Development and evolution of hydroponic systems in protected agriculture: a scientometric analysis and systematic review.

Desarrollo y evolución de los sistemas hidropónicos en agricultura protegida: un análisis cienciométrico y una revisión sistemática.

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Abstract
Traditional agriculture faces increasing limitations in addressing global challenges such as climate change, water scarcity, and soil degradation. In this context, hydroponic systems have emerged as an efficient and sustainable alternative within protected agriculture. Despite their expansion over recent decades, no comprehensive review has yet been conducted to analyze their evolution from a chronological and scientometric perspective. Therefore, the aim of this study is to reconstruct the historical and technological trajectory of hydroponic systems applied in greenhouse environments. To achieve this, a systematic review was carried out following PRISMA guidelines, based on 545 scientific publications indexed in Scopus and Web of Science, covering the period from 2004 to 2025. The findings identified three key stages of development: an initial phase of conceptual consolidation, a period of intensive growth through technological integration, and an emerging phase characterized by modular and adaptive solutions. This evolution has been shaped by the increasing incorporation of technologies such as artificial intelligence, IoT sensors, and automated control systems, along with the adoption of circular economy principles. In practical terms, the results provide guidance for future research and policy-making aimed at designing hydroponic systems that are resilient, efficient, and inclusive, with strong potential to enhance food security and promote sustainable agriculture globally.

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Keywords: Agricultural sustainability, aeroponics, efficiency, cultivo, circular economy, green crop.

Resumen

La agricultura tradicional enfrenta crecientes limitaciones frente a desafíos globales como el cambio climático, la escasez de agua y la degradación del suelo. En este contexto, los sistemas hidropónicos han emergido como una alternativa eficiente y sostenible en agricultura protegida. A pesar de su expansión en las últimas décadas, no existía hasta ahora una revisión que analizara su evolución desde una perspectiva cronológica y con enfoque cienciométrico. Por ello, el presente estudio tiene como objetivo reconstruir la trayectoria histórica y tecnológica de los sistemas hidropónicos aplicados en invernaderos. Para alcanzar este propósito, se aplicó una revisión sistemática bajo los lineamientos PRISMA, utilizando las bases de datos Scopus y Web of Science, con un total de 545 publicaciones académicas analizadas entre 2004 y 2025. Los resultados permitieron identificar tres etapas de desarrollo: una fase inicial de consolidación conceptual, una fase de crecimiento intensivo por integración tecnológica, y una etapa emergente caracterizada por soluciones modulares adaptativas. Este proceso ha estado marcado por el uso creciente de tecnologías como inteligencia artificial, sensores IoT y control automatizado, así como por la adopción de principios de economía circular. En términos prácticos, los hallazgos permiten orientar futuras investigaciones y decisiones de política pública hacia el diseño de sistemas hidropónicos resilientes, eficientes e inclusivos, con alto potencial para fortalecer la seguridad alimentaria y la sostenibilidad agrícola global.

Palabras clave: Sostenibilidad agrícola, aeroponía, eficiencia, cultivo, economía circular, cultivo verde

1. Introdución

Greenhouse cultivation using hydroponic systems has gained prominence in modern agriculture due to its ability to optimize resource use and facilitate food production in controlled environments. This technique replaces soil by allowing plants to absorb nutrients directly dissolved in water. Various studies have shown that these types of systems can reduce water usage by up to 90% compared to conventional agriculture, in addition to increasing yields by between 20% and 50% per square meter, depending on the type of crop [1]. Thanks to these benefits, hydroponics emerges as a sustainable alternative in the face of challenges such as climate change, declining fertile land, and population growth especially in cities or regions with degraded soils.

Although numerous studies exist on hydroponics and its application in protected environments, no review has been found that chronologically explores how hydroponic systems in greenhouses have evolved. Most of the works focus on technical aspects, such as nutrient management, energy efficiency, or the performance of specific crops, without offering a historical perspective that allows for understanding the development of this technology from its early applications to the current automated systems [2]. Moreover, few investigations link these advances to the specific needs of small-scale farmers or densely populated urban communities. However, recent studies have begun to explore how urban hydroponics can shorten supply chains, increase production efficiency, and promote sustainable agriculture in unconventional spaces [3]; [2]; [4].

In order to address these gaps, this article aims to provide a chronological review of the development of hydroponic systems applied in greenhouses, highlighting the main scientific and technical advancements. To achieve this, a systematic review methodology was employed based on PRISMA criteria, using searches conducted in the Scopus and Web of Science databases. Filters were applied according to the period (1980–2025), type of publication (peer-reviewed scientific articles), and keywords related to hydroponic systems and protected agriculture. Unlike previous studies, this review proposes a comprehensive approach: beyond technical aspects, it reconstructs a timeline that illustrates how these systems have evolved from their early passive forms to intelligent technologies incorporating sensors, artificial intelligence, and circular economy principles. The resulting theoretical framework not only synthesizes existing knowledge but also provides relevant input for future research and for decision-making in the design and implementation of these systems [5].

The results show that the development of hydroponic systems in greenhouses has been driven by technological innovation, evolving from manual structures to automated platforms with climate control, nutrient solution recirculation, and digital monitoring. Three main stages were identified: an initial phase of basic adoption (1980–1999), a second stage of expansion and technological improvement (2000–2014), and a more recent stage characterized by the incorporation of emerging technologies such as artificial intelligence, renewable energy, and precision agriculture (2015–2025) [6]; [7]; [8]. These advancements have not only enhanced yield per cultivated area but also facilitated access to hydroponics for different types of producers, including those in urban and peri-urban settings.

The article continues with a detailed description of the methodology used for the selection and analysis of the most relevant studies. It then presents the key findings in chronological order, aiming to illustrate the technological evolution of hydroponic greenhouses from their origins to the present. Finally, it analyzes the implications of these advancements in terms of sustainability, innovation in agricultural production, and their potential to strengthen food security in various contexts.

2. Methodology

This study was based on a systematic review and a scientometric analysis to evaluate the development and evolution of hydroponic systems within the context of protected agriculture. To ensure the collection of high-quality and relevant scientific information, bibliographic resources available through the National Library System (Sinab) of the National University of Colombia were accessed, which facilitated the identification of specialized studies. A comprehensive literature search was conducted using the Scopus and WoS databases, both recognized for their broad coverage of specialized academic literature and rigorous publication selection processes. These platforms have been used in similar studies, such as the scientometric analysis by Mauricio et al. [9], on the use of activated charcoal and probiotics in mouthwashes or toothpastes, using WoS as the primary source and applying bibliometric indicators to assess the dynamics, spatiotemporal evolution, and trends in the dental field. The search parameters applied, as well as the detailed results obtained from each database, are described in Table I.

Table I. Search criteria and results obtained in WoS and Scopus for the systematic review of hydroponic systems in protected agricultura

Parameters	Web of Science	Scopus
Range	1977 - 2025	
Date	April 3, 2025	
Document type	Paper	
Words	ARTICLE TITLE (greenhouse) AND ARTICLE TITLE, ABSTRACT, KEYWORDS (hydroponic) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English")	
Results	250	484
Total	545	

According to the established criteria, a broad time range was defined (1977–2025), and the search was limited to scientific articles (document type: paper) written in English. The key terms included 'greenhouse' in the title and 'hydroponic' in the title, abstract, or keywords. Initially, 250 records were identified in WoS and 484 in Scopus. After removing duplicates, a total of 545 studies were selected for analysis. Once the search results from each database were obtained, the Google Colab environment, a cloud-based platform that enables the interactive execution of Python and R code, was used. Through a Python script, bibliometric data were read, processed, and visualized. The code implemented in Google Colab allowed for the extraction of relevant information from WoS and Scopus; co-authorship, co-citation, and temporal evolution analyses were conducted, generating network graphs, summary tables, and longitudinal visualizations of scientific production. The information obtained through this process included indicators such as the total number of publications, citations, international and author collaboration, as well as the identification of the most relevant journals and topics in the field, which are presented in Figure 1.

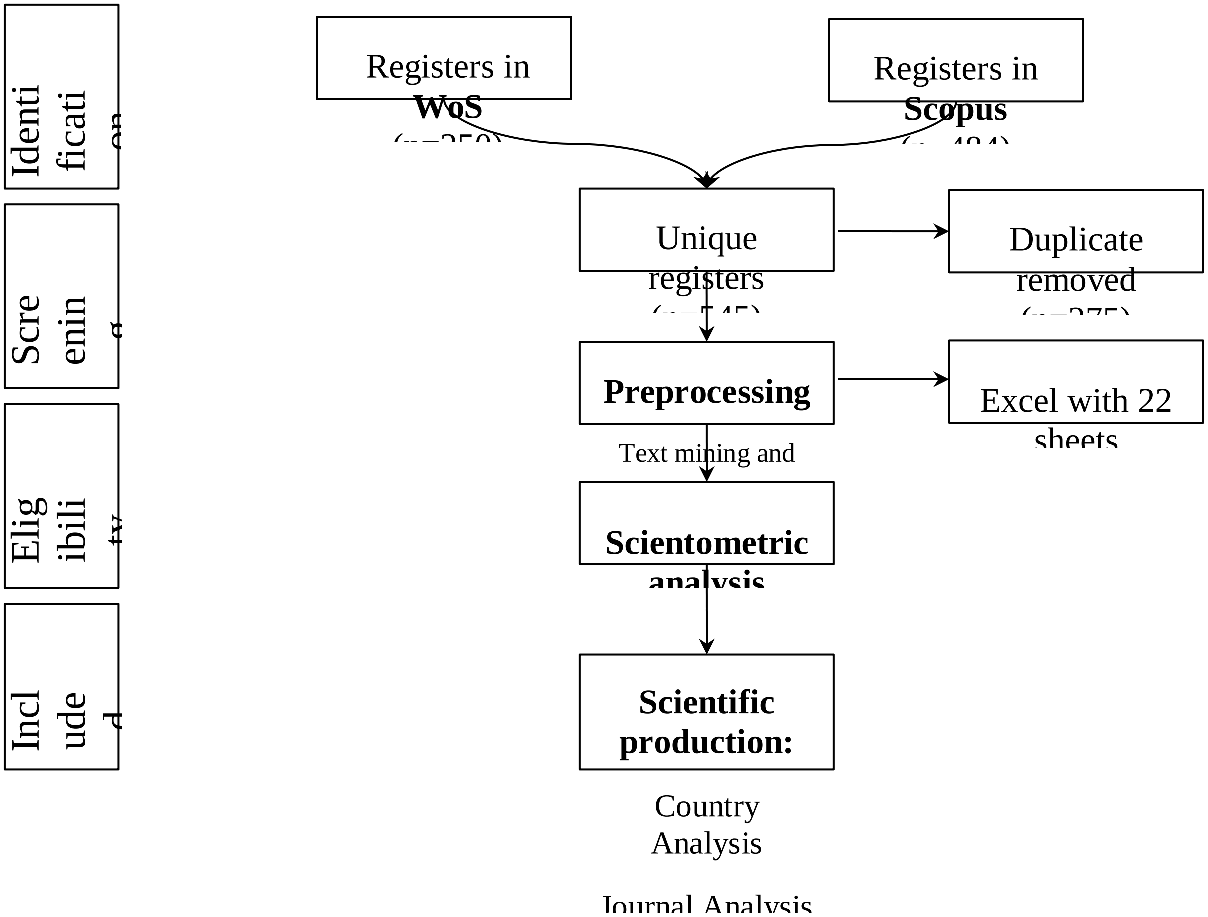

Figure 1. Flowchart of the selection and analysis process of scientific records on hydroponic systems.

In line with the methodological advances proposed by Fleta-Asín et al. [10] in their article, our methodology incorporates innovative data processing and visualization techniques to address similar challenges in bibliometric analysis. While their work introduces the FLEMUSA algorithm to mitigate spatial disparity through interactive 2D and 3D maps, logarithmic scales, and the exclusion of countries without data, our approach also leverages Python tools in Google Colab to process data from WoS and Scopus, generating dynamic visualizations that include co-authorship networks, co-citation patterns, and temporal trends. Similar to their proposal, our script enables a clear representation of complex indicators such as international collaboration and thematic evolution, facilitating the interpretation of spatial and temporal heterogeneities. By employing open-source code and interactive graphics, both methods aim to enhance transparency and accessibility in data analysis, albeit applied to different contexts theirs addressing global geographic disparity, and ours focusing on the bibliometric mapping of scientific networks. This methodological synergy underscores the importance of flexible computational solutions to address biases and inequalities in data visualization

3. Results

Scientific Annual Production

It is of fundamental importance to analyze annual scientific production, as it allows for the estimation of both the generation of knowledge and the level of interest that a specific topic elicits within the academic community. In this case, the analysis focuses on hydroponic systems applied to protected agriculture, a field that has gained increasing relevance in the context of agricultural sustainability, climate change, and the need to optimize the use of water and energy resources.

For this analysis, the period between 2004 and 2025 has been taken as a reference. The main sources used were the indexed databases Scopus and WoS. In general terms, it is observed that Scopus contains a higher number of academic articles compared to WoS in each year, which may be attributed to its broader coverage of technological and agricultural topics. The annual growth rate has been particularly significant since 2019, in response to the need for more efficient, intelligent, and adaptable production systems in the face of water and climate stress contexts

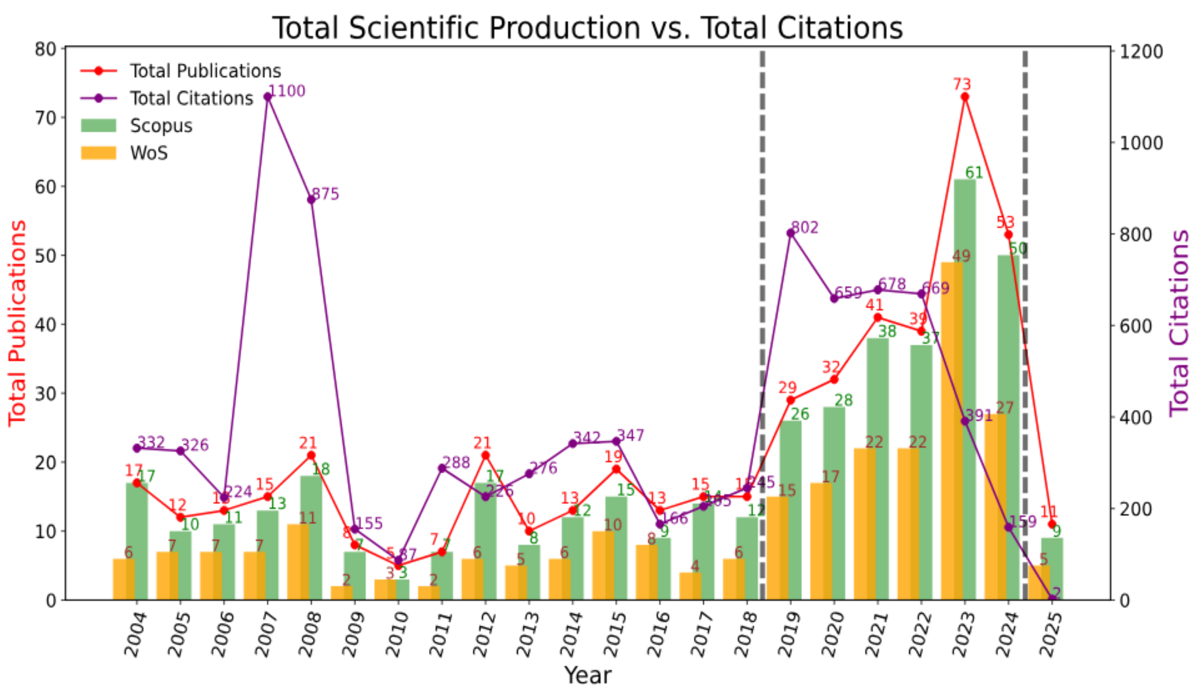

Figure 2. Graph of scientific production and citations in Scopus and WoS (2004–2025) focusing on the development and evolution of hydroponic systems in agriculture.

Based on the behavior shown in the bar chart, three clearly differentiated periods have been identified. In the first interval (2004–2018), scientific output remains relatively stable, with few publications per year and limited citation accumulation, indicating an emerging interest focused on exploratory studies and theoretical foundations. In the second interval (2019–2024), there is a marked increase in both publications and citations, driven by the incorporation of emerging technologies such as artificial intelligence, IoT sensors, and automated control systems. Finally, the third interval (2025) represents the current phase, where, although the number of publications is not yet quantitatively significant, the studies are notable for their modular approach, adaptability to extreme climatic conditions, and potential to consolidate sustainable and replicable solutions. This analysis not only illustrates the chronological progress of hydroponic research, but also identifies the scientific and technological milestones that have driven its development transforming this field into a strategic line of agricultural innovation on a global scale.

Period of Stability and Foundations (2004–2018)

During this period, scientific production remained relatively stable, with a total of 306 publications, representing approximately 48% of the overall dataset. Although there were some fluctuations, this period reflects an initial stage in which hydroponic systems in protected agriculture were beginning to be explored, mainly from conceptual and comparative approaches. In 2008, a significant peak in citations (1,100) was recorded, suggesting the publication of foundational studies. One of the most cited papers in this phase was by Sessions and Valtorta, who emphasized the importance of data quality in the application of artificial intelligence in agriculture [11]. Likewise, Holloway et al. applied support vector machines (SVM) to predict relationships between transcription factors and regulatory genes, and optimized their model using validated databases [12]. Comparative studies of systems such as NFT, DWC, and aeroponics also stood out. For instance, Hutchinson et al. [4] demonstrated that each system offers specific advantages depending on the crop type. During this period, Scopus led in the number of publications, highlighting its broad coverage of emerging literature in this field.

Period of Accelerated Growth and Technological Integration (2019–2024)

In this second phase, a clear shift is observed: scientific production increased significantly, with 329 publications, accounting for 52% of the total. This growth was both quantitative and qualitative, driven by the integration of emerging technologies in hydroponic systems, such as automation, artificial intelligence, IoT sensors, and renewable energy. Citations also rose notably, with peaks recorded in 2020 and 2022, each exceeding 800 citations. Among the most influential articles is the work by Marouani et al. [3], who proposed a smart greenhouse combining solar energy, AI, and environmental sensors to optimize the microclimate. Also notable is Choudhary et al. [13], who implemented a digital twin for hydroponic farms based on monitoring 89 environmental variables.

Raju et al. [13] developed a low-cost intelligent system controlled via a mobile application, capable of adjusting nutrients in real time. Similarly, Wang et al. [14] presented a smart system for controlling agricultural greenhouses that combines IoT sensors with machine learning techniques. This solution allows real-time adjustment of key factors such as temperature, humidity, and lighting. Thanks to its precision and adaptability, the system is particularly useful in hydroponic contexts, where maintaining stable and optimized conditions for crop development is essential. This period represents the consolidation of the field, positioning hydroponic systems as a key strategy within smart and sustainable agriculture, especially in the face of challenges posed by climate change and urban growth [14].

Current Period (2025)

Although only 10 publications were recorded in 2025, representing about 2% of the total, this year marks a transitional stage towards more sophisticated approaches focused on modularity, adaptability to different climatic conditions, and scalability. As is typical in recent years, citations have yet to fully reflect the impact of these publications.

One of the most relevant studies is by Bua et al. [15], who developed the GymHydro system: a modular and intelligent solution designed to face extreme climatic conditions such as droughts and floods. This system employs edge computing, LoRa communication, and PID light control; furthermore, it is especially useful in rural areas or locations with limited connectivity. This period reflects a transition towards more adaptable systems that seek not only technical efficiency but also social inclusion, environmental sustainability, and technological access in both urban and rural contexts.

Country Analysis

Table II shows the top 10 countries with the greatest impact (citations) on the development and evolution of hydroponic systems in protected agriculture, including quality (quartile) and their annual production. Considering this, the USA is the country with the highest scientific output, accounting for 17.25% of the publications, followed by Greece with 7.61%, noting that this percentage is significantly lower compared to the USA, with 52 fewer publications than the leading country. It is also noticeable that the country with the highest impact is Canada, with 1,092 citations. Interestingly, Spain has the highest number of publications in high-quality journals (Q1), although the USA has the majority of its publications distributed among Q1, Q2, and Q3 journals.

Table II. Contributions by Country in Hydroponics Research for Protected Agriculture.

	Production		**Citation**					
Country	**Count**	**Percentage(%)**	**Count**	**Percentage(%)**	**Q1**	**Q2**	**Q3**	**Q4**
USA	93	17.25	894	12.85	15	14	15	3
GREECE	41	7.61	884	12.71	10	7	13	6
MÉXICO	38	07.05	300	4.31	5	5	17	7
CANADÁ	35	6.49	1092	15.7	10	6	6	1
ITALY	31	5.75	302	4.34	6	3	6	4
SPAIN	27	05.01	750	10.78	16	0	7	3
JAPAN	22	04.08	213	03.06	3	5	3	2
CHINA	19	3.53	242	3.48	5	3	1	4
IRÁN	19	3.53	239	3.44	9	3	3	1
INDONESIA	17	3.15	62	0.89	0	2	3	0

One of the most recent studies from the United States, the leading country in scientific production on this topic with 17.25% of published articles, was research in controlled environment agriculture that evaluated the yield and efficiency of four hydroponic systems (DWC, NFT, vertical towers, and aeroponics) in a greenhouse setting, using arugula and lettuce. The study analyzed water, energy, and space use, as well as biomass production. Results showed that arugula performed best in aeroponics, while lettuce had better performance in DWC and NFT. This study highlights the importance of choosing the appropriate system for more sustainable and efficient production [6].

In Greece, which ranks second in citations (12.71%) despite a smaller production volume (7.61%), recent research on greenhouse agriculture has focused on sustainable technologies. On one hand, they evaluated tomato quality using decoupled hydroponic and aquaponic systems (DAP), demonstrating that DAP offers comparable quality in lycopene and beta-carotene [16]. On the other hand, they utilized hydroponic effluents to cultivate microalgae for biostimulants, achieving positive results in nutrient absorption and biomass recovery [17]. Both studies reflect Greece's approach toward more circular and efficient production, supported by strong academic reception.

In Mexico, which represents 7.05% of the scientific production in the area, research on greenhouse agriculture has shown a focus on improving horticultural crops through the use of hydroponic systems, aligning with international efforts to achieve more efficient and sustainable production. Similar to the United States, where different hydroponic systems were compared based on their yield and efficiency [6], Mexican studies have evaluated the performance of different varieties under controlled conditions.

Additionally, in line with Greece's focus on more circular and resilient production, the use of silicon nanoparticles was investigated to improve water use efficiency in tomato under water stress, achieving increases of up to 56.3% in water efficiency [18]. At a systemic level, conventional and hydroponic production were also compared in physical and environmental terms, revealing that hydroponics, although more energy-intensive, allows yields up to 11 times higher [1]. Finally, 53 advanced lines of round-type tomato were evaluated under hydroponic conditions, identifying varieties with better yield and quality that even surpass commercial cultivars, thus promoting national genetic improvement [19]. These studies demonstrate that Mexico follows a convergent line with leaders such as the U.S. and Greece, combining efficiency, sustainability, and genetic improvement in greenhouse agriculture.

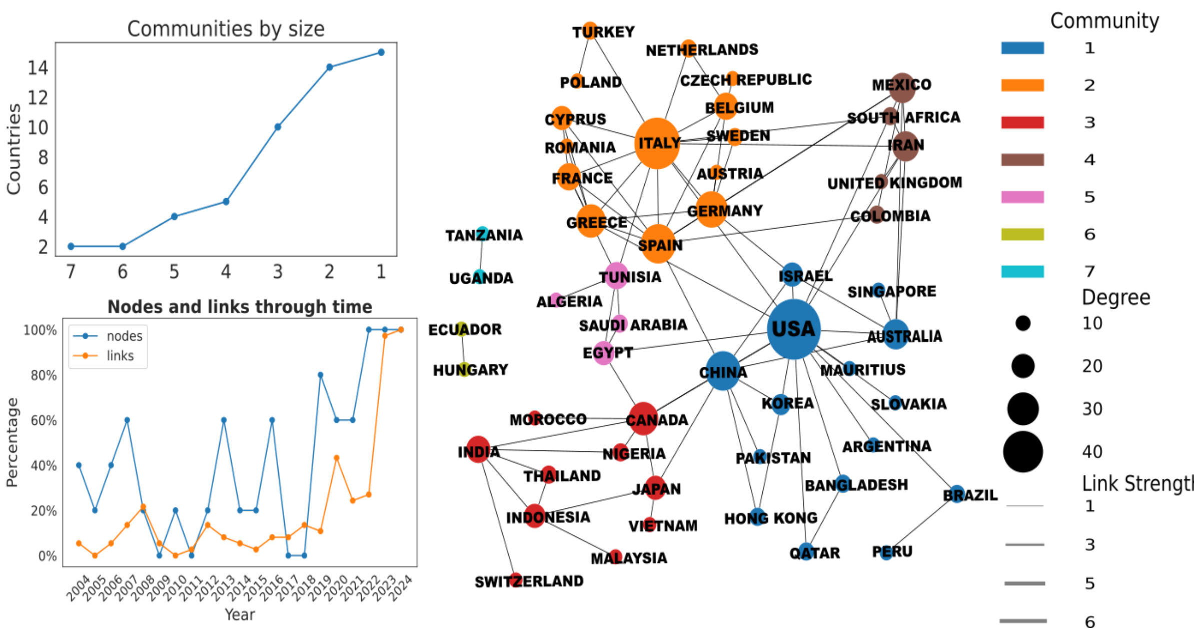

Figure 3. International collaboration network in agricultural research: Countries, communities, and temporal evolution

In Figure 3, the central network graph is presented, which displays communities by size, immediately highlighting the United States (USA) as the largest node and the central country of community 1 (blue), the most extensive and dense. This leadership is confirmed by the fact that the USA contributes 17.25% of the articles published in the field [20]; [21]. The predominance of the USA in terms of connections ("Degree") suggests it acts as a hub and facilitator of collaborations, consistent with its role as the main scientific producer [22]. Surrounding the USA are countries such as Australia, Singapore, and Israel, forming a strong research network with links that, although not precisely quantified in terms of strength visually, imply sustained interaction [23]; [24]. The presence of other communities, such as the mainly European orange cluster with Germany, France, and Italy [25]; [26], and the Asian red cluster with India, Indonesia, and Thailand [27]; [28], indicates the formation of regional or thematic collaboration clusters where countries within the same community tend to interact more closely.

The graph "Nodes and links through time" illustrates the remarkable expansion of the agricultural research network over two decades. There is an overall upward trend in both the number of countries involved (nodes) and the number of collaborations (links). From 2004, when participation was minimal, up to 2024, the network has experienced almost steady growth, reaching peaks close to 100% of the nodes and links in recent years. This evolution suggests a growing globalization of research in the field, with more actors joining the scientific conversation and establishing collaborative ties. The occasional fluctuations in the link trend may reflect funding cycles, shifting research focuses, or the consolidation of existing collaborations, but the overall trend is toward an increasingly dense and interconnected network.

Journal Analysis

Table III compiles the main scientific journals where academic production in the field of horticulture is concentrated, considering relevant indicators such as the number of publications indexed in Web of Science (WoS) and Scopus, ISSN, impact factor, h-index, and quartile according to the Scimago ranking. It is noteworthy that a considerable portion of these journals belongs to the Q1 quartile, which suggests that research in this field is being disseminated through high-quality publications. Among the most representative journals are *Journal of Cleaner Production*, *Scientia Horticulturae*, and *Frontiers in Plant Science*. These journals not only have significant impact factors (some exceeding a value of 1), but also high h-indexes, such as *Frontiers in Plant Science* (h = 246) and *Journal of Cleaner Production* (h = 354), evidencing their academic relevance.

Table III. Most prominent journals in hydroponic systems research: productivity and scientific impact indicators.

Journal	Wos	Scopus	ISSN	Impact factor	h-index	Quartile
Acta Horticulturae	0	94	5677572	0,158	74	Q4
Hortscience	26	14	23279834	0,391	109	Q2
Horttechnology	7	9	19437714	0,373	68	Q2
Journal Of Cleaner Production	8	8	09596526	2,174	354	Q1
Horticulturae	8	8	23117524	0,647	48	Q1
Scientia Horticulturae	6	7	3044238	0,899	155	Q1
Aip Conference Proceedings	0	7	15517616	0,153	90	-
Sustainability (Switzerland)	0	7	20711050	0,688	207	Q1
Frontiers In Plant Science	6	6	1664462X	1,163	246	Q1

Journal of Cleaner Production, recognized for its high scientific impact, has established itself as a key platform for disseminating research on sustainability in hydroponic systems. Two recent studies published in this journal critically and multidimensionally address the environmental and economic challenges of these systems in current contexts. The first article employs a life cycle assessment (LCA) approach to demonstrate that integrating compost and biochar can significantly reduce the negative environmental impacts in hydroponic tomato production, especially regarding human health and natural resource use. This study highlights the relevance of adopting circular bioeconomy models as a viable solution to waste generated in hydroponic crops [3].

Meanwhile, the second article conducted a thermo-economic evaluation revealing the advantages of passively cooled greenhouses in arid regions. It shows how hydroponic systems, besides significantly reducing water use (up to 46%), present a more favorable environmental and economic performance than traditional methods, even under extreme climatic conditions. Both studies reinforce the positioning of this journal as a reference in applied research on sustainability and emerging technologies in protected agriculture [29].

In contrast, *Frontiers in Plant Science*, a Q1 journal with a solid impact factor of 1.163, complements this systemic approach by advancing technical knowledge in hydroponics. Recently, the journal has published key studies on efficient irrigation and fertigation management in protected crops. For example, a recent investigation demonstrated that using moisture sensors for automated fertigation control in hydroponic strawberries significantly improves yield and efficiency in water and energy use, highlighting the potential of strategies based on lower moisture thresholds [30]. Likewise, another study proposed an innovative model to predict daily water consumption in hydroponic tomatoes. This model, based on light interception and basic meteorological data, represents a crucial advancement for improving irrigation management precision without the need for direct plant measurements [26].

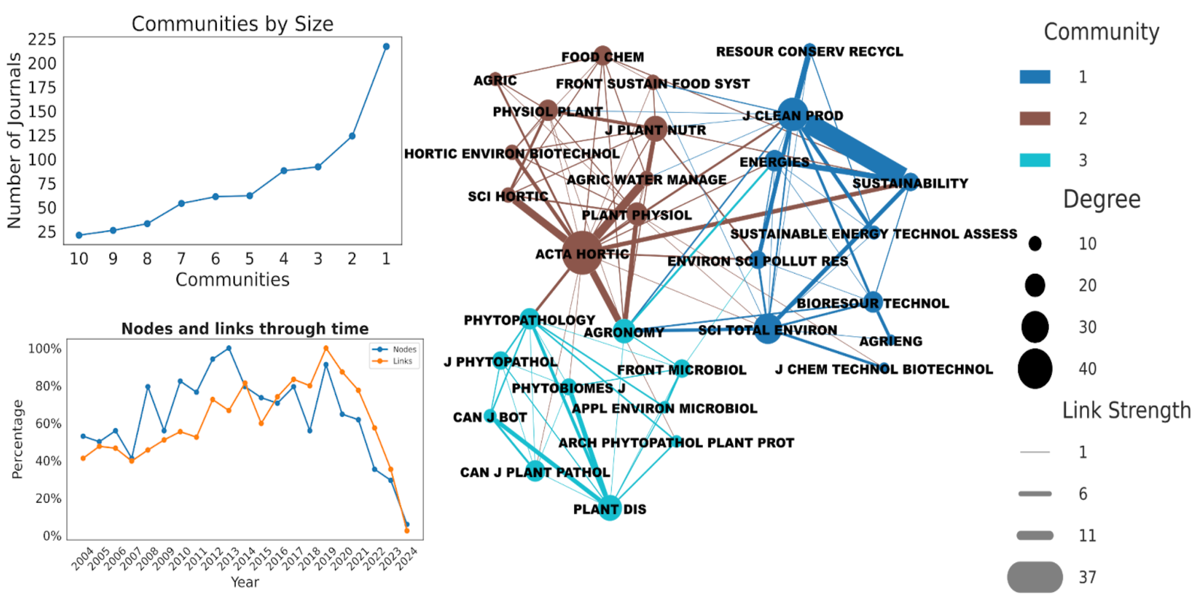

Figure 4. Mapping of scientific journals in sustainable agriculture: thematic communities, degree of connection, and publication dynamics.

In Figure 4, the central network graph, titled "Community," is the focal point of this analysis, revealing the interconnection among different scientific journals. Community 1 (blue) is centered on sustainability and environmental topics, with prominent nodes such as *Journal of Cleaner Production*, *Sustainability*, *Sustainable Energy Environ Technol Assess*, and *Bioresource Technol* [31]; [32]; [1]. The large size of *Journal of Cleaner Production* and *Sustainability* suggests they are central journals in this group, with a high degree of interconnection and a broad focus on sustainability and environmental impact. The strong connection between these journals indicates substantial collaboration or cross-referencing in their publications.

Community 2 (brown) appears to group journals more focused on agronomic, physiological, and crop production aspects, including *Acta Hortic.*, *Hortic Environ Biotechnol*, *Plant Physiol*, *Sci Hortic*, and *Agric Water Manage* [33]; [34]. The *Acta Hortic.* node is notably large, indicating its importance and wide reach within this community [35]; [36]. This suggests that these journals address the more technical and biological aspects of agriculture, with an interest in optimizing yield and resource management at the plant and crop level.

Community 3 (cyan), although perhaps smaller in number of nodes, seems concentrated on plant pathology and microbiology, with journals such as *Phytopathology*, *J Phytopathol*, *Front Microbiol*, and *Plant Dis* [37]; [38]; [39]. The size of *Phytopathology* suggests it is an important reference in this field. This community represents a specialization within agriculture, addressing challenges related to diseases and microorganisms in crops.

On one hand, the "Nodes and links through time" graph illustrates the evolution of publication activity and collaboration in the network over time, from 2004 to 2024. An upward trend is observed in the percentage of nodes (active journals) and links (collaborations/thematic connections) from 2004 until approximately 2017–2018, indicating growth and greater interconnection in the field of study. However, from 2018 onwards, there is a significant decline in the percentage of nodes and, especially, links. This drop in recent years (2020–2024) could suggest possible fragmentation, shifts in publication trends, consolidation into fewer journals, or even a bias in the represented data that warrants further investigation to understand the causes of this slowdown in connectivity.

On the other hand, the "Communities by Size" graph shows the distribution of the number of journals per community. It is evident that Community 1 (the blue one, focused on sustainability) is the largest, hosting the greatest number of journals (over 200). This suggests that research on sustainability in agriculture is a vast and growing field, with a large volume of dedicated publications. Subsequent communities (2, 3, etc.) are progressively smaller, which could indicate greater specialization or a smaller volume of journals within those thematic domains.

Author Analysis

The scientometric analysis of authors allows identifying the main researchers who have made significant contributions to the development of hydroponic systems in protected agriculture, highlighting both their productivity and impact within the scientific community. Based on data collected from Scopus and Web of Science (WoS), a co-authorship network and a comparative table were created with key indicators such as total number of publications, citations, h-index, and connectivity metrics like Effective Size, Constraint, and CDI (Centrality Degree Index).

Table IV. Author productivity, citations, and collaboration indicators

Author	Papers Total	Total Citations	H-Index	Effective Size	Constraint	CDI
Katsoulas N	15	157	5	53.59	0.07	0.18
Bouadila S	11	134	5	30.83	0.1	0.19
Cantliffe D	11	140	7	10.73	0.21	0.19
Ntinas G	9	143	6	3.4	0.51	0.38
Savvas D	8	230	6	88.91	0.04	0.16
Shaw N	8	94	6	12.33	0.19	0.15
Bartzanas T	7	33	3	18.74	0.17	0.19
Giacomelli G	7	56	4	26.35	0.1	0.18
Kittas C	7	112	4	38.43	0.1	0.22
Kubota C	7	114	6	86.89	0.04	0.16

In terms of article productivity ("Papers Total"), Katsoulas N [40]; [41]; [42] leads with 15 publications, closely followed by Bouadila S [43] and Cantliffe D [44], both with 11. However, productivity is not the only impact indicator. When observing "Total Citations," Savvas D stands out significantly with 230 citations despite having 8 articles, suggesting a high impact per publication [45]; [46]. Other authors with a considerable number of citations include Ntinas G (143) and Cantliffe D (140). The H-Index offers a combined measure of productivity and citations [47]; [48]. In this regard, Cantliffe D shows the highest H-Index (7), followed by Ntinas G, Savvas D, Shaw Ny, and Kubota C (all with 6), indicating a solid research trajectory with consistently cited publications [49], [50]; [51].

The "Effective Size" is an indicator of the diversity of an author's collaborators, reflecting the extent of their collaboration network. In this sense, Savvas D presents the highest "Effective Size" (88.91) [52], followed by Kubota C (86.89) [53] and Katsoulas N (53.59) [53]. A high "Effective Size" suggests that these authors have a broad and varied collaboration network, which is crucial for knowledge dissemination and interdisciplinarity. The "Constraint" measures the degree to which an author's network is concentrated around few collaborators or groups. A low value indicates a more open and less redundant network. Katsoulas N, Savvas D, and Kubota C exhibit the lowest "Constraint" values (0.07, 0.04, and 0.04 respectively), reinforcing the idea that their collaboration networks are diverse and not overly concentrated. On the other hand, Ntinas G has the highest "Constraint" (0.51), suggesting a more closed or redundant network [47].

Finally, the "CDI" (Centrality Diversity Index) evaluates the diversity of central roles an author holds within their network. Higher values indicate greater diversity. CDI values are relatively similar among most authors, ranging from 0.15 to 0.38, which may indicate that many authors maintain consistent centrality roles within their respective networks.

Based on these indicators, Savvas D and Kubota C can be identified as highly impactful authors, with a significant number of citations and a broad, diverse collaboration network (high "Effective Size" and low "Constraint"). Although Katsoulas N is the most productive author, their citation impact is moderate compared to Savvas D. Cantliffe D stands out for their H-Index, positioning them as an author with sustained impact over time. These researchers, through their productivity, impact, and collaborative capacity, are the fundamental pillars contributing to the advancement of knowledge in hydroponic systems for protected agriculture.

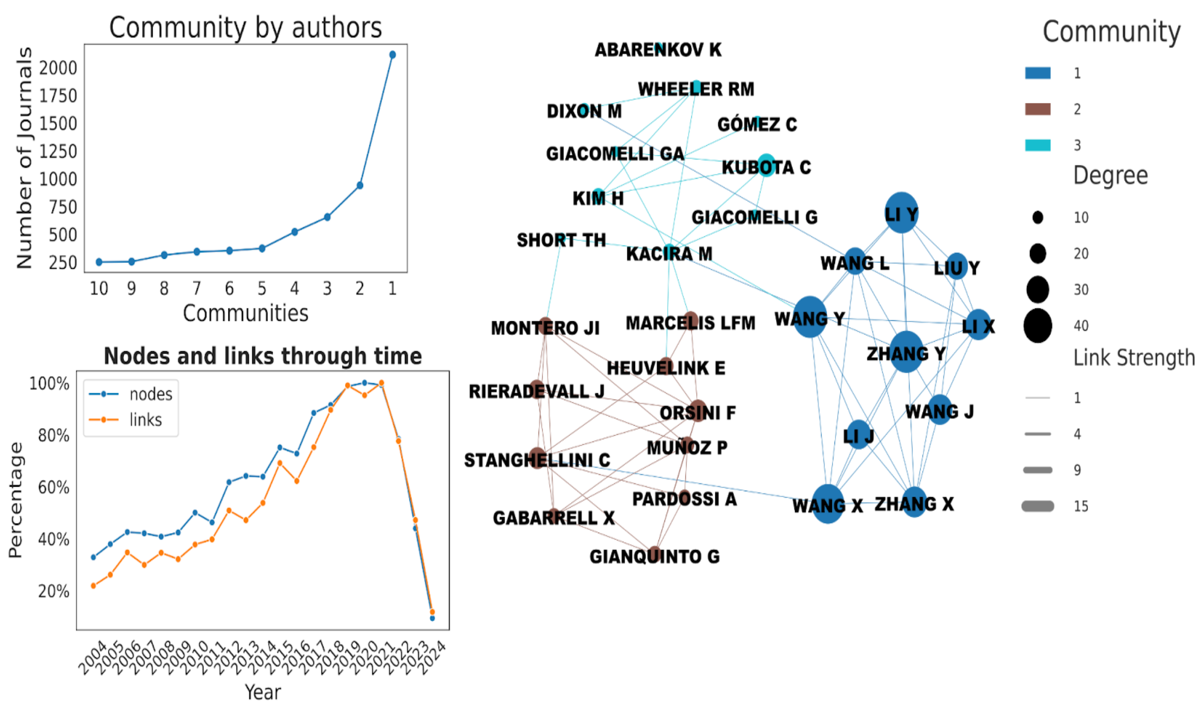

Figure 5. Collaboration network of prominent authors and their interconnections

In Community 2 (brown), authors who, although active, might have a collaboration network more centered around a specific group or with a lower density of connections to the dominant blue community are grouped. Authors such as Montero JI, Rieradevall J, Stanghellini C, Pardossi A, and Gianquinto G are part of this cluster. The strength of the links within this community is visible, but their connections with Community 1 appear to be fewer or weaker compared to the internal connections of the blue community. This could indicate thematic specialization or a more regionalized collaboration network, or a lower volume of joint publications with the dominant community.

Finally, Community 3 (cyan) is the smallest and most dispersed, with authors like Abarenkov K, Wheeler RM, Dixon M, Gómez C, and Short TH. The connections within this community appear less dense or have weaker links compared to the other two. It could represent a group of authors with a more niche focus, or with less frequent collaborations, or whose publications tend to be more individual rather than massive coauthorship. The presence of Giacomelli GA and Kubota C as connecting nodes between the cyan and blue communities (and in the case of Giacomelli GA, also with the brown) is important, as they act as “bridges” between different research groups [54]; [55].

The "community by authors" graph indicates that "Community 1" (blue) is by far the largest in terms of authors (exceeding 2000), which is consistent with its density and the large nodes observed in the network graph. The other communities are significantly smaller, so the graph likely shows that the largest author community contributes to the greatest number of journals, which is an interesting but less direct metric for author analysis. Given the coherence with the node sizes in the network, the interpretation of "number of authors" is more likely.

Lastly, the "Nodes and Links Through Time" graph shows the evolution of the percentage of nodes (active authors) and links (collaborations) in the network over time (2004–2024). A steady growth trend in author participation and collaboration formation is observed from 2004 to 2018–2019, reaching almost 100% of the network. This indicates a progressive increase in the number of researchers joining the hydroponics field and in the density of their collaborations.

However, there is a drastic and concerning drop in the percentage of nodes and links starting in 2020. Both author participation and collaborations reduce significantly, returning to levels similar to those of 2006–2007. This abrupt decrease in recent years could have several explanations: first, data bias, meaning that data for the most recent years (2020–2024) might be incomplete or not fully updated at the time of extraction; second, consolidation of collaborations, i.e., fewer active authors or collaborations, possibly due to consolidation into very specific research groups; third, a change in publication dynamics, where authors might be opting to publish less in coauthorship or in journals not counted in this network; and fourth, the impact of external events although less likely in a specific research field global events (such as pandemics) could have temporarily affected productivity and collaboration in some sectors.

Conclusions

This systematic review, complemented by a rigorous scientometric analysis, demonstrates that hydroponic systems implemented in protected agriculture have undergone a remarkable evolutionary process, transitioning from basic configurations to sophisticated, technologically advanced solutions integrated with sustainability principles. Based on the examination of 545 scientific articles retrieved from high-level databases (Scopus and Web of Science), three key stages in this evolution were identified: an initial phase focused on conceptual construction (2004–2018), an intensive expansion phase with technological incorporation (2019–2024), and a recent phase (2025) oriented toward modular, adaptable, and resilient systems against extreme climatic conditions.

Beyond this established timeline, the results reveal that hydroponics has ceased to be a marginal technology and has positioned itself as a strategic tool to address global challenges such as water stress, loss of fertile soils, and increasing urban pressure on food production. Throughout this trajectory, systems like NFT, DWC, and aeroponics have shown variable performance depending on the crop type and specific conditions, underscoring the importance of differentiated technical approaches tailored to implementation contexts.

Additionally, a geographic concentration of knowledge was identified in countries such as the United States, reflecting asymmetry in scientific production at a global scale and highlighting the limited participation of the Global South regions. Nevertheless, significant contributions from Mexico, Greece, and Canada stand out, both for their scientific quality and for their orientation toward circular, sustainable, and resilient models.

Together, this review not only provides an updated overview of hydroponic advances in protected environments but also calls for rethinking its development from a comprehensive approach that articulates technical, environmental, and social variables. Promoting contextualized research, expanding scientific cooperation, and aligning knowledge with public policies will be fundamental steps to consolidate sustainable, equitable, and relevant hydroponic systems.

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