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COMPUTATIONAL FLUID DYNAMICS APPLICATIONS IN VERTICAL AND INDOOR FARMING: A BIBLIOMETRIC REVIEW OF MICROCLIMATE AND VENTILATION STUDIES

Edwin Villagran*[1], John Espita[2], Jorge Flores-Velasquez[3], Cruz Ernesto Aguilar[4], Jader Rodriguez[5]

[1, 2, 5]Corporación Colombiana de Investigación Agropecuaria—Agrosavia, Centro de Investigación Tibaitata, Km 14, vía Mosquera-Bogotá, Mosquera 250040, Colombia.
[3]Colegio de Postgraduados Campus Montecillos, Carretera Mexico Texcoco, Km. 36.52, Texcoco 56230, Mexico.
[4]Tecnologico Nacional de Mexico/ITS de los Reyes, Carretera Los Reyes-Jacona, Col. Libertad, Los Reyes de Salgado 60300, Mexico.

[1]https://orcid.org/0000-0003-1860-5932, [2]https://orcid.org/0000-0003-2684-655X, [3]https://orcid.org/0000-0003-0895-4645, [4]https://orcid.org/0000-0001-5120-022X, [5]https://orcid.org/0000-0002-5346-092X

Email: *evillagran@agrosavia.co, jjespitia@agrosavia.co, jorgelv@colpos.mx, ernesto.ar@losreyes.tecnm.mx, jrodriguezc@agrosavia.co

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ABSTRACT

Vertical and indoor farming have emerged as sustainable alternatives to address challenges associated with population growth, urbanization, and food security. In this context, computational fluid dynamics (CFD) has become a key tool for analyzing and optimizing microclimate conditions, ventilation, and air distribution in controlled environment agriculture (CEA) systems. This study aims to systematically characterize the scientific production related to the application of CFD in vertical and indoor farming through a bibliometric approach. Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, 52 documents indexed in Scopus and published between 2015 and 2025 were analyzed. The results reveal sustained growth in the field, with a high degree of geographic and editorial concentration, as well as an intellectual structure dominated by a limited core of authors, institutions, and journals. Network and keyword analyses indicate a thematic evolution from studies primarily focused on airflow toward more integrated approaches that incorporate energy efficiency and microclimate optimization. These findings enable the identification of research trends, knowledge gaps, and future opportunities, particularly for the development of CFD-based solutions applicable to low-cost indoor farming systems.

I. INTRODUCTION

Currently, agricultural production faces increasing challenges associated with global population growth, accelerated urbanization, climate variability, mounting pressure on natural resources, and the need to ensure food security [1]. In this context, controlled environment agriculture, particularly plant factories with artificial lighting (PFAL) and vertical farming systems, has emerged as a viable technological alternative for sustainably intensifying plant production [2]. These systems enable precise control of key environmental variables, such as temperature, humidity, and light intensity, regardless of external climatic conditions, allowing for year-round production and the cultivation of high-quality crops [3].

Within PFAL systems, air movement plays a decisive role in shaping the microclimate, particularly within and around dense plant canopies, where convective heat and mass transfer processes govern leaf temperature, relative humidity, and carbon dioxide concentration [4], [5]. Insufficient airflow can promote the formation of vertical thermal gradients associated with artificial lighting and non-uniform gas distributions, thereby negatively affecting crop physiological performance [6]. Numerous studies have shown that an appropriate range of air velocity, typically between 0.1 and 1.3 m s^{-1}, can enhance plant photosynthesis and transpiration by increasing gas exchange and reducing the resistance of the leaf boundary layer [7].

However, the microclimate within PFAL systems is highly dynamic, resulting from the coupling of light, temperature, humidity, airflow, and carbon dioxide (CO_2) concentration, to which plants respond through physiological adaptation mechanisms [8]. Air stagnation within the plant canopy can generate heterogeneous microclimates, reduce crop quality, and induce physiological disorders such as tip burn in young leaves [9]. In addition, the increasing use of light-emitting diodes (LEDs), whose energy and spectral efficiency has transformed agricultural lighting, introduces additional thermal loads that must be effectively dissipated to prevent disturbances to the microclimate [10]. Although previous research has examined airflow in PFAL systems, studies that simultaneously integrate the aerodynamic obstruction of the plant canopy and the thermal dissipation of LED lighting systems remain relatively scarce [9].

In this context CFD has become a key tool for performing detailed analyses of the interactions among ventilation, heat transfer, and microclimate, thereby supporting the design and optimization of more efficient and resilient vertical and indoor farming systems. Different investigations have applied CFD simulations to optimize ventilation system design, ensuring suitable air velocities at plant surfaces and enhancing convective heat and mass exchange [11]. Subsequent studies have assessed thermo-fluid uniformity in vertical agricultural systems, proposing flow efficiency indicators to compare air supply and exhaust configurations, thereby demonstrating improvements in microclimatic conditions and reductions in energy consumption [12].

Complementarily, laboratory-scale experimental studies have examined the interaction between photosynthetic physiology and airflow, using measured data as boundary conditions to validate CFD models [13].Likewise, CFD-based studies have examined airflow and temperature distributions in plant factories housed within shipping containers, as well as the design of perforated air ducts to generate more homogeneous airflow patterns across cultivation tables [14], [15]. Nevertheless, many of these studies focus on partial components of the production system, whereas more comprehensive approaches have examined entire cultivation cells, comparing different ventilation configurations through uniformity indicators in order to optimize the microclimate in plant factories at a commercial scale [16].

In this context, bibliometric analysis emerges as an appropriate methodological tool to systematize, quantify, and visualize the evolution of scientific knowledge in an emerging and highly interdisciplinary field such as the application of computational fluid dynamics (CFD) in vertical and indoor farming. Beyond a traditional narrative review, bibliometrics enables the identification of patterns of scientific production, impact, and collaboration, as well as intellectual structures, thematic clusters, and research trends, thereby providing an objective and reproducible overview of the state of the art [17], [18]. This approach is particularly relevant in domains where the rapid expansion of the literature and the diversity of methodological approaches hinder the identification of dominant research lines, knowledge gaps, and future directions, which are essential for guiding both academic research and applied technological development [19].

Under this perspective, the main objective of this study is to systematically analyze the scientific production related to the application of CFD in vertical and indoor farming systems, using bibliometric techniques and network analysis to characterize its temporal evolution, geographical distribution, key actors, thematic structure, and research trajectories. In particular, this work seeks to address the following research questions: (i) how has scientific research on CFD applied to controlled environment agriculture been structured and evolved in terms of production, collaboration, and thematic approaches? and (ii) what are the main research lines, conceptual gaps, and emerging trends that can guide future studies aimed at the microclimatic, energy, and operational optimization of indoor cultivation systems? These questions guide the development of the analysis and enable the linkage of bibliometric findings with scientific and technological challenges relevant to the advancement of the field

II. METHODOLOGY

II.1 GENERAL APPROACH AND PRISMA FRAMEWORK

The present study adopts a bibliometric approach supported by the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, with the aim of ensuring a transparent, reproducible, and methodologically rigorous literature selection process [20]. Although this work does not constitute a traditional systematic review, the application of the PRISMA flow enabled a clear and well-documented structuring of the identification, screening, eligibility, and inclusion stages of the analyzed documents. This approach is particularly suitable for emerging and interdisciplinary research fields, such as the application of CFD in vertical and indoor farming systems, where thematic and methodological diversity necessitates a well-defined protocol to delimit the analytical corpus.

II.2 SOURCE OF INFORMATION AND SEARCH STRATEGY

The bibliographic search was conducted exclusively in the Scopus database, selected for its broad coverage of peer-reviewed scientific literature in engineering, agricultural sciences, numerical modeling, and controlled environment systems. Access to the database was carried out on January 1, 2026, ensuring the inclusion of the most recent records available at the time of analysis. The search strategy was designed to identify studies addressing the application of CFD-based simulations to the analysis of microclimate, ventilation, and air distribution in vertical farming, indoor agriculture, and plant factory systems. To this end, the search equation was structured around three main conceptual dimensions: (i) plant production systems under controlled environments. (ii) computational fluid dynamics and numerical simulation techniques, and (iii) microclimatic and ventilation-related variables.

The equation was applied to the title, abstract, and keyword fields (TITLE-ABS-KEY) and was formulated as follows: (("vertical farming" OR "indoor farming" OR "indoor agriculture" OR "plant factory" OR "plant factories" OR "plant factory with artificial lighting" OR PFAL OR "controlled environment agriculture" OR "indoor plant production" OR "indoor horticulture") AND ("computational fluid dynamics" OR CFD OR "CFD simulation" OR "fluid flow simulation" OR "airflow simulation" OR "air flow simulation" OR "heat transfer simulation" OR "numerical simulation" OR "3D simulation") AND (microclimate OR "air distribution" OR "temperature distribution" OR "humidity distribution" OR "CO_2 distribution" OR ventilation OR "ventilation design" OR "indoor climate" OR "thermal environment")). No restrictions were applied with respect to country, geographic region, or language, to obtain a comprehensive and global overview of the scientific development of the field and to avoid biases arising from territorial or linguistic limitations.

II.3 INCLUSION AND EXCLUSION CRITERIA

Clear inclusion and exclusion criteria were established to ensure the thematic coherence and methodological relevance of the selected documents. The inclusion criteria comprised: scientific articles, review papers, and conference proceedings indexed in Scopus; studies employing computational fluid dynamics (CFD) as the primary analytical tool; research focused on vertical farming, indoor agriculture, plant factories, or controlled environment agriculture; and publications without restrictions on language or country of institutional affiliation. Conversely, the exclusion criteria included: documents that did not use CFD as a central methodology; experimental or conceptual studies lacking numerical simulation; duplicate records or entries with incomplete bibliographic metadata; and publications not directly related to microclimate, ventilation, air distribution, or thermal behavior in indoor agricultural systems

II.4 PRISMA-BASED SELECTION PROCESS

The document selection process followed the stages established by the PRISMA framework (Figure 1). During the identification phase, the application of the search equation in Scopus yielded an initial total of 64 records. Following a preliminary screening of titles and abstracts, 4 documents were excluded as they did not correspond to studies based on CFD modeling. Subsequently, during the screening and eligibility phases, a more detailed evaluation of the full texts was conducted, leading to the exclusion of an additional 8 publications due to thematic inconsistencies or the absence of an explicit focus on vertical or indoor farming. As an outcome, a definitive corpus of 52 documents was consolidated, all of which fully met the established methodological and conceptual criteria and constituted the basis for the bibliometric analysis developed in this study.

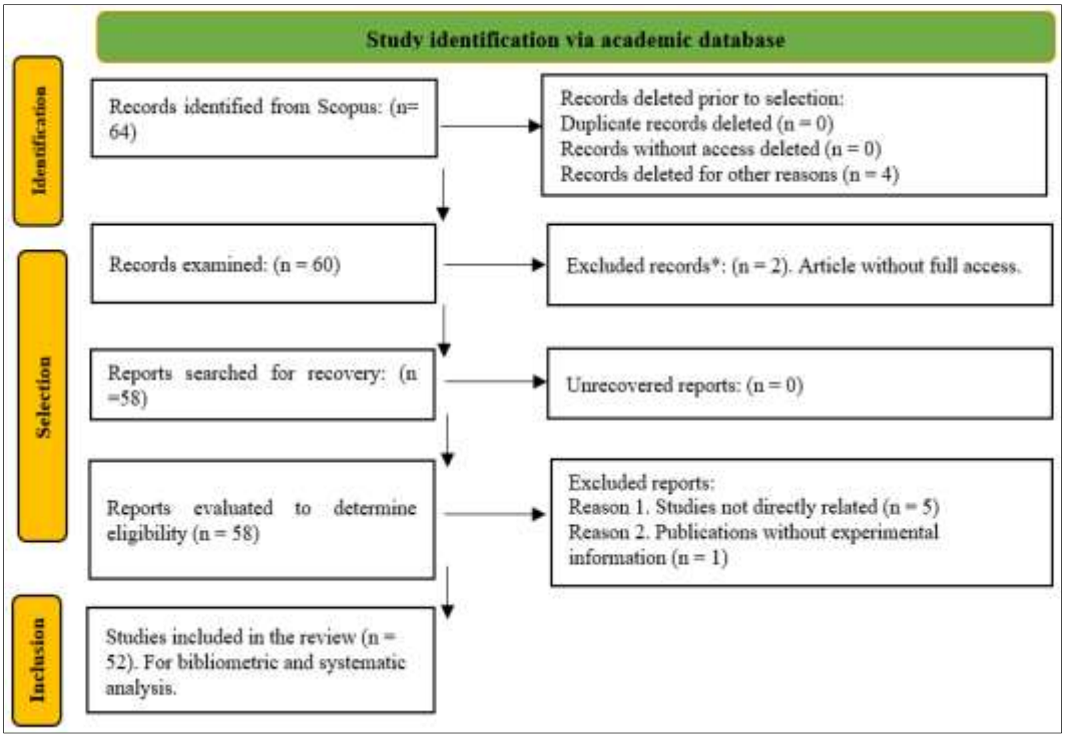

Figure 1: Development approach of the bibliometric review.
Source: Authors, (2026).

II.5 BIBLIOMETRIC PROCESSING AND ANALYTICAL TOOLS AND METHODOLOGICAL RESULT

The final records were exported from Scopus in CSV format and processed through a bibliometric analysis workflow supported by specialized tools. The main processing was conducted using the Bibliometrix package within the R environment and its graphical interface Biblioshiny, which enabled the calculation of indicators related to scientific production, impact, collaboration, and the intellectual structure of the field. Additionally, VOSviewer was employed for the construction and visualization of co-authorship, keyword co-occurrence, and bibliographic coupling networks, as well as for the identification of thematic clusters. The integration of the PRISMA flow with advanced bibliometric tools and network analysis enabled a rigorous structuring and examination of the scientific corpus on the application CFD in vertical and indoor farming.

This approach made it possible not only to quantify the evolution and distribution of scientific production, but also to reveal the intellectual structure of the field by identifying countries, institutions, and authors with central roles, as well as patterns of collaboration and bibliographic coupling. Complementarily, co-occurrence and multiple correspondence analyses allowed the delineation of coherent thematic clusters and dominant conceptual axes, highlighting the convergence between fluid dynamic modeling, microclimate control, energy efficiency, and crop response. Overall, the applied methodology provides an integrated and hierarchical overview of the state of the art and establishes a solid foundation for future comparative research and for the development of studies aimed at the microclimatic, energy, and operational optimization of controlled environment agriculture systems through CFD.

III. RESULTS AND DISCUSSION

III.1 BIBLIOMETRIC PROCESSING AND ANALYTICAL TOOLS AND METHODOLOGICAL RESULT

Write in detail the research project, including background and limitations. The selection of materials and methods, procedures and equipment must be justified so that the work can be reproduced. Modifications or new methods must be described in detail. You must clearly define the universe and specify how the sample was selected and why it is representative. Data processing represents the practical development of a theoretical basis, deriving the model equations to program the calculation algorithm, according to the need. In materials, they include the technical specifications and the quantities, the origin and, if necessary, the method for its elaboration.

III.2 OVERVIEW

The bibliometric analysis focused on the period from 2015 to 2025, during which 52 scientific documents published across 30 different sources were identified, confirming that the application of computational fluid dynamics (CFD) in vertical and indoor farming is a relatively recent field undergoing rapid consolidation. Scientific production exhibits an annual growth rate of 6.5%, indicating a significant increase in academic interest over the past decade. A total of 198 authors contributed to the analyzed literature, with no single-authored publications, highlighting the highly collaborative and multidisciplinary nature of this research area, with an average of 8.62 co-authors per document. However, international collaboration remains limited (13.46%), suggesting opportunities to strengthen global research networks. The analyzed literature shows an average age of 3.5 years, reflecting a recent and active scientific base, while academic impact is moderate, with an average of 9.64 citations per document. Finally, the presence of 170 author keywords and 373 cited references indicate considerable thematic diversity and a field that is still in the process of conceptual structuring.

III.3 NUMBER OF DOCUMENTS PUBLISHED

The annual evolution of scientific production between 2015 and 2025 shows a clearly increasing trend in research related to the application of computational fluid dynamics (CFD) in vertical and indoor farming (Figure 2). During the initial years of the analyzed period (2015–2017), production was incipient, with only one to two documents published per year, reflecting the emerging nature of the field. From 2018 onward, a gradual increase can be observed, reaching a first notable milestone in 2019 with five publications, followed by a temporary decline in 2020, possibly attributable to global disruptions in scientific activity. Nevertheless, from 2021 onward, scientific output recovered and has since maintained a sustained upward trajectory. This trend intensifies markedly in the most recent years of the period, with 7 documents published in 2023, 10 in 2024, and a peak of 15 publications in 2025, confirming a recent acceleration of academic interest in this topic. The linear regression fit ($y = 1.123x - 2263.35$) and its coefficient of determination ($R^2 = 0.719$) indicate that a substantial proportion of the variability in scientific output can be explained by the temporal factor, evidencing a structured rather than random growth pattern. Taken together, these results suggest that the application of CFD in vertical and indoor farming systems has progressed from an exploratory phase to a stage of consolidation and expansion, positioning itself as a relevant research axis within controlled environment agriculture.

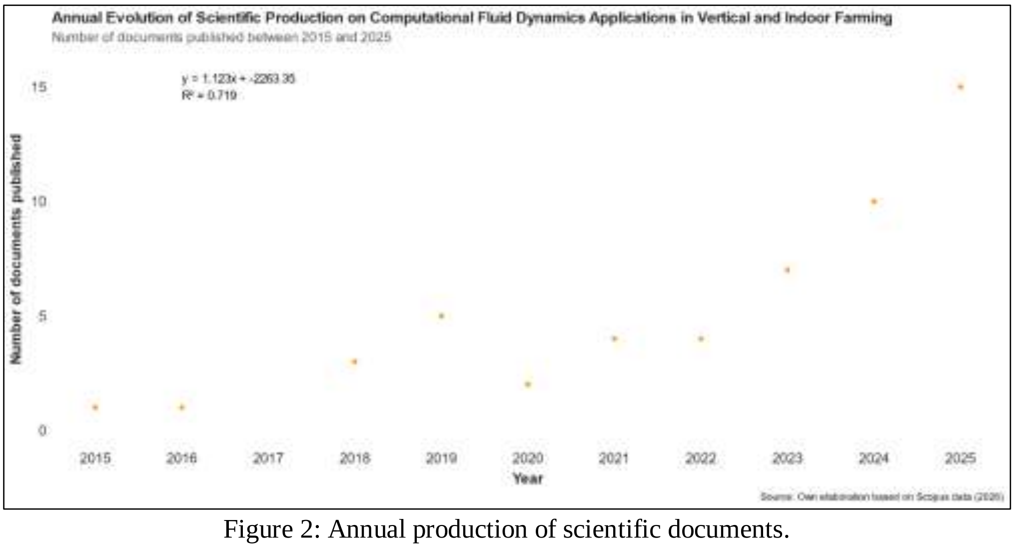

Figure 2: Annual production of scientific documents.
Source: Authors, (2026).

III.4 TYPES OF DOCUMENTS PUBLISHED

The distribution of documents by type for the period 2015–2025 (Figure 3) shows a clear predominance of scientific articles, with 35 publications, confirming that research on computational fluid dynamics (CFD) applications in vertical and indoor farming is primarily disseminated through indexed journals, reflecting an increasing level of academic maturity and validation [18]. Conference papers constitute the second most frequent document type, with 12 publications, indicating that the field maintains an active component of discussion in scientific forums and specialized conferences. In contrast, review articles (3), as well as conference reviews (1) and book chapters (1), represent a relatively small proportion, suggesting that the field is still in a phase of conceptual consolidation, with clear opportunities for the development of synthesis studies and integrative reviews in the future.

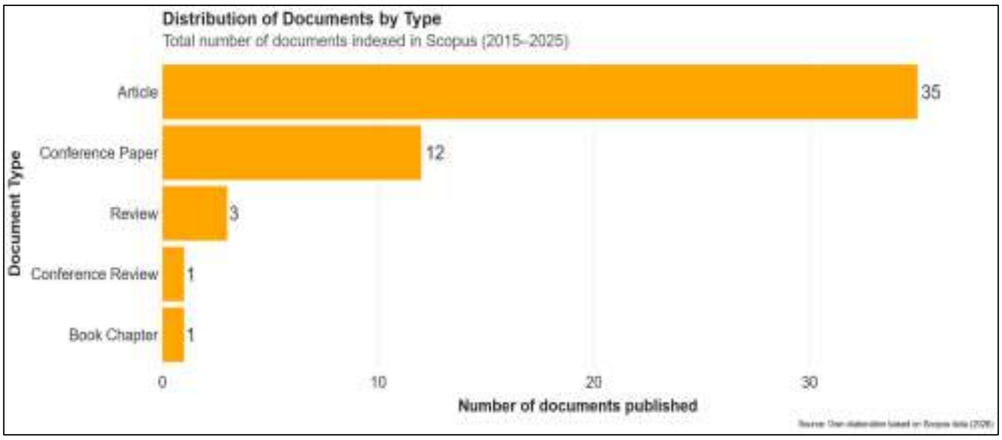

Figure 3: Types of documents published around knowledge analyzed.
Source: Authors, (2026).

III.5 COUNTRIES WHERE SCIENTIFIC PRODUCTION ORIGINATES

The geographic distribution of scientific production reveals a clear concentration of knowledge in a limited number of countries, a pattern that is characteristic of emerging and highly specialized technological fields such as the application of computational fluid dynamics (CFD) in vertical and indoor farming (Figure 4). China emerges as the leading global contributor, with 16 documents, significantly surpassing the other countries analyzed. This leadership suggests strong national investment in controlled environment agriculture, numerical modeling, and the optimization of production systems, as well as a strategic alignment with food security and technological development policies [21]. At a second level, the United States (5 documents) and several European countries such as the Netherlands and Belgium (4 documents each) stand out, which have historically been leaders in agricultural innovation, environmental engineering, and intensive cultivation technologies [8].

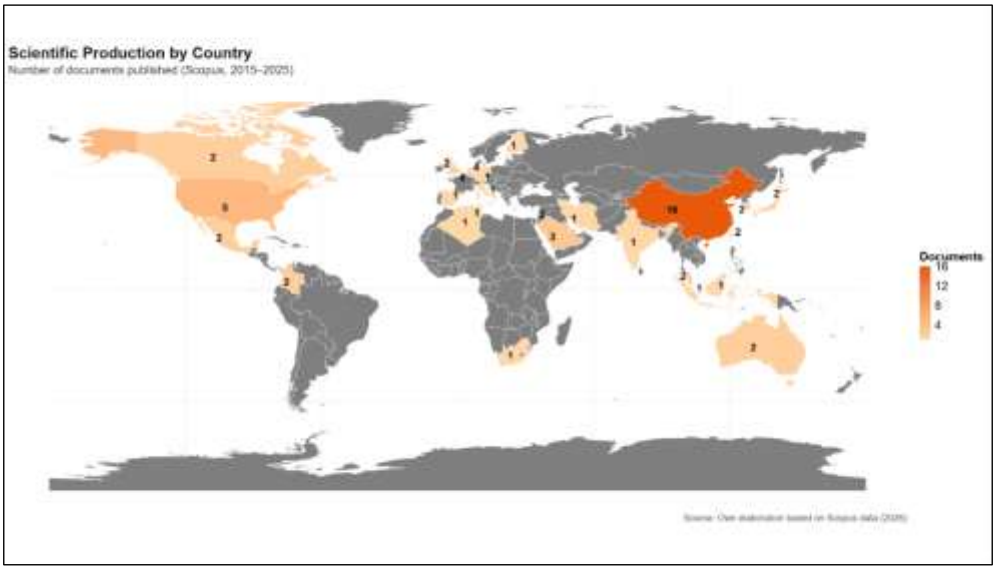

Figure 4: Document production by country.
Source: Authors, (2026).

At a regional scale, Europe and Asia account for most of the scientific production, with notable contributions from countries characterized by technologically advanced agricultural systems and a strong tradition in applied research, such as the United Kingdom, Germany, Italy, Finland, and Spain, albeit with more modest individual outputs. In Asia, beyond China, a distributed participation is observed among Japan, South Korea, Taiwan, India, Indonesia, and Malaysia, reflecting a growing interest in technological solutions for food production in highly urbanized and densely populated contexts [22]. Likewise, the presence of Middle Eastern countries such as Saudi Arabia, Israel, and Iran indicates that vertical farming and microclimate control through CFD are perceived as key tools for addressing adverse climatic conditions and water scarcity, as these controlled systems can mitigate the impacts of climate variability and resource limitations, directly contributing to food security through sustainable production in urban and arid environments [23].

On the other hand, participation from Latin America and Africa remains limited, with isolated contributions from countries such as Mexico, Colombia, Canada, Australia, Algeria, Tunisia, and South Africa, generally with one or two documents per country. This distribution suggests the existence of regional gaps in research capacity, computational infrastructure, and funding, while also indicating a significant potential for future expansion [24]. Overall, the figure highlights a highly centralized global structure dominated by countries with strong economies and well-established scientific ecosystems, while simultaneously underscoring the need to foster international collaboration and knowledge transfer to balance the development of the field on a global scale.

III.6 BIBLIOGRAPHIC COUPLING NETWORK BETWEEN COUNTRIES

Bibliographic coupling is a bibliometric technique used to analyze the cognitive structure of a scientific field based on the references shared among documents, authors, or countries (Figure 5). Two nodes are bibliographically coupled when they cite one or more references in common, indicating thematic or methodological affinity, regardless of whether they directly cite each other [25], [26]. In this type of network, nodes represent units of analysis (in this case, countries), while links indicate the existence of shared references, and their thickness reflects the strength of the relationship. Total link strength quantifies the intensity of a node's connections with the rest of the network, allowing the identification of central and peripheral actors within the scientific system [18]. Bibliographic coupling is particularly useful for analyzing emerging fields, as it captures early structural relationships within the body of knowledge and has been widely validated in bibliometric studies.

From an analytical perspective, the network exhibits a clearly centralized structure, with China as the dominant node, showing the highest total link strength (100) and many documents (16) and citations (112). This indicates that Chinese scientific output is not only quantitatively significant but also shares a strong bibliographic foundation with multiple countries, positioning China as a structuring hub of the field. Alongside China, the Netherlands (total link strength = 79) and the United States (64) stand out; despite producing fewer documents, they display a high degree of intellectual integration, likely associated with their longstanding leadership in controlled environment agriculture, thermal engineering, and numerical modeling. The density of links among these countries suggests the existence of convergent research lines, particularly in ventilation, microclimate analysis, and the optimization of indoor systems.

Conversely, the network also reveals countries with low publication output but strategically strong connections, such as Colombia, Mexico, and the United Kingdom, each with only two documents yet a relatively high link strength (40), indicating strong thematic alignment with the main research cores of the field. In contrast, countries such as Saudi Arabia and Taiwan show very low link strength values, reflecting more isolated scientific production or weaker bibliographic convergence with the rest of the network. Overall, these results suggest that although the field is experiencing growing geographical expansion, its intellectual structure remains dominated by a limited number of highly interconnected countries, reinforcing the need to promote more balanced international collaborations to diversify perspectives, contexts, and applications of computational fluid dynamics in vertical and indoor farming.

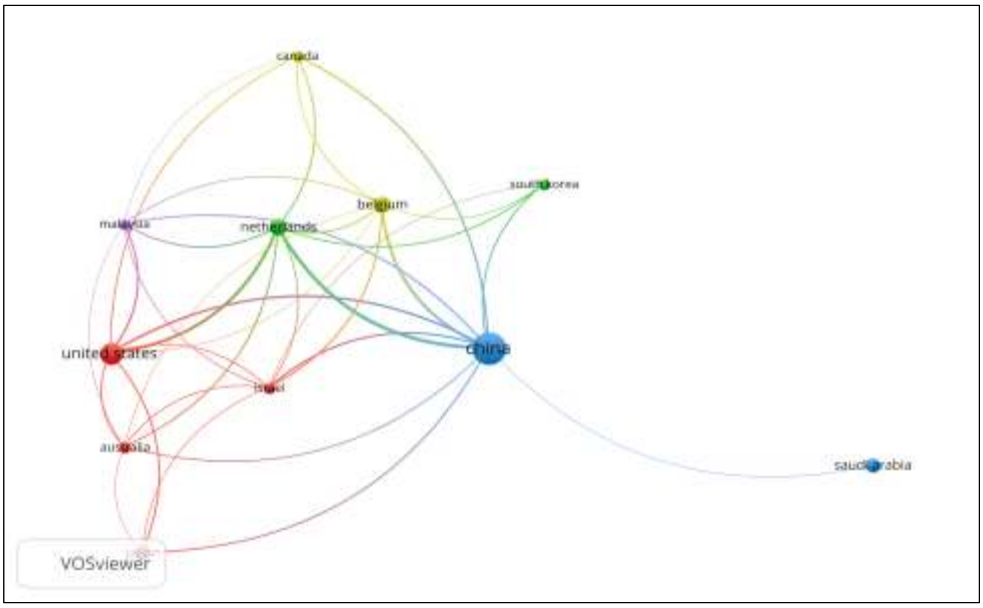

Figure 5: Bibliographic coupling network between the countries of authorship of academic documents.
Source: Authors, (2026).

III.7 LEADING INSTITUTIONS IN SCIENTIFIC PRODUCTION

The distribution of scientific output by institutions shows a moderate concentration of academic leadership within a limited number of organizations, which is consistent with the highly specialized and technical nature of research on the application of computational fluid dynamics (CFD) in vertical and indoor agriculture (Table 1). The University of Arizona emerges as the most productive institution, with five published documents, reflecting its prominent role in research on microclimate analysis, environmental engineering, and the modeling of controlled environment agricultural systems [11], [27]. They are followed by the Chinese Academy of Agricultural Sciences, Technische Universiteit Eindhoven, and Ghent University, each with four publications, indicating a strong contribution from both academic institutions and national research centers to the methodological development and applied use of CFD in this domain [28–30].

Likewise, the presence of the Ministry of Agriculture and Rural Affairs of the People's Republic of China, with three documents, is particularly noteworthy, as it highlights the direct involvement of governmental bodies in the generation of scientific knowledge. This participation suggests a strategic orientation toward technology transfer and the formulation of public policies grounded in scientific evidence [15]. Overall, this institutional pattern indicates that progress in the field is driven both by universities with strong capabilities in engineering and agricultural sciences and by public entities with coordination and funding capacity, fostering an integrated approach that links fundamental research with practical application. Nevertheless, the limited institutional dispersion also points to opportunities to broaden the range of participating actors and to promote greater institutional diversification in future research efforts.

Table 1: Leading institutions in academic production.

Institution	Number of documents published	Website
The University of Arizona	5	https://www.arizona.edu/
Chinese Academy of Agricultural Sciences	4	https://www.caas.cn/en/
Technische Universiteit Eindhoven	4	https://www.tue.nl/en/
Universiteit Gent	4	https://www.ugent.be/
Ministry of Agriculture and Rural Affairs, PRC	3	https://english.moa.gov.cn/

Source: Authors, (2026).

III.8 LEADING AUTHORS IN SCIENTIFIC PUBLICATIONS

The analysis of the most influential authors reveals a consolidated core of researchers and professor-researchers who have made substantial contributions to the advancement of knowledge on the application of Computational Fluid Dynamics (CFD) in vertical and indoor farming (Table 2). Among them, Murat Kaçira and T. van Hooff, both holding professor-researcher positions, stand out for their high scientific impact, with 3,300 and 5,163 citations and h-indices of 32 and 35, respectively, evidencing a sustained and cross-cutting influence within the field. In contrast, Hui Fang, Luyang Kang, and Wito Plas, identified primarily as researchers, exhibit a consistent and specialized scientific output, with a stronger focus on specific aspects of microclimate, ventilation, and plant–airflow interactions. This diversity reflects different level]s of academic maturity and scientific positioning, while collectively shaping the intellectual foundation of the domain.

Table 2: Top five authors with the highest scientific productivity in the subject area analyzed.

Author	Number of documents	Total citations	H-index	Affiliation	Country
Fang, Hui	5	815	18	Chinese Academy of Agricultural Sciences	China
Kaçira, Murat	5	3,300	32	The University of Arizona	United States
Kang, Luyang	4	612	12	Technische Universiteit Eindhoven	China
Plas, Wito	4	10	2	Ghent University	Belgium
Van Hooff, T	4	5,163	35	Technische Universiteit Eindhoven	Netherlands

Source: Authors, (2026).

From a thematic perspective, Hui Fang's research focuses on a detailed analysis of airflow within the plant canopy, incorporating advanced elements such as the aerodynamic resistance of the crop and the thermal dissipation associated with LED lighting systems. This approach contributes to a more realistic representation of microclimatic conditions in plant factories, enabling a better understanding of air–plant interactions and their implications for environmental uniformity and crop performance [15], [28]. Complementarily, Murat Kaçira's studies address environmental uniformity in multilayer systems by combining CFD simulations with the analysis of both computational and physical parameters. This integrated approach strengthens methodological validation and enhances the practical applicability of the models, supporting their use in the design and optimization of vertical and indoor farming systems [27], [31]. Along the same lines, Luyang Kang contributes research focused on optimizing the performance of air distribution systems, evaluating variables such as airflow rate and the use of baffles.

This work reflects a clear emphasis on efficient engineering design for vertical farming systems, with CFD used as a decision-support tool to enhance airflow uniformity and overall microclimatic control [29], [32]. Finally, the contributions of Wito Plas and T. van Hooff represent a significant advance in the sophistication of CFD models, particularly through the incorporation of realistic plant geometries and the detailed evaluation of air supply location in multi-layer systems. While Plas focuses on resolving the microclimate at the individual leaf scale [30], [33], Van Hooff contributes with studies of a more systemic scope, combining numerical accuracy with strong applied relevance [31], [34]. Taking together, this group of authors constitutes the intellectual backbone of the field, integrating experimental, numerical, and optimization-based approaches, and demonstrating a clear evolution from simplified models toward increasingly realistic representations aimed at improving environmental performance in controlled environment agriculture.

III.9 BIBLIOGRAPHIC COUPLING NETWORK BETWEEN AUTHORS

The bibliographic coupling network among authors is a bibliometric technique that makes it possible to identify intellectual affinities between researchers based on the shared references cited in their publications [35]. In this type of network, the nodes represent authors whose size is associated with their productivity or relative weight within the network, while the links indicate the existence of shared references, reflecting thematic or methodological similarities (Figure 6). The total link strength quantifies the intensity of these connections with other authors, and the overlay visualization incorporates a temporal dimension, in which node colors allow the analysis of the chronological evolution of scientific production and the emergence of more recent research lines [36]. From an analytical perspective, the network exhibits a clearly hierarchical structure, with Hui Fang, Murat Kaçira, Luyang Kang, and T.van Hooff as central nodes, characterized by high total link strength values (150, 128, 125, and 125, respectively).

This indicates a widely shared bibliographic base and a key role in the intellectual articulation of the field. Authors such as Wu Gang, Li Kun, and Cheng Ruifeng appear closely connected to Hui Fang, forming a cohesive sub core associated with recent studies on microclimate and ventilation in vertical farming systems. The temporal visualization further reveals a progressive evolution of the field, where authors with cooler tones (≈2020–2021), such as Kaçira, represent foundational contributions, while nodes in warmer tones (≈2023–2024), such as Plas, De Paepe, and Kang, reflect a recent expansion toward more advanced and realistic CFD models. Overall, the network confirms that knowledge development in this domain is supported by a consolidated core of highly interconnected authors, with a gradual transition from pioneering studies toward more sophisticated and specialized approaches in recent years.

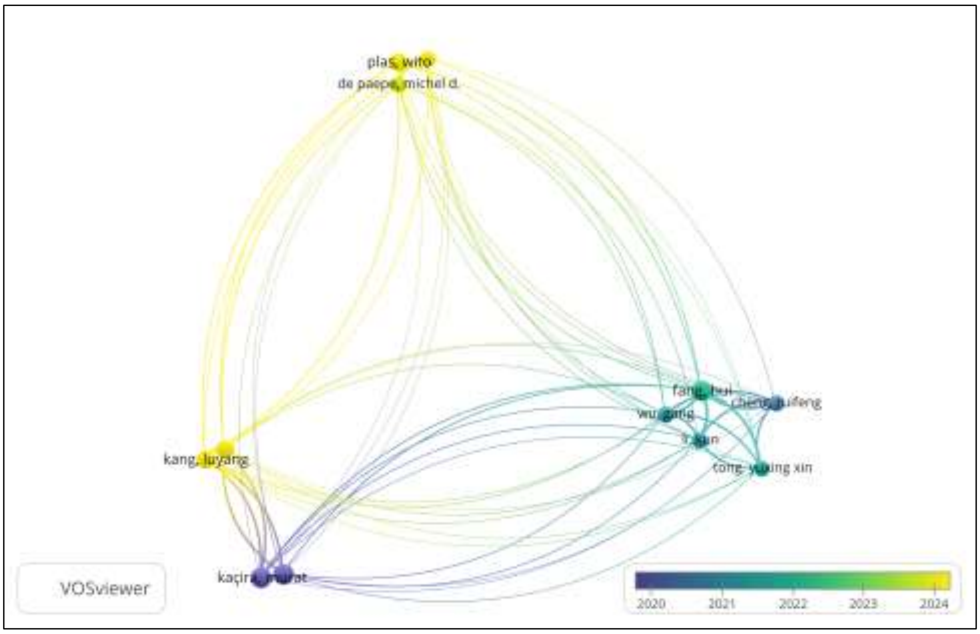

Figure 6: Bibliographic coupling network between the authors of published documents.
Source: Authors, (2026).

III.10 MAIN SOURCES OF PUBLICATION SELECTED BY THE AUTHORS

The distribution of scientific output by journals reveals a concentration in sources specialized in horticulture, biosystems engineering, and controlled environment agriculture, reflecting the interdisciplinary nature of applying computational fluid dynamics (CFD) to vertical and indoor farming (Table 3). *Acta Horticulturae* ranks as the journal with the highest number of publications (8 documents), serving as a relevant forum for disseminating applied studies and experimental results in protected horticulture, despite its Q4 classification. This quantitative leadership suggests that the field still relies on specialized proceedings and series as key outlets for reporting technical advances and case studies, particularly during phases of methodological development and validation.

In contrast, high-impact, top-quartile journals such as *Biosystems Engineering*, *Horticulturae*, *Agriculture*, and *Agronomy* (all classified as Q1) publish fewer documents but provide greater scientific visibility and methodological rigor. In particular, *Biosystems Engineering* stands out by combining a relevant volume of publications (5 documents) with a high h-index (142) and a strong focus on modeling, optimization, and analysis of complex agricultural systems, closely aligned with CFD-based approaches. The recurrent presence of MDPI journals, headquartered in Switzerland, also indicates a growing tendency toward open-access and rapid-dissemination platforms, which contributes to the international consolidation and expansion of the field. Overall, this editorial pattern suggests a gradual transition from specialized outlets toward higher-impact journals, reflecting the increasing maturity of research on CFD applications in vertical and indoor agriculture.

Table 3: Main journals selected for publication.

Journal	Number of documents	Editorial office	SJR Ranking	H-index	Country
Acta Horticulturae	8	International Society for Horticultural Science	Q4	74	Belgium
Biosystems Engineering	5	Academic Press	Q1	142	United States
Horticulturae	2	Multidisciplinary Digital Publishing Institute (MDPI)	Q1	48	Switzerland
Agriculture	2	Multidisciplinary Digital Publishing Institute (MDPI)	Q1	84	Switzerland
Agronomy	2	Multidisciplinary Digital Publishing Institute (MDPI)	Q1	114	Switzerland

Source: Authors, (2026).

On the other hand, the local impact of publication sources assesses the influence of journals within the specific corpus analyzed, based on bibliometric indicators such as the h-index, g-index, and m-index, together with the total number of citations (TC), the number of publications (NP), and the year in which each journal first contributed to the field (PY_start) (Table 4). In this context, the h-index reflects the balance between productivity and impact within the analyzed set, the g-index emphasizes the concentration of citations in the most influential articles, while the m-index enables comparisons among journals by accounting for the time elapsed since their initial contribution to the research area [37].

When considered jointly, these indicators make it possible to identify not only the most productive publication sources, but also those with greater intellectual relevance and more recent growth in research on CFD applied to vertical and indoor agriculture. From an analytical perspective, *Biosystems Engineering* clearly emerges as the publication source with the highest local impact, presenting the highest h-index (4), the highest g-index (5), and a substantial volume of total citations (251) since 2016. This confirms its role as a central and structuring journal within the field, particularly in studies focused on the modeling and optimization of agricultural systems. In contrast, *Acta Horticulturae*, although it records a higher number of publications (NP = 8), exhibits a more limited local impact in terms of citations, suggesting a role more oriented toward technical dissemination than toward the production of highly cited articles.

Conversely, journals such as *Agriculture* and *Horticulturae* display relatively high m-index values (0.667 and 0.5, respectively), despite their recent incorporation into the field (from 2023–2024 onward), indicating a rapid accumulation of impact and a growing interest in publishing CFD-related research in Q1 open-access platforms. Taken together, these results highlight a progressive transition of the field toward journals with higher impact and visibility, reflecting a process of scientific maturation and thematic consolidation

Table 4: Impact of journals publishing on the subject analyzed.

Journal	h_index	g_index	m_index	TC	NP	PY_start
Biosystems Engineering	4	5	0,364	251	5	2016
Acta Horticulturae	2	3	0,222	31	8	2018
Agriculture	2	2	0,667	17	2	2024
Horticulturae	2	2	0,5	25	2	2023
Agronomy	1	2	0,2	13	2	2022

Source: Authors, (2026).

III.11 BIBLIOGRAPHIC COUPLING NETWORK BETWEEN JOURNALS

The bibliographic coupling network (Figure 7) among journals makes it possible to identify intellectual affinities based on the references shared by articles published in different sources, revealing how knowledge is structured and disseminated within a specific scientific field [25]. In the analyzed network, the nodes represent scientific journals, whose size is associated with the number of documents or their relative weight within the corpus, while the links indicate the intensity of bibliographic coupling, measured through the total link strength. The overlay visualization also incorporates a temporal dimension, in which node colors reflect the average year of publication, allowing the analysis of the temporal evolution and chronological positioning of each journal within the development of research on CFD applied to vertical and indoor agriculture.

From an analytical perspective, the network highlights *Biosystems Engineering* as a central structural node, with high connectivity and strong links to horticultural and agricultural journals, confirming its role as a bridge between biosystems engineering and advanced agricultural applications. *Acta Horticulturae* appears closely connected to this core, although with an earlier coloration (≈2018–2019), suggesting a relevant role during the initial dissemination phase of the field, particularly for applied studies and specialized proceedings. In contrast, *Horticulturae*, *Agriculture*, and *Agronomy* exhibit more recent color tones (≈2022–2024) and clear connections to the central core, indicating the progressive incorporation of Q1 open-access journals, where the CFD approach is increasingly integrated into broader discussions on sustainability, intensive production, and controlled environment agriculture. Overall, the network reveals an editorial transition of the field from traditional specialized outlets toward higher-impact and more visible international journals, reflecting a process of scientific maturation and thematic consolidation.

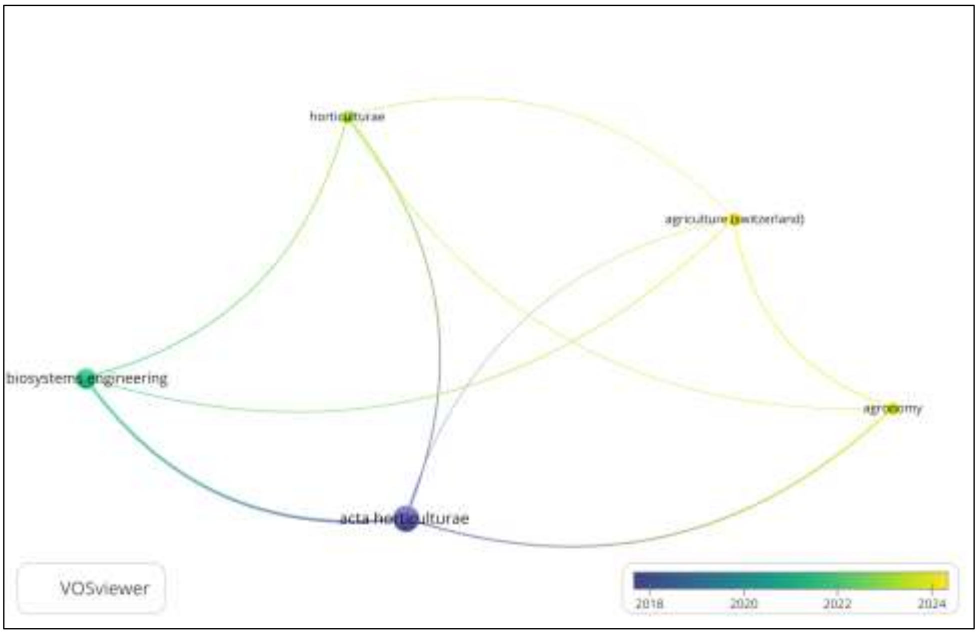

Figure 7: Network linking journals where academic documents are published.
Source: Authors, (2026).

III.12TOP FIVE MOST CITED ARTICLES

The identification of the five most cited articles on the application of Computational Fluid Dynamics (CFD) to vertical and indoor agriculture makes it possible to recognize the conceptual and methodological lines that have shaped the development of the field over the past decade. The clear predominance of publications in *Biosystems Engineering* (three out of the five articles) highlights the central role of this journal as an editorial hub for knowledge on the microclimatic modeling of controlled environment agricultural systems. Overall, these studies address a common challenge microclimate uniformity across different scales and contexts, consolidating CFD as a key tool for the design, evaluation, and optimization of indoor farming systems (Table 5).

The three most cited articles published in *Biosystems Engineering* show a progressive evolution in the complexity of CFD models and in the evaluation criteria employed. The work by Zhang et al. [11], with the highest number of citations (120), establishes a fundamental starting point by demonstrating that the design of the air circulation system can be optimized through three-dimensional simulations aimed at reducing flow variability and preventing physiological disorders in crops. Subsequent studies, such as that by Fang et al. [15] and Zhang & Kaçira [16], expand this approach by incorporating additional physical elements such as canopy aerodynamic resistance, LED thermal dissipation, and quantitative metrics of climate uniformity reflecting a transition from descriptive models toward predictive and comparative tools capable of evaluating multiple ventilation configurations based on objective indicators.

By [38], published in *Energy and Buildings*, introduces a relevant conceptual extension of the field by analyzing the effects of vertical farming beyond the production system itself, specifically on the natural ventilation of residential buildings. This study demonstrates that the incorporation of vertical vegetation can generate contrasting effects on urban thermal comfort, depending on the proportion and arrangement of vegetated modules. Its inclusion among the most cited works indicates that the use of CFD in vertical farming has begun to intersect with disciplines such as urban engineering and bioclimatic architecture, thereby expanding the traditional scope of the field.

For its part, the most recent work by the group of [39], published in *Applied Thermal Engineering*, represents a stage of methodological maturity characterized by the integration of thermo-fluid phenomena, moisture transport, and experimental validation in real multi-layer systems. Although its citation count is lower due to its recent publication, the study introduces dimensionless uniformity indices and an integrated approach that links microclimate, energy efficiency, and crop growth quality. This type of contribution points toward the use of CFD not only as an analytical tool, but also as direct support for operational and energy-related decision-making in vertical farming systems. From a comparative perspective, the five articles share the use of three-dimensional CFD as their core methodological approach, but they differ in terms of scale of analysis, variables considered, and final objectives.

While earlier studies primarily focus on airflow velocity distribution, more recent works incorporate thermo-hygrometric variables, statistical uniformity metrics, and experimental validation. This progression suggests that scientific impact is closely linked to the ability of studies to integrate physical realism, practical applicability, and comparable metrics, thereby enhancing their reuse as references in subsequent research. In summary, the analysis of the top five most cited articles confirms that research on CFD applied to vertical and indoor agriculture has evolved from approaches centered on localized airflow improvements toward more systemic and integrated models, with productive, energetic, and urban implications. These works have not only established the methodological foundations of the field but have also outlined its main future trajectories, in which microclimate optimization, energy efficiency, and interaction with the built environment emerge as priority research axes.

Table 5: Most cited documents.

Document	Title	Citations	Reference	Journal
1	A CFD study on improving air flow uniformity in indoor plant factory system	120	[11]	Biosystems Engineering
2	A CFD analysis on improving lettuce canopy airflow distribution in a plant factory considering the crop resistance and LEDs heat dissipation	61	[15]	Biosystems Engineering
3	Analysis of climate uniformity in indoor plant factory system with computational fluid dynamics (CFD)	55	[16]	Biosystems Engineering
4	Effects of vertical farming on natural ventilation of residential buildings	34	[38]	Energy and Buildings
5	Thermo-fluid dynamic analysis of the air flow inside an indoor vertical farming system	23	[39]	Applied Thermal Engineering

Source: Authors, (2026).

III.13 KEYWORDS MOST FREQUENTLY USED BY DOCUMENT AUTHORS

From a quantitative and thematic perspective, the keyword cloud reveals a conceptual structure clearly dominated by the study of the air environment in controlled environment agriculture systems (Figure 8), once it is acknowledged that the high frequency of the term CFD (43 occurrences) directly reflects the focus of the search strategy. Excluding this methodological term, the most recurrent concepts are *Air* (19), *Plant Factory* (17), and *Ventilation* (15), indicating that a substantial proportion of the corpus concentrates on the characterization and control of airflow in plant factories and vertical farming systems [28], [40]. Likewise, the frequency of *Airflow* and *Crops* (8 occurrences each), together with *Cultivation* (7) and *Plant Growth* (6), reflects a balanced orientation between the optimization of physical variables and crop productive responses, suggesting that CFD is used not only to describe fluid dynamic phenomena but also to support decision-making related to agricultural performance [11], [28], [41].

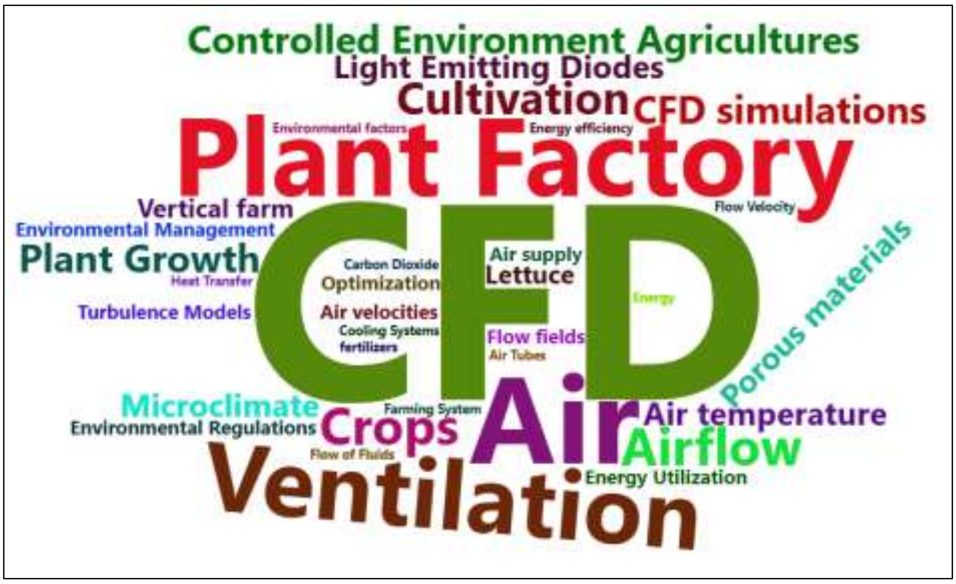

Figure 8: Word cloud of terms used by authors.
Source: Authors, (2026).

At a second level of analysis, the consistent appearance of medium-frequency terms such as *Microclimate*, *Air temperature*, *Light Emitting Diodes*, and *Porous materials* (5 occurrences each) indicates a growing interest in the interaction between ventilation, thermal conditions, artificial lighting, and structural components of the system, which are key elements for the integrated design of efficient indoor environments [42–44]. n parallel, the presence of keywords associated with *Energy Utilization*, *Optimization*, *Environmental Management*, and *Environmental Regulations* (3 occurrences) points to a gradual incorporation of energy efficiency, sustainability, and regulatory compliance criteria, although these aspects still hold a relatively limited weight within the field [45], [46]. Finally, the low frequency of terms such as *Carbon Dioxide*, *Heat Transfer*, and *Cooling Systems* (2 occurrences) suggests that these aspects, although recognized as relevant, remain underexplored, opening clear opportunities for future research aimed at more fully integrating thermal management, CO_2 concentration, and energy performance into CFD models applied to vertical and indoor agriculture [8], [47].

III.14 KEYWORD CO-OCCURRENCE NETWORK

The keyword co-occurrence network (Figure 9) is a bibliometric tool used to identify the conceptual structure and the main thematic axes of a research field based on the frequency with which specific terms appear jointly in scientific documents [48]. In this network, the nodes represent keywords, whose size reflects their relative relevance within the corpus, while the links indicate semantic relationships, that is, the co-occurrence of concepts within the same document [17]. Cluster analysis, based on the density and proximity of these links, makes it possible to group terms into coherent thematic subfields, facilitating the identification of dominant research lines, emerging areas, and interdisciplinary connections. In the context of applying Computational Fluid Dynamics (CFD) to controlled environment agriculture, this network is particularly useful for understanding how physical, biological, and energy-related variables are integrated in the study of microclimate and ventilation in indoor systems.

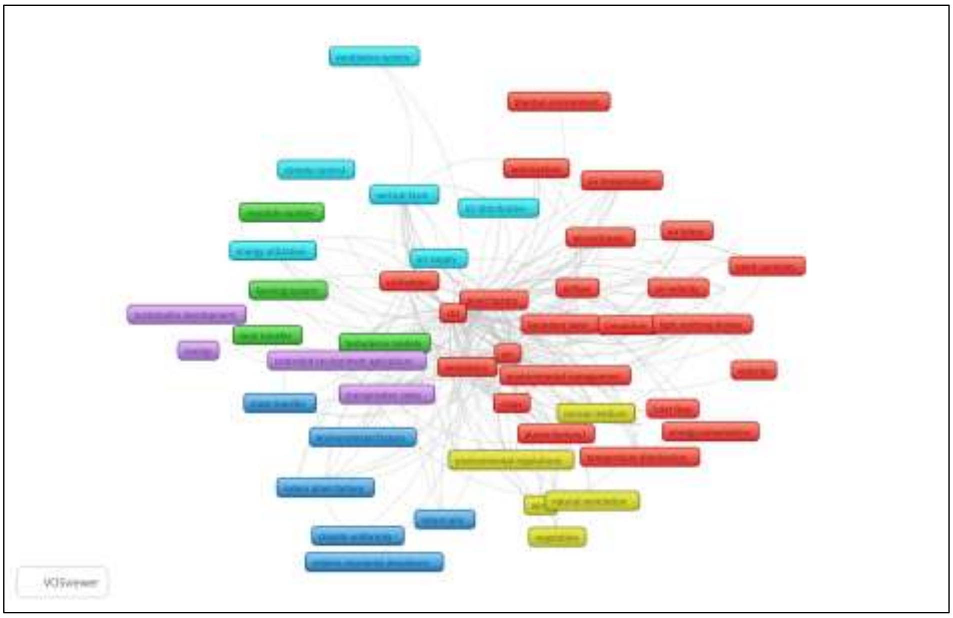

Figure 9: Keyword co-occurrence network of published documents.
Source: Authors, (2026).

Red Cluster: Microclimate, Ventilation, and Air Dynamics in Plant Factories: This cluster is the largest and densest in the network (30 items) and represents the core thematic nucleus of the field of study. It is composed of fundamental terms such as *air temperature*, *air velocity*, *airflow*, *boundary layer*, *ventilation*, *microclimate*, *plant factory*, *plant canopies*, *crops*, *cultivation*, *lettuce*, and *light emitting diodes*. The co-occurrence of these concepts indicates that research is strongly focused on the detailed analysis of air behavior and the thermal environment within plant factories, with particular emphasis on the interaction between airflow, the plant canopy, and artificial lighting [41], [43], [49–51]. The simultaneous presence of *CFD*, *simulation*, and *optimization* confirms that these phenomena are primarily addressed through advanced numerical modeling, aimed at optimizing microclimatic conditions to enhance crop growth and uniformity [29], [34], [52].

Green Cluster: Fluid Dynamics Fundamentals and Energy Transfer: This cluster groups terms such as *energy efficiency*, *heat transfer*, *turbulence models*, *Reynolds number*, *flow of fluids*, *experimental study*, and *indoor vertical farming*, representing the methodological and theoretical foundation of CFD applications. This cluster reflects research focused on the physical and numerical validation of models, as well as on the accurate representation of flow regimes and heat transfer mechanisms [31], [32], [53]. Although its size is smaller than that of the central cluster, its strong connection to the latter indicates that these studies provide essential scientific support to ensure the reliability of CFD simulations applied to indoor agricultural systems [28], [53].

Dark Blue Cluster: Climate Uniformity and Mass Transport: The cluster is dominated by terms such as *carbon dioxide*, *mass transfer*, *transport properties*, *climate uniformity*, *relative standard deviations*, *return airs*, and *indoor plant factory*. This thematic group focuses on the spatial distribution of gases and transport properties, with particular attention to microclimate homogeneity within closed cultivation systems [47], [54]. The presence of statistical indicators suggests an interest in quantifying internal environmental variability, a critical aspect for ensuring uniform crop growth and efficient resource use, but one that still appears as a less developed research line compared to ventilation and airflow studies [55], [56].

Yellow Cluster: Natural Ventilation and Semi-Porous: The cluster integrate concepts such as *natural ventilation*, *wind*, *porous medium*, *flow fields*, *vegetables*, and *environmental regulations*. This cluster represents a line of research oriented toward the interaction between external conditions and indoor systems, as well as the use of porous media models to represent the aerodynamic resistance of crops [38], [42]. Its presence indicates an effort to increase the realism of CFD models by incorporating passive ventilation conditions, regulatory constraints, and hybrid scenarios between closed and semi-open systems.

Purple Cluster: Sustainability, Energy, and Physiological Processes: The cluster groups terms such as *controlled environment*, *cooling systems*, *energy*, *fertilizers*, *sustainable development*, and *transpiration rates*. This cluster highlights an emerging dimension of the field related to sustainability, efficient energy use, and the integration of crop physiological processes into microclimate analysis [30], [57]. Although its relative weight is lower, its connection to the central cluster suggests a growing trend toward more holistic approaches, in which CFD is used not only to optimize airflow but also to assess energy and environmental impacts [45], [58].

Light Blue Cluster: Design and Operation of Ventilation Systems: The cluster includes terms such as *air distribution*, *air supply*, *ventilation system*, *energy utilization*, *climate control*, and *vertical farm*. This cluster acts as a bridge between CFD modeling and practical implementation, focusing on the design and operation of ventilation systems in vertical farming facilities [34], [40], [59], [60]. Its intermediate position within the network reflects its integrative role, linking fluid dynamic fundamentals with the operational management of indoor climate, which is essential for translating simulation results into real-world applications.

III.15 MULTIPLE CORRESPONDENCE ANALYSIS OF INTELLECTUAL STRUCTURE

Multiple Correspondence Analysis (MCA) is an exploratory statistical technique used to reduce the dimensionality of categorical data and to graphically represent the associations between variables and categories within a low-dimensional space. Unlike co-occurrence networks, MCA does not focus solely on the frequency of joint appearances, but rather on the geometric proximity between terms, allowing the identification of latent patterns, conceptual oppositions, and semantic groupings [61], [62]. In bibliometric studies, this technique is particularly useful for complementing network analyses, as it facilitates the interpretation of how concepts are organized around dominant conceptual axes [63].

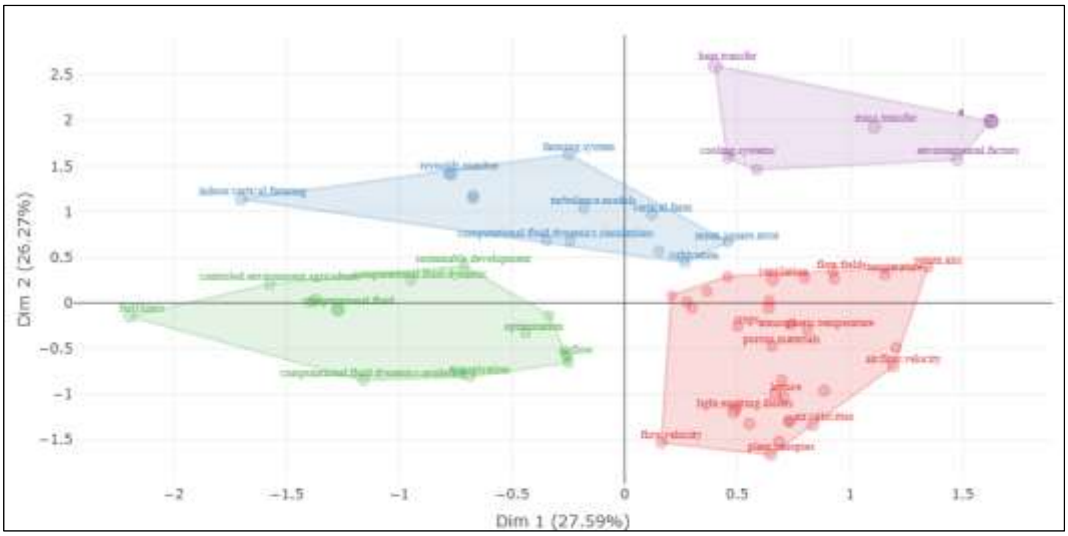

Figure 10: Analysis of dominant axes of intellectual structure analyzed.
Source: Authors, (2026).

In Figure 10 analyzed, the first two dimensions explain a substantial proportion of the total variability (Dim 1: 27.59% and Dim 2: 26.27%), indicating a well-defined conceptual structure. Dimension 1 clearly separates terms associated with the physical optimization of airflow and ventilation (right side), such as *airflow*, *air velocity*, *ventilation*, *porous materials*, and *light emitting diodes*, from those linked to more systemic and methodological approaches (left side), such as *computational fluid dynamics simulations*, *turbulence models*, *Reynolds number*, and *controlled environment agriculture*. This opposition suggests that the field is structured around studies focused on the design and operational performance of indoor systems versus works centered on the development and validation of numerical models.

Dimension 2, in turn, introduces a vertical differentiation between research focused on thermal and transfer management (*heat transfer*, *cooling systems*, *mass transfer*, *environmental factors*), located in the upper part of the plane, and studies more closely related to the plant canopy and air–plant interactions (*plant canopies*, *lettuce*, *air velocities*, *flow velocity*), situated in the lower part. This distribution indicates that, although both approaches are interconnected, there are differentiated research lines that prioritize, respectively, the energy–thermal control of the system and the microclimatic response at the crop scale. Overall, the MCA confirms the complementarity between engineering and biological approaches in the application of CFD to controlled environment agriculture, providing a structural perspective that reinforces and deepens the results obtained through keyword co-occurrence networks.

III.16 LIMITATIONS OF THE STUDY

This study presents several limitations inherent to both the bibliometric design and the information retrieval strategy. First, the search was conducted exclusively in the Scopus database, which, although it ensures high quality and multidisciplinary coverage, may underrepresent literature indexed in other databases (e.g., Web of Science, IEEE Xplore) as well as relevant grey literature for an applied field such as CFD in indoor agriculture. Second, the final corpus (52 documents) reflects a still emerging domain; therefore, some indicators (citations, local h-index, or network centrality) may be influenced by temporal window effects and by the uneven accumulation of citations between recent and foundational articles. In addition, the search equation itself includes methodological terms (CFD/ "computational fluid dynamics"), which may introduce a dominance bias of keywords such as CFD in co-occurrence analyses, reducing the relative visibility of substantive concepts such as CO_2, heat transfer, or VPD within the visualizations.

To address these limitations, several methodological decisions were adopted to strengthen the validity and traceability of the study. Regarding document coverage, a broad search strategy was implemented (with no restrictions by country or language), and a PRISMA-based workflow with explicit screening was applied (64 initial records; exclusion of 4 non-CFD studies and 8 due to thematic misalignment), enhancing transparency and reproducibility of the final corpus. With respect to citation and recency biases, results were interpreted by combining performance metrics (production, citations, indices) with structural analyses (bibliographic coupling, co-occurrence, and MCA), ensuring that the interpretation of the field did not rely solely on cumulative indicators. Finally, to reduce the dominance effect of the term "CFD" in semantic analyses, the interpretation of keyword clouds and networks explicitly differentiated between "methodological" terms (inherent to the search filter) and "thematic" terms, prioritizing the substantive analysis of clusters and conceptual relationships related to ventilation, microclimate, air distribution, energy, and mass transport.

III.17 FUTURE RESEARCH TRENDS AND CHALLENGES

One of the main emerging trends in research on the application of Computational Fluid Dynamics (CFD) in vertical and indoor agriculture is the transition from simplified models toward increasingly realistic and integrated representations of cultivation systems. Recent studies show a growing interest in incorporating detailed plant geometries, dynamic porous canopy models, and thermal sources associated with LED lighting, as well as in simultaneously integrating multiple microclimatic variables (temperature, humidity, air velocity, and CO_2 concentration). This evolution points to the use of CFD not merely as a descriptive tool, but as a predictive support for the comprehensive design and optimization of vertical farms, enabling the evaluation of complex operational scenarios prior to real-world implementation.

Nevertheless, significant methodological and conceptual challenges remain. Among these, the limited integration of crop physiological processes such as photosynthesis, transpiration, and stress responses into CFD models stands out, as these processes are still treated in a simplified or decoupled manner in many studies. In addition, critical variables such as the spatial distribution of CO_2, vapor pressure deficit (VPD), and latent heat transfer continue to be underrepresented compared to airflow analysis. This is compounded by the scarcity of full-scale experimental validations and longitudinal studies capable of assessing the microclimatic and energy performance of indoor systems over time, which restricts the generalizability of results and their industrial adoption

Looking ahead, research is expected to advance toward interdisciplinary and decision-oriented approaches, combining CFD with optimization techniques, artificial intelligence, and digital twins for the real-time control of vertical farms. The integration of energy analyses, sustainability assessments, and economic considerations represents another key axis for strengthening the practical applicability of CFD models. Furthermore, the reinforcement of international collaborations and the development of comparative studies across different indoor system typologies will help reduce regional gaps and consolidate a more robust knowledge framework. Overall, these trends and challenges outline a research agenda aimed at maximizing the productive, energy, and environmental efficiency of controlled environmental agriculture through the advanced use of CFD.

IV. CONCLUSIONS

From a quantitative perspective, the bibliometric analysis confirms that the application of Computational Fluid Dynamics (CFD) in vertical and indoor agriculture constitutes an emerging research field that is nevertheless in a clear phase of consolidation, with sustained growth in scientific production during the 2015–2025 period and a marked acceleration in recent years. The analyzed corpus, consisting of 52 documents published across 30 sources, reveals a high degree of geographical and editorial concentration, led mainly by China, the United States, and several European countries, as well as by journals specialized in biosystems engineering and controlled environment agriculture.

Bibliographic coupling and co-authorship networks display a highly centralized structure, supported by a relatively small core of authors and institutions with strong intellectual interconnections, indicating that the development of the field has been driven primarily by foundational contributions and recurrent collaborations rather than by a broad dispersion of approaches. From a conceptual standpoint, the results show that CFD has become a key tool for understanding and optimizing microclimate conditions in controlled environment agriculture systems, particularly with respect to ventilation, airflow distribution, and thermal uniformity.

The analysis of keywords, co-occurrence networks, and multiple correspondence analysis indicates that the thematic core of the field is structured around air–plant interactions, plant canopies, LED lighting, and energy efficiency, while variables such as CO_2 distribution, mass transport, and the integration of crop physiological processes remain at an early stage of development. This conceptual structure suggests a progressive evolution from approaches focused on localized airflow improvements toward more integrated models aimed at the simultaneous optimization of productive, energy, and environmental performance in vertical and indoor farming systems.

Looking ahead to future research, it is recommended to move toward more accessible, integrated, and decision-oriented CFD models, particularly in the context of low-cost indoor agriculture and in regions with limited resources. In this regard, priority should be given to developing approaches that combine simplified yet representative geometries, small-scale experimental validation, and clear metrics of uniformity and efficiency, enabling the transfer of generated knowledge to growers and designers of indoor systems with lower technological capacity.

In addition, integrating CFD with optimization tools, intelligent control strategies, and simplified energy analyses could facilitate the design of modular, scalable, and economically viable solutions. Finally, fostering international collaborations and comparative studies across different socioeconomic contexts will help broaden the impact of CFD as a strategic tool for improving the sustainability, resilience, and accessibility of controlled environment agriculture at a global scale

V. AUTHOR’S CONTRIBUTION

Conceptualization: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Methodology: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Investigation: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Discussion of results: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Writing – Original Draft: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Writing – Review and Editing: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Resources: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Supervision: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.
Approval of the final text: Edwin Villagran, John Espita, Jorge Flores-Velasquez, Cruz Ernesto Aguilar, Jader Rodriguez.

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