Density: Indicates how well developed a theme is internally, even if it is not strongly related to other themes.

The results of the thematic classification for Latin America are presented in Figure 8. The study of the effect of nanomaterials on germination and plant growth is the dominant motor theme, exhibiting high degrees of centrality and density. Another motor theme is the evaluation of physiological and biochemical responses (antioxidants, flavonoids) of species such as lettuce under hydroponic cultivation models and the incorporation of chitosan. A third theme in this region of the map involves nano-biostimulation studies in in vitro crops, using specific models (tomato, Solanaceae). The theme of superabsorbent materials and controlled-release technologies in the context of water scarcity and optimal crop nutrition shows moderate centrality and density, suggesting it is cross-cutting in the research. In the upper-left area of the chart, the theme of irrigation systems and mineral nutrition (boron) of substrates in nurseries for seedling quality shows high density but low centrality, making it a niche theme. Among themes with low centrality and density are the use of polymers and nanofertilizers for soil amendment, and the use of biochar and biosolids in cultivation substrates, particularly for papaya. Finally, the term 'nanoparticle' appears as a central but sparse theme, reflecting the importance of this concept as a foundation for the overall research.

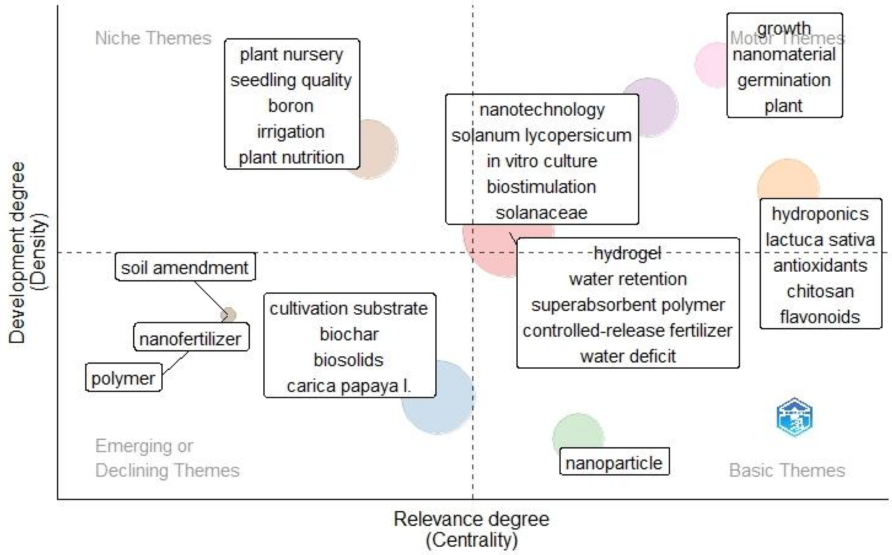

Figure 8. Thematic classification — Latin America.

The results of the thematic classification for the global context are presented in Figure 9. In the motor core of the research, plant growth metrics, hydroponics as an experimental medium, the sustainable agriculture approach, and the integration of nanotechnology as a structural axis are distinguished. A second grouping of highly central but moderately dense themes corresponds to physiological processes (xylem sap), water stress and water use efficiency, contaminants/heavy metals (cadmium), and tomato as a model crop. The cluster of nanoparticles, plant physiology (roots), green synthesis, nutrient recycling, biochar use, and in vitro cultivation systems forms a core of central or transitional themes. Another grouping near the center with high density corresponds to factors associated with abiotic stress conditions (salinity, aluminum) (Taiz et al., 2015), micronutrients (iron), and chitosan. Two niche themes with high density and low centrality are observed: the use of silver nanoparticles as nanometric elicitors and their impact on physiological factors of model seedlings (carnation), and the evaluation of the capacity of rice to recycle potassium through bleeding sap analysis. On the other hand, the study of superabsorbent materials applied in green roof substrates represents a basic research theme, as it has a high degree of relevance but is underdeveloped.

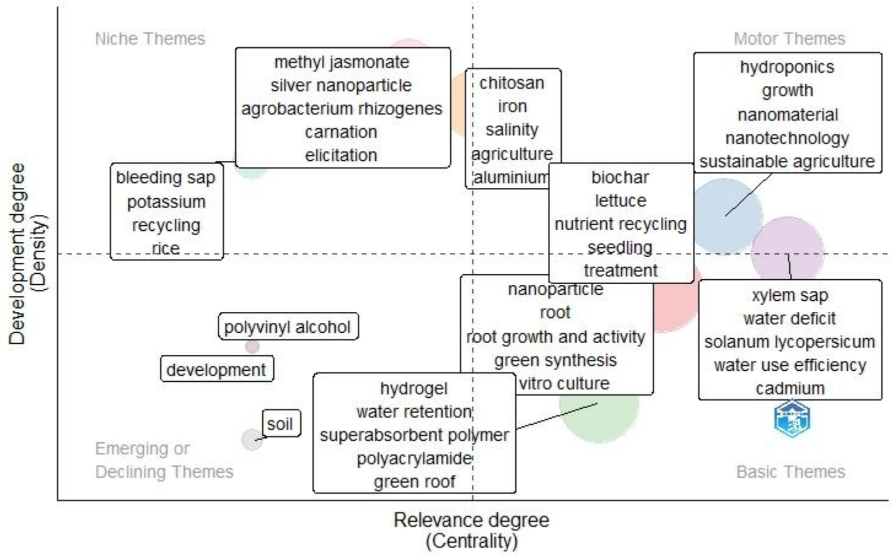

Figure 9. Thematic classification — World.

3.3 Collaboration Networks

Graphical representations of the collaboration relationships between countries and academic institutions in the context of scientific publication on the topic of interest between 2015 and 2025 are presented. Each node represents an entity; its area corresponds to the number of documents by that entity. The intensity of the lines represents the number of co-publications between entities.

Figures 10 and 11 show the relationships between the leading countries, and Figures 12 and 13 show the relationships between the leading educational institutions.

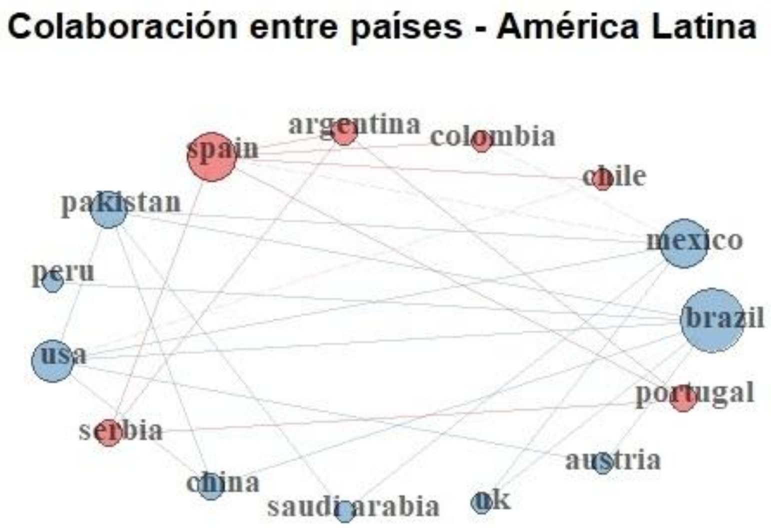

Figure 10. Collaboration between leading countries — Latin America.

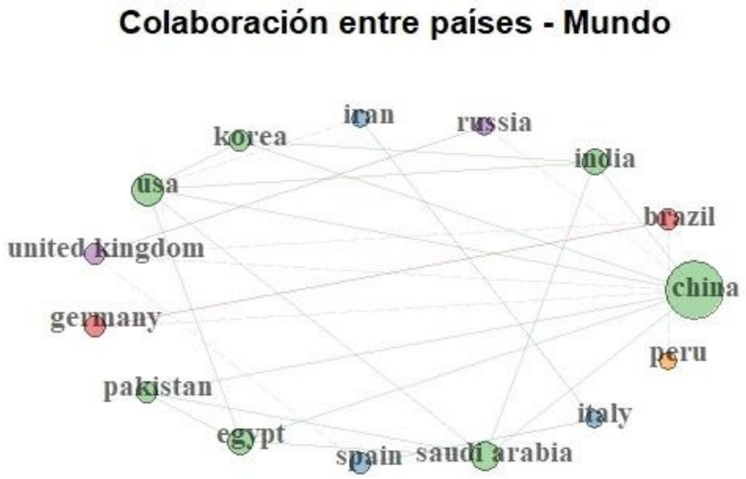

Figure 11. Collaboration between leading countries — World.

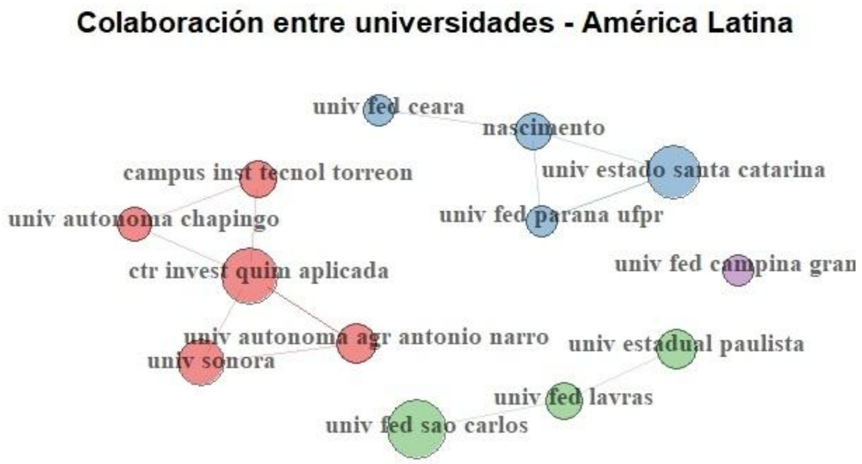

Figure 12. Collaboration between universities — Latin America.

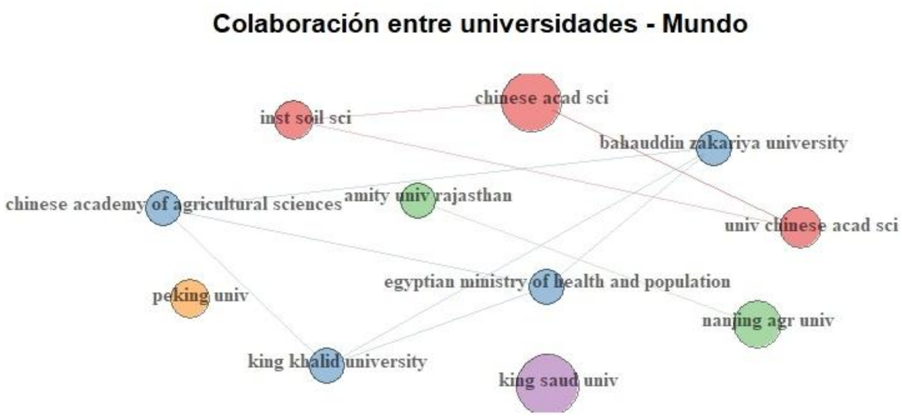

Figure 13. Collaboration between universities — World.

In Figure 10, the presence of two groups is evident: in one, Latin American countries such as Brazil, Mexico, and Peru stand out, while in the other, Colombia, Chile, and Argentina are prominent. This division suggests that Latin America does not conduct research jointly as a single bloc. Brazil and Mexico stand out as the main articulating nodes of scientific production. The presence of European countries as extra-regional research articulators is also observed.

In Figure 11, a much more interconnected collaboration network across diverse regions is observed, with a predominance of China as the densest and most central node, accompanied by the United States and several European countries. An emerging Asian bloc (India, South Korea, Iran, and Pakistan) is also evident. Brazil is the only Latin American country with a significant presence in this global collaboration network.

Regarding collaboration between universities, it is more robust in the global research context: Figure 12 shows a limited and dispersed structure with few articulating nodes, while Figure 13 shows much more consolidated inter-institutional networks.

4. Conclusions

4.1 Scientific Production

The scientific production on the use of nanostructures in the development of artificial substrates and their evaluation by root parameters in Latin America and the world has maintained a steady rate of production between 2015 and 2025. Among the documents analyzed for Latin American research, Brazil is the most active country, accounting for 48% of the total (44 publications), while in the global context, China is the most active, with 23% of the total (39 publications).

Furthermore, the scientific production in both contexts conforms to the bibliometric laws of Lotka and Bradford; that is, a small percentage of authors and sources accounts for the majority of scientific publications on the topic of interest.

4.2 Conceptual Analysis

The comparative analysis of the key terms of the research in Latin America and the world reveals fundamental differences: Latin America presents a technological application approach, focused on substrate optimization for agricultural production and on solutions to the region's water scarcity problems. In contrast, in the global context, research has been exploratory and innovative in nature, centering on the integration of nanotechnology in substrate development, the study of plant physiological and biophysical processes, and the environmental impact of these technologies. This suggests that research in Latin America and the world is complementary, in the sense that the former provides applied validation for problems of regional relevance, while the latter provides the mechanistic foundations and the general theoretical framework.

4.3 Collaboration Networks

Regarding scientific collaboration on the topic of interest, few countries represent dense and broadly interconnected nodes. In Latin America, the collaboration structure of countries and institutions is more fragmented and dependent on scientific powers, while in the global context, the network is more complete and integrated, with a broader and more balanced relationship among several leading research countries, which favors the development of global knowledge.

5. Limitations

The documents used for the analysis come exclusively from the Web of Science and Scopus databases; therefore, documents not indexed by these databases are not part of the analysis.

The conceptual analyses depend solely on the keywords of the documents; thus, the information contained in the title, abstract, and body of the document is not part of such analyses, nor are relevant documents lacking standardized terminology.

The lack of normalization of author names in the databases prevents obtaining faithful representations of bibliometric indices and author collaboration networks.

The country of a document is assigned according to the institutional affiliation of the authors, which may not correspond to the country associated with the empirical context of the study.

6. Search Equations

Equation 1: *(soilless OR growing media OR hidroponía OR hidroponia OR hydroponic* OR growth substrate OR culture substrate OR porous medium OR (substrate* AND (artificial OR synthetic OR polymer* OR foam OR hydrogel OR composite))) AND (nanoparticle* OR nanocomposite* OR nanocellulose OR nanomaterial* OR biochar OR activated carbon OR clay* OR zeolite* OR vermiculite OR perlite OR natural fiber* OR coconut coir OR peat moss OR wood fiber* OR rice husk OR bagasse OR hydrogel* OR superabsorbent polymer* OR SAP) AND (rhizosphere OR capillar* OR water retention OR root architecture OR root development OR root growth OR rooting OR raíz OR raices OR enraizamiento OR capilaridad OR retención*)*

Equation 2: *(nanoparticle* OR nano-particle* OR nanoclay* OR nanocellulose* OR nano-structure* OR nanostructure* OR nano-enhanced OR nano-modified OR nanocomposite*) AND (cultivation substrate OR horticultural substrate OR soilless substrate OR plant substrate OR growing medium OR growth medium OR planting medium OR rooting medium OR nursery substrate OR potting medium OR hydroponic* OR container production OR nursery production) AND (hydrogel* OR polymer* OR superabsorbent OR water retention OR* *capillar* OR porosity OR biochar OR compost OR organic amendment OR peat substitute OR vermiculite OR perlite OR cocopeat OR coconut coir OR wood fiber OR plant growth OR root growth OR seedling* OR crop production OR vegetative growth OR water use efficiency OR irrigation management OR plant* OR crop* OR agricultur* OR horticultur* OR hydroponic* OR soilless OR growing medium OR substrate*)*

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