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Agricultura en ambientes controlados, técnicas de control y su relación con la extracción de aceites esenciales: un análisis cienciométrico*

Controlled Environment Agriculture, Control Techniques, and Their Relationship with Essential Oil Extraction: A Scientometric Analysis

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Abstract

Controlled Environment Agriculture (CEA) has emerged as a fundamental strategy to optimize agricultural production through precise management of environmental variables such as temperature, humidity, light, and nutrients. This research presents a scientometric analysis of the scientific evolution in CEA during the period 2004-2025, with particular attention to its application in specialized crops for essential oil production. Through a systematic search in Web of Science and Scopus databases, 862 unique records were identified and analyzed following the PRISMA methodology. The results reveal exponential growth in research from 2015 onwards, with three distinct periods: initial growth (2004-2009, 23.27%), decline (2010-2014, -15.91%), and accelerated expansion (2015-2025, 50.41%).

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The United States leads scientific production with 339 publications (40.5%) and 5,998 citations, followed by Canada, India, Germany, and China. Predominant technologies include LED lighting systems, IoT sensors, automated monitoring, and vertical farming. The journal Frontiers in Plant Science positions itself as the main dissemination platform with 41 articles and an h-index of 246. International collaboration analysis evidences consolidated networks between European, Asian, and American countries, facilitating technology transfer. Although the specific relationship between CEA and essential oils remains underexplored, the consolidation of environmental control technologies and the growing demand for high-value products position this field as strategic for addressing global challenges of food security, climate change, and sustainability. It is concluded that CEA represents a research area with great projection, suggesting that future research should focus on the synergy between controlled systems and the production of secondary metabolites, essential oils, and bioactive compounds.

Keywords: Controlled Environment Agriculture (CEA), essential oils, scientometric, agricultural control techniques, precision agriculture, environmental monitoring, vertical farming, scientific collaboration.

Resumen

La agricultura en ambientes controlados (CEA) ha emergido como una estrategia fundamental para optimizar la producción agrícola mediante la gestión precisa de variables ambientales como la temperatura, la humedad, la luz y los nutrientes. Esta investigación presenta un análisis cienciométrico de la evolución científica en CEA durante el período 2004-2025, con especial atención a su aplicación en cultivos especializados para la producción de aceites esenciales. A través de una búsqueda sistemática en las bases de datos Web of Science y Scopus, se identificaron y analizaron 862 registros únicos siguiendo la metodología PRISMA. Los resultados revelan un crecimiento exponencial en la investigación a partir de 2015, con tres períodos distintos: crecimiento inicial (2004-2009, 23.27%), decrecimiento (2010-2014, -15.91%) y expansión acelerada (2015-2025, 50.41%). Los Estados Unidos lideran la producción científica con 339 publicaciones (40.5%) y 5,998 citaciones, seguidos por Canadá, India, Alemania y China. Las tecnologías predominantes incluyen sistemas de iluminación LED, sensores IoT, monitoreo automatizado y agricultura vertical. La revista Frontiers in Plant Science se posiciona como la principal plataforma de difusión, con 41 artículos y un índice h de 246. El análisis de colaboración internacional evidencia redes consolidadas entre países europeos, asiáticos y americanos, lo que facilita la transferencia de tecnología. Aunque la relación específica entre CEA y aceites esenciales aún permanece poco explorada, la consolidación de tecnologías de control ambiental y la creciente demanda de productos de alto valor posicionan a este campo como estratégico para abordar los desafíos globales de seguridad alimentaria, cambio climático y sostenibilidad. Se concluye que la CEA representa un área de investigación con gran proyección, sugiriendo que futuras investigaciones deberían enfocarse en la sinergia entre los sistemas controlados y la producción de metabolitos secundarios, aceites esenciales y compuestos bioactivos.

Palabras clave: Agricultura en ambientes controlados, Aceites esenciales, Análisis cienciométrico, Técnicas de control agrícola, Agricultura de precisión, Monitoreo ambiental, Agricultura vertical.

1. Introduction

Modern agriculture faces the challenge of ensuring efficient, sustainable, and adaptable crop production under increasingly variable environmental conditions. In this context, Controlled Environment Agriculture (CEA) has emerged as a key strategy to maximize crop yields, minimize resource use, and enhance the quality of plant products [1]. This approach allows for precise management of environmental variables such as temperature, humidity, light intensity, carbon dioxide concentration, and nutrient availability, thereby enabling intensive and continuous production—even in regions with adverse climates or limited arable land [2].

CEA has been applied not only to traditional horticultural crops but also to aromatic and medicinal plants, due to its capacity to modulate the phytochemical profile of these species by adjusting specific environmental conditions [3], [4]. Numerous studies have shown that factors such as light type, LED spectrum, nitrate-to-ammonium ratio in the substrate, and water management can significantly influence the synthesis of secondary metabolites, including the volatile compounds responsible for essential oils. This level of control opens new avenues for the standardized, high-quality production of essential oils, which are in demand across the pharmaceutical, cosmetic, and food industries .

Additionally, the integration of technologies such as IoT sensors, automated environmental monitoring systems, and agricultural robotics has enabled CEA to evolve into more sophisticated forms, including plant factories and vertical farming. These advancements position CEA as a viable alternative to address the challenges of food security, climate change, and increasing urbanization [5].

This study presents a scientometric analysis of the scientific evolution surrounding Controlled Environment Agriculture, with a particular focus on its application in specialized crops used for essential oil production [6]. Although the initial search targeted the relationship between environmental control techniques and essential oil quality, the bibliographic analysis revealed that most of the scientific output is concentrated on general research about CEA [7]. Consequently, the study was reoriented toward a comprehensive characterization of the field, identifying publication trends, the most influential articles, predominant technologies, and emerging research lines related to the use of controlled systems for the cultivation of high-value plants [7].

The main objective of this research is to analyze scientific trends related to CEA, with a focus on control techniques and their potential application in essential oil extraction through a scientometric study [8]. Specifically, the study aims to identify the temporal evolution of scientific production on CEA, as well as to determine the countries, authors, and journals with the highest volume and impact of publications in this area. In addition, it seeks to assess international collaboration in the field of agricultural control technologies and to explore the potential relationship between CEA and essential oil production [9].

2. Methodology

The relationship between the control of environmental variables in agricultural crops and their impact on the quality of derived products, particularly essential oils, was explored. To address this objective, the following search query was formulated: ("essential oil crops" AND "control techniques") OR ("controlled environment agriculture") (see Table I). However, after the data collection and refinement process, it was found that the majority of the retrieved documents focused primarily on the field of CEA rather than specifically on crops intended for essential oil production.

Table I. Search parameters used in the Scopus and WoS databases.

Parámetro	Web of Science	Scopus
Range	2004 - 2025	
Date of consultation	3 de Abril del 2025	
Type of documents	Articles	
Consultation	("essential oil crops" and "control techniques") or ("controlled environment agriculture")	
Number of articles	514	810
Total number of articles in both journals	862	

Given that the dataset collected exhibited a clear thematic concentration on CEA, the analysis was reoriented toward a scientometric perspective of this field, recognizing its growing relevance in sustainable agricultural production, the technological intensification of the sector, and its potential applicability to specialized crops. This adjustment not only ensures the appropriate use of the dataset obtained but also contributes to providing a useful characterization of the current state and research trends in CEA. Nonetheless, the study also examines the annual scientific output by country on the topics of CEA and essential oil extraction.

For the collection of bibliographic data, the Web of Science (WoS) and Scopus databases were utilized, covering a 21-year period (2004–2025). These databases were selected because they are the principal sources of scientific information worldwide and are widely used for research evaluation [10]. In the results of the query, Scopus retrieved the highest number of articles, totaling 810, while WoS retrieved 514 articles. After removing duplicates, the combined dataset comprised 862 unique articles related to the research topic [11], [12], [13].

Figure 1 presents the flowchart illustrating the methodology followed for the collection and scientometric analysis of the data. The PRISMA methodology was applied to manage the resulting data, allowing for a systematic review at each stage of the process [14]. In the identification stage, the results obtained from each database were compiled, and after removing 462 duplicate records, a total of 862 unique records remained. In the screening stage, relevant data were extracted, organized, and stored in 29 Excel files. Subsequently, a scientometric analysis was conducted, focusing on scientific production within the field [15], [16], [17], [18].

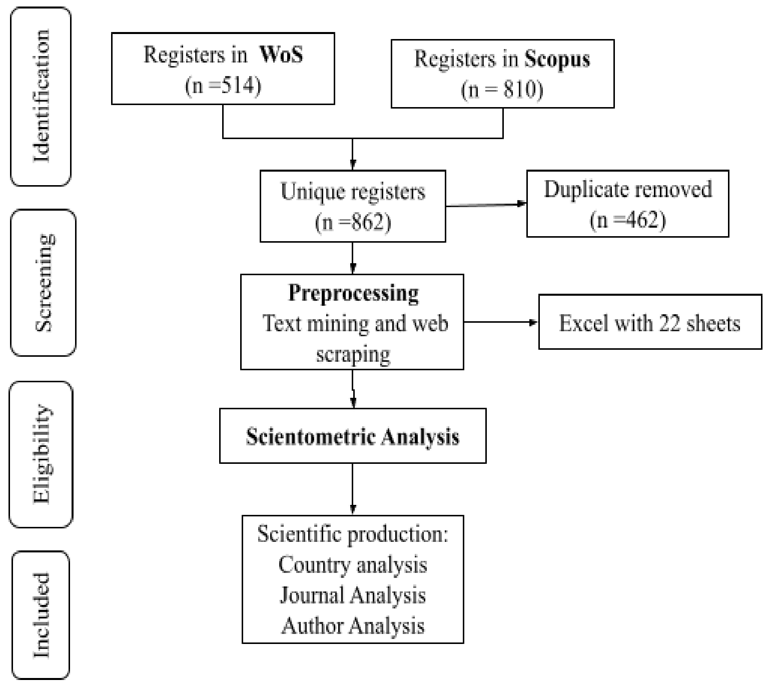

Figure 1. Detailed illustration of the information collected.

3. Results

3.1 Scientific Annual Production

Figure 2 illustrates the growing interest in controlled environment agriculture and the development of control techniques applied to plant cultivation, particularly in contexts aiming to optimize production environments through the management of variables such as temperature, humidity, light, and nutrients. Since 2015, the number of published articles on this topic has increased exponentially, with Scopus emerging as the database with the highest volume of publications. In 2024, Scopus surpassed the WoS by 69 additional articles. On the other hand, the highest citation peak was recorded in 2022, with a total of 2,532 citations. However, despite the increase in scientific output in recent years, a decline in the number of citations has been observed since 2022, with 2024 closing with a total of 772 citations.

Figure 2 can be divided into three distinct periods. The first period (2004–2009) experienced a growth of 23.27%. In contrast, the second period (2010–2014) showed a decrease in the number of publications, with a decline of 15.91% compared to the first period. However, during the third period (2015–2025), a significant growth of 50.41% was observed.

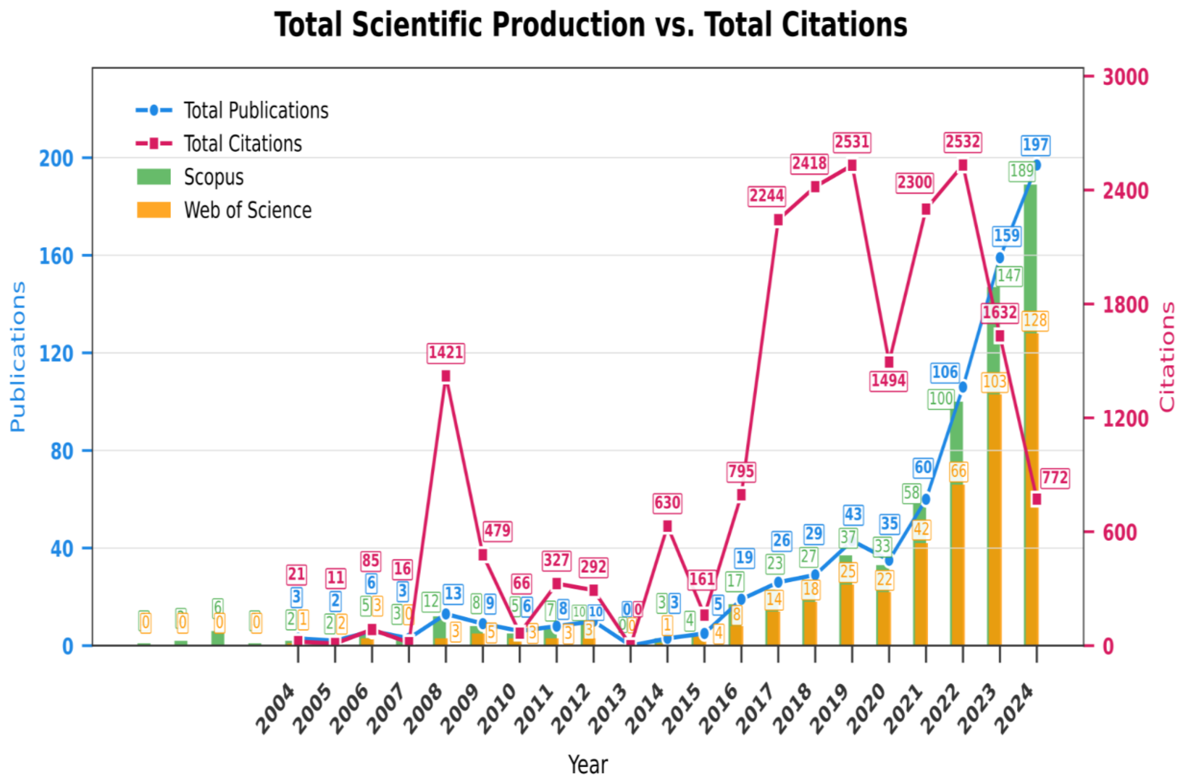

Figure 2. Comparación anual de la producción científica total y las citas en Scopus y WoS (2004-2024).

3.2 Period 1 (2004 - 2009)

During the analyzed period, a 23.27% increase in scientific output was observed, reaching a peak of 1,421 citations. Notably, the work by Massa, Gioia D. et al. accumulated 691 citations [19], indicating that this study has not only attracted attention due to its technological contributions but has also become a crucial reference within the academic community. The article discusses how the ability to adjust and optimize the cultivation environment using LED lighting not only enhances crop yields but also establishes new methodologies within controlled environment agriculture. Thus, the study underscores the need to implement sustainable and precise agricultural methods through the adoption of new technologies.

Another notable study is that of Park, William D., which explores the molecular mechanisms regulating tuber formation, with a total of 138 citations [20]. This research demonstrates how factors such as photoperiod, nitrogen levels, and gene expression can modulate the accumulation of these proteins in tissues such as stems and petioles. Additionally, the article by Beaman et al., with 42 citations [21], offers an experimental approach to optimizing plant yield in controlled environments. The study highlights that excessive lighting can lead to energy waste without improving yield, a finding particularly relevant for high-efficiency agricultural systems.Furthermore, the study by Kubota et al., which has accumulated 42 citations [22], demonstrates that through the precise management of factors such as light intensity, temperature, and nutrient availability, it is possible to significantly increase the accumulation of lycopene, an antioxidant compound with health-promoting properties in humans.

3.3 Period 2 (2010 - 2014)

During this period, a 15% decrease was observed compared to the previous period. However, in 2014, an article by Darko E., Heydarizadeh P., et al., stood out with a total of 367 citations [23]. This study examines how the use of LED technologies for artificial lighting allows for the simulation of natural light and the precise control of both light intensity and spectrum. Such control not only enhances the efficiency of photosynthesis (primary metabolism) but also induces substantial changes in the synthesis of secondary metabolites. These compounds are essential for enriching the nutritional and functional profile of crops. The article demonstrates that by adjusting light quality, it is possible to “design” crops with specific characteristics that align with current demands for sustainability and food security.

During this period, new methods for monitoring agricultural variables also began to emerge, providing deeper insights into nutrient management and flow. In this context, the article by Bamsey et al., with a total of 85 citations [24], highlights the importance of selective ion sensors for precise nutrient management in closed agricultural systems, both on Earth and in space contexts. Ion sensors can provide real-time feedback to optimize plant growth, minimize fertilizer waste, and reduce environmental impacts.

Finally, the article by Despommier, with a total of 163 citations [25], proposes an innovative solution to the agricultural challenges posed by climate change, the loss of arable land, and foodborne diseases. The author suggests that vertical farming, developed within tall buildings with controlled environments, can ensure safe, continuous food production located near urban centers. This approach not only reduces the environmental footprint of traditional agriculture but also enables more efficient management of resources such as water and energy. Thus, vertical farming is presented as a resilient alternative to global food insecurity and a key tool for sustainability in densely populated urban contexts.

3.4 Period 3 (2015 - 2024)

The growth observed during this period was significantly higher compared to previous periods, with an increase of 50.41%. During this timeframe, scientific interest increasingly focused on how the management and application of technologies are essential for enhancing the quality of high-value crops. The first highly influential article, published in 2017 by Kurt Benke and Bruce Tomkins, accumulated 590 citations [26]. This article highlights how vertical farming can address current challenges by maximizing spatial and resource efficiency, enabling continuous and localized production that minimizes risks related to food insecurity, excessive input use, and high transportation costs. It also identifies both the benefits (including increased productivity, reduced environmental impact, and improved biosecurity) and the challenges (such as high initial costs and limitations in crop variety) of vertical farming. As observed, this study aligns with the scientific publication trends identified in the previous period.

Additionally, the article by Shamshiri et al., with a total of 363 citations [27], offers a comprehensive overview of how CEA is evolving towards highly automated urban systems, such as plant factories. The study also identifies opportunities and challenges in the transition towards efficient and resilient urban agriculture, emphasizing the key role of automation, the Internet of Things (IoT), and predictive modeling in developing sustainable solutions for food security.

The article by Bantis et al., with 300 citations [28], presents an exhaustive review of technological and scientific advancements in the use of LED lighting for horticulture in controlled environments. The study documents substantial improvements in yield, nutritional quality, control of morphological development, secondary metabolism, and energy efficiency. Moreover, it analyzes the effects of specific wavelength combinations (red, blue, green, infrared, UV) on processes such as photosynthesis, flowering, antioxidant accumulation, and adaptation to environmental stress.

Furthermore, during this period, one of the most cited articles (110 citations) was by Ranka Junge et al., which evaluates the current strategic challenges of aquaponics [29]. As expected, over the past decade, scientific production has increasingly oriented toward sustainability and environmental care, assessing strategies and current challenges to achieve maximum productivity with minimal resource use.

Similarly, the article by Zhang et al., with 108 citations [30], provides an extensive review of the nutritional value, functional properties, and pre- and post-harvest management strategies of microgreens, an emerging crop in modern controlled-environment agriculture. The study highlights that these tender sprouts concentrate high amounts of vitamins (such as vitamin C), trace minerals (copper, zinc, selenium), and bioactive phytochemicals (carotenoids, phenolics), often exhibiting higher antioxidant capacity than their mature counterparts.

In the current context, where sustainability and energy efficiency have become fundamental pillars for agricultural development, numerous review studies have systematically addressed technological advances in controlled environments. These articles provide a detailed overview of the latest strategies, tools, and models designed to maximize plant productivity while optimizing resource use [31], [32], [33], [34], [35], [36], [37].

3.2. Country Analysis

The analysis of scientific output by country, based on the data presented in Table II, reveals an uneven geographical distribution in research on control techniques during the period 2004–2024. The United States leads scientific production with 339 publications, representing 40.5% of the total, and has accumulated 5,998 citations, which accounts for 46.73% of the total research impact. This predominance reflects the significant investment in agronomic research and the adoption of advanced technologies, such as controlled environment agriculture and its relationship with essential oil quality [38].

Table II. Scientific Production and Impact by Country

Country	Production		Citation		Quality			
	Count	%	Count	%	Q1	Q2	Q3	Q4
Usa	339	40.5	5998	46.73	119	37	33	18
Canada	42	5.02	589	4.59	17	5	3	1
India	38	4.54	460	3.58	6	2	2	3
Germany	37	4.42	417	3.25	21	6	1	1
China	36	4.3	343	2.67	20	7	5	1
Italy	31	3.7	341	2.66	19	0	3	1
United Kingdom	30	3.58	335	2.61	21	2	0	2
Korea	17	2.03	70	0.55	12	2	1	0
Japan	16	1.91	378	2.94	2	1	4	1
Netherlands	15	1.79	451	3.51	10	1	0	3

Other notable countries include Canada, with 42 publications (5.02%) and 589 citations (4.59%), and India, with 38 publications (4.54%) and 460 citations (3.58%). India's contribution correlates with its high plant biodiversity and the interest in controlling environmental variables in agricultural settings, which drives research focused on botanical extracts and sustainable methods [39]. Germany and China also contribute significantly, with 37 and 36 publications respectively, standing out in high-impact (Q1) journals, with 21 and 20 articles in this category, respectively.

Italy, with 31 publications (3.7%) and 341 citations (2.66%), is notable for its focus on intensive cultivation techniques and the controlled release of compounds [40]. Meanwhile, countries such as the United Kingdom, South Korea, Japan, and the Netherlands show lower publication counts (ranging between 15 and 30 publications) but maintain notable impact, particularly Japan with 378 citations (2.94%) and the Netherlands with 451 citations (3.51%).

The quality of publications, measured by quartile distribution, indicates that the United States, Germany, and the United Kingdom concentrate the majority of their articles in Q1 journals, reflecting high academic relevance. In contrast, countries like India exhibit a more diverse distribution across quartiles, indicating a mix of high-impact research and more localized studies.

Furthermore, recent studies confirm that China and India have notably increased their scientific output on biological control techniques and precision agriculture over the past five years. Additionally, Brazil has emerged as a relevant actor in essential oil research, particularly within the context of Amazonian biodiversity and organic agriculture [41], [42].

International collaboration remains a key factor in advancing research. European countries, particularly Germany, Italy, and the Netherlands, lead collaborative networks with Asia and the Americas, facilitating the transfer of technology and knowledge related to sustainable control techniques [43] (see Figure 3).

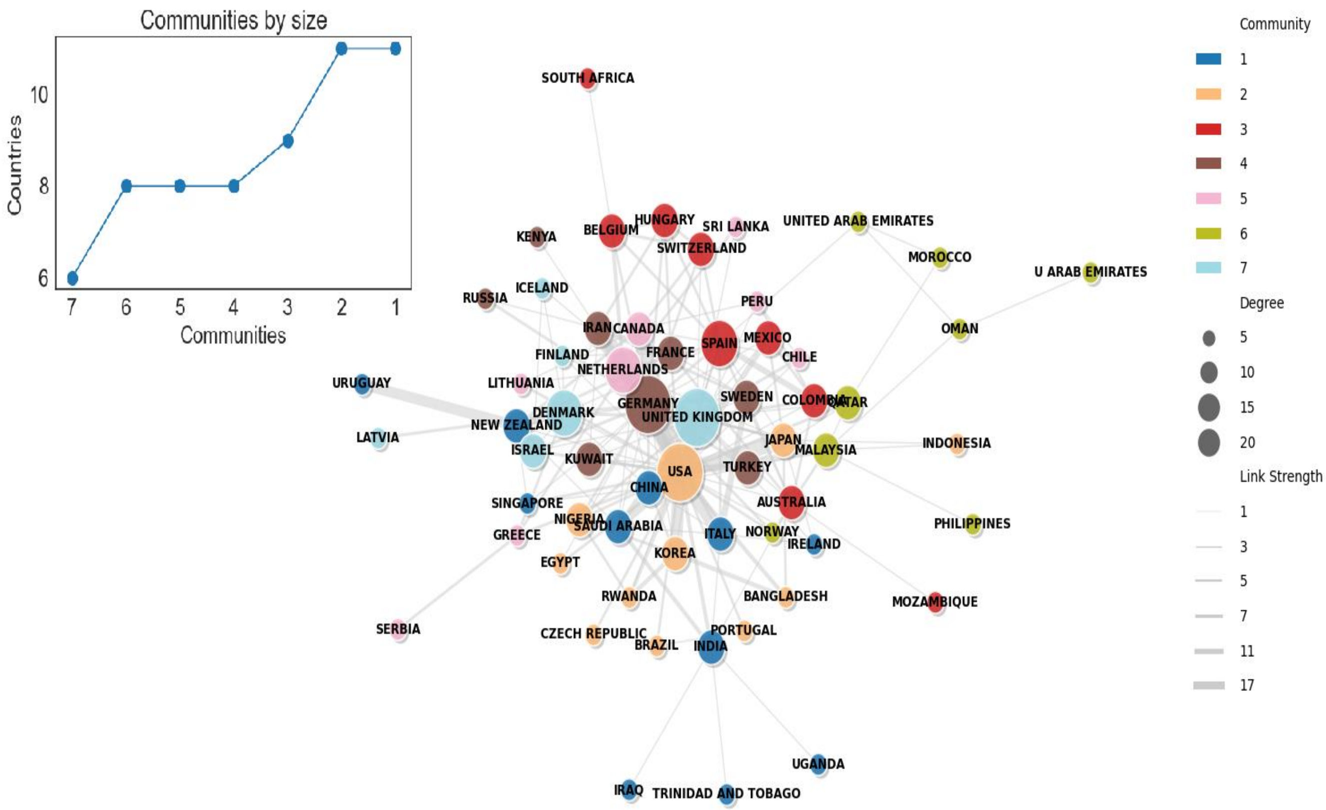

Figure 3. Collaboration Network Among Countries

3.3. Journal Analysis

The analysis of journals publishing research on control techniques in agriculture, presented in Table III, reveals the main platforms for scientific dissemination in this field during the period 2004–2024. The table includes metrics such as the number of articles published in the WoS and Scopus, the h-index of the journals, and their quartile classification, allowing for an evaluation of their impact and academic relevance. Frontiers in Plant Science stands out with 41 articles indexed in both WoS and Scopus and an h-index of 246, positioning it in the Q1 quartile, which reflects its significant influence in agronomic research. It is followed by Horticulturae, with 36 articles in WoS and 35 in Scopus, also classified in Q1, with an h-index of 48, indicating its growing relevance in studies on specialized crops. HortScience, with 50 articles in WoS and 36 in Scopus, has an h-index of 109 and is classified in Q2, consolidating itself as a key platform for applied research in the field.

Table III. Scientific Production and Impact by Journal

Journal	Wos	Scopus	h-index	Quartile
Acta Horticulturae	0	78	74	Q4
Hortscience	50	36	109	Q2
Frontiers In Plant Science	41	41	246	Q1
Horticulturae	36	35	48	Q1
Plants	0	19	116	Q1
Sustainability (Switzerland)	0	18	207	Q1
Horttechnology	16	17	68	Q2
Agronomy	0	16	114	Q1
Journal Of Cleaner Production	13	13	354	Q1
Frontiers In Sustainable Food Systems	12	12	70	Q1

Other notable journals include Sustainability (Switzerland) and Agronomy, both classified in Q1, with 18 and 16 articles in Scopus, respectively, and high h-indices (207 and 114), reflecting their focus on sustainable practices. The Journal of Cleaner Production, with 13 articles in both databases and an h-index of 354 (Q1), stands out for its emphasis on clean technologies applied to agriculture. On the other hand, Acta Horticulturae, with 78 articles in Scopus but none in WoS, is positioned in Q4 with an h-index of 74, suggesting a focus on more specific or regional research.

The analysis of journals reveals a clear preference for publications in Q1, which account for 60% of the articles, reflecting the high quality of scientific output in this field. This distribution highlights the importance of interdisciplinary and high-impact platforms for disseminating advances in control techniques, such as the use of biostimulants as insecticides, repellents, fungicides, and antifeedants within sustainable agriculture and precision technologies [44].

3.4. Author Analysis

Analyzing scientific collaboration networks enables the identification of networking methods employed by the most influential researchers in the field of crop control for essential oil production. Additionally, it allows for the assessment of each author's impact through their scientific output, network structure, and the diversity within their collaboration networks.

Table IV presents the ten most productive researchers between 2004 and 2024, considering indicators such as the total number of publications, citations, h-index, and network metrics, including effective size, constraint, and the Collaborative Diversity Index (CDI). In terms of scientific output, the authors Giacomelli, Kubota, and Van rank in the top three, respectively. However, this does not necessarily indicate that they are the most impactful authors. For example, Gruda, with 13 publications, has accumulated 332 citations and an h-index of 7, while Lopez, with 12 publications, has 305 citations and also an h-index of 7. These two authors, therefore, demonstrate significant influence within the field.

Table IV. Top 10 Most Outstanding Authors

Author	Papers Total	Total Citations	H-Index	Effective_Size	Constraint	CDI
Giacomelli G	15	110	5	42.31	0.08	0.13
Kubota C	15	213	6	162.89	0.02	0.12
Van I M	15	193	7	3.5	0.41	0.67
Aliniaeifard S	14	121	5	141.39	0.03	0.12
Kacira M	14	69	5	102.19	0.03	0.1
Ferrarezi R	13	70	4	1.0	0.65	0.2
Gruda N	13	332	7	49.67	0.06	0.19
Li Y	13	41	4	481.28	0.01	0.05
Lopez R	12	305	7	49.63	0.06	0.12
Mattson N	11	146	6	28.0	0.08	0.33

These patterns are further supported by the collaborative diversity index, with the highest values observed for Van (0.67), Mattson (0.33), and Ferraresi (0.20). This suggests that their academic networks may exhibit greater collaborator variety. However, in Van's case, this value does not entirely align with his effective network size (3.5) and high constraint score

(0.41), which indicates a more closed and redundant network. In contrast, Mattson and Ferraresi display a better balance between network diversity and connections to less redundant groups, allowing them to benefit from more varied and independent collaborations. This dynamic fosters diversity in scientific production, ultimately contributing to the development of new technologies.

Overall, the results demonstrate that scientific contribution in the field of crop control for essential oil production is not solely determined by the number of publications, but also by the relevance and influence of the research, as well as the extent to which researchers engage with more diverse academic networks. This analysis reveals the existence of distinct academic profiles within the field: some are more focused on research output, others on academic influence, and others on building more open and diverse collaborative networks. This diversity of profiles enriches the research landscape, particularly in areas related to agricultural sustainability and the advancement of innovative technologies.

Conclusions

The present scientometric analysis revealed a sustained growth in scientific production related to CEA between 2004 and 2024. This growth has been accompanied by an increase in the quality and diversity of research, driven primarily by countries such as the United States, Germany, China, and India. The implementation of environmental control technologies, including LED lighting, nutrient sensors, and automation systems, has been among the most recurrent and highly cited topics, demonstrating the current relevance of technological innovation within the agricultural sector.

The results also highlight the consolidation of high-impact scientific journals, such as Frontiers in Plant Science and Horticulturae, as well as the strategic role of specific authors and institutions that lead global collaboration networks. Additionally, patterns were identified linking the development of CEA with the growing interest in specialized crops, including those used for the extraction of essential oils, although this relationship has not yet been widely explored in the literature.

Finally, it is concluded that controlled environment agriculture represents a research field with significant potential to address global challenges such as climate change, food security, and the sustainable use of resources. In this regard, future research could focus more specifically on studying the synergy between CEA and the production of high value-added products, such as secondary metabolites, essential oils, and bioactive compounds, considering both technical aspects and their economic and environmental impacts.

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