Martins *et al. Discover Sustainability* (2026) 7:874
https://doi.org/10.1007/s43621-026-03396-2

Discover Sustainability

REVIEW **Open Access**

Research trends and knowledge gaps in sustainable urban agriculture: a scientometric analysis

Taline Carvalho Martins[1*], Thais Queiroz Zorzeto Cesar[2†], Fábia Barbosa da Silva[1†], Ítalo Moraes Rocha Guedes[3†], Edson Luiz Souchie[4†], Caíke da Rocha Damke[1†], Vinício da Cunha Doro[1†] and Fabiano Guimarães Silva[1*†]

†Thais Queiroz Zorzeto Cesar, Fábia Barbosa da Silva, Ítalo Moraes Rocha Guedes, Edson Luiz Souchie, Caíke da Rocha Damke, Vinício da Cunha Doro and Fabiano Guimarães Silva contributed equally to this work.

*Correspondence:
Taline Carvalho Martins
taline.carvalho@ifgoiano.edu.br
Fabiano Guimarães Silva
fabiano.silva@ifgoiano.edu.br

Full list of author information is available at the end of the article

Abstract

Urban agriculture plays a strategic role in sustainability, food security, and climate adaptation in cities, where temperature emerges as a key variable. This study conducted a scientometric and qualitative analysis to investigate how temperature has been addressed in the scientific literature on urban agriculture between 2020 and 2025. A total of 244 documents were retrieved from Scopus and Web of Science, followed by a qualitative screening that resulted in 20 articles with high thematic relevance. The results reveal a strong geographic concentration of research in Asia–Pacific countries and a rapid expansion of publications after 2022. The qualitative analysis enabled the classification of studies into three main groups: Group A (open and semi-open systems), Group B (building-integrated and protected systems), and Group C (fully controlled indoor environments). Group C represents the majority of studies (55%), indicating a strong research focus on high-technology systems such as plant factories. Group B accounts for (30%), highlighting growing interest in energy integration between agriculture and buildings, while Group A represents only (15%), showing that open-field urban agriculture remains underexplored in terms of temperature. Temperature is addressed at different scales: as a microclimatic regulator in open environments, as a mediator of energy exchange in building-integrated systems, and as a high-precision control variable in fully controlled systems. Despite its central role, temperature-focused studies remain limited, revealing gaps in empirical validation and multi-scale integration. These findings highlight a technological shift toward controlled environment agriculture and the need for integrated approaches combining microclimate regulation, energy efficiency, and precision control.

Keywords Plant factory, Urban farming, Environmental control, Temperature

1 Introduction

Urban agriculture stands out as a relevant strategy to promote food security, environmental sustainability, and social inclusion in urban centers by strengthening local food systems and encouraging the efficient use of resources; therefore, it aligns with the

United Nations Sustainable Development Goals (SDGs), particularly SDGs 2, 11, 12, and 13 [1], and has become increasingly established in contemporary cities through both greenhouses located in urban areas and controlled environments such as vertical farms [2], in which controlled environment agriculture (CEA) systems employ technologies to optimize plant growth and maximize efficiency in the use of resources such as land, water, and energy [3, 4].

Among the arguments supporting this cause are: the need to increase food production due to population growth [5, 6]; land-use efficiency [7]; challenges related to food security and transport distances; climate change and climate independence [8]; and efficient natural resource management, including water-use efficiency and the reduction of pollution and chemical inputs [9]. Thus, food cultivation in urban environments emerges as a viable alternative for decentralized and resilient food production [10–12].

This practice helps mitigate greenhouse gas emissions, reduces dependence on long supply chains, increases the use of underutilized spaces, and encourages the adoption of healthier and more affordable dietary habits [13]. In this context, urban agriculture combines technological innovation, environmental responsibility, and social inclusion, reinforcing the role of cities as spaces for production, education, and sustainability [14].

In parallel with this agricultural evolution, urban spaces and the construction industry have been undergoing a profound digital transformation based on the pillars of Industry 4.0, requiring increasingly complex systems integration and multidisciplinary approaches in the planning of built environments [15]. Similarly, global digitalization is fundamentally transforming the foundations of agricultural production, driving what is widely characterized as Agriculture 4.0 and smart farming. This transition enables the application and deep integration of frontier technologies into agricultural practices–such as big data, the Internet of Things (IoT), artificial intelligence (AI), sensors, robotics, ubiquitous connectivity, 3D printing, digital twins, and blockchain [16]. The convergence of these cutting-edge innovations within built spaces is a key factor that strongly fosters the advancement and efficiency of urban agriculture systems. These technological advances are particularly relevant in controlled environment agriculture.

In the context of agricultural production in urban areas, the concept of controlled environment agriculture plays a central role, as it encompasses the set of interactions between physical factors – such as light, temperature, humidity, and ventilation – and plant physiological responses [3, 17, 18]. In cultivation systems established on rooftops, balconies, courtyards, or urban lots, environmental conditions are strongly influenced by the surrounding urban structure, resulting in spatial and temporal variability [19, 20]. Productive systems embedded in urban environments are subject to complex microclimatic conditions arising from interactions among buildings, construction materials, and the lack of green areas, which significantly modify controlled environment agriculture [21, 22].

In urban areas, high temperatures and the low capacity for heat dissipation affect plant physiological processes, compromising crop productivity and quality [23]. Understanding and managing these effects are essential for developing adaptation strategies and for planning urban spaces that are more resilient, efficient, and environmentally balanced [24, 25].

Urban agriculture systems are embedded in environments strongly influenced by city configurations, where high building density, the use of impermeable materials, and scarce vegetation favor heat accumulation and reduce the efficiency of thermal dissipation [26]. These factors contribute to the formation of urban heat islands and to the amplification of diurnal and seasonal thermal variations, generating heat-stress conditions that directly affect plant physiological performance [27]. Studies in tropical cities show that the intensity of heat islands is significantly higher in dense urban centers than in areas with native vegetation, and can exhibit extreme thermal differences exceeding 6 °C during the dry season [28].

Prolonged exposure to high temperatures can impair processes such as photosynthesis, transpiration, and growth, reducing crop productivity and quality [29]. Understanding and mitigating these effects is essential for managing thermal conditions in controlled environment agriculture and for strengthening productive viability in urban environments. Despite the growing relevance of the topic, there remains a significant gap in the scientific literature regarding the integration between urban agriculture and temperature control [30, 31].

Most existing studies address thermal control in conventional agricultural contexts, without considering the microclimatic and structural particularities of cities. This fragmentation limits the development of practices and policies aimed at optimizing thermal conditions in controlled environment agriculture in urban settings and restricts advances in knowledge about the factors that determine the success of production systems in densely built areas.

Bibliometric and scientometric approaches have been widely used to explore the evolution of scientific fields, enabling the identification of research trends, influential authors, collaboration networks, and emerging knowledge gaps. These methods provide a systematic understanding of the development of research domains and help guide future scientific agendas [32].

In this context, the present study aims to analyze how the variable temperature has been addressed in the scientific literature on urban agriculture between 2020 and 2025. To achieve this objective, the study proposes the following specific objectives: (i) to map the scientific production related to urban agriculture and thermal control in these systems using the Scopus and Web of Science databases; (ii) to conduct a scientometric analysis in order to identify research trends, including the most prominent journals, countries, and institutions, as well as scientific collaboration networks; (iii) to examine the thematic structure of the literature through keyword co-occurrence analysis, identifying the main research axes related to temperature; (iv) to perform a qualitative analysis of the studies most closely aligned with the topic, seeking to understand how temperature has been investigated across different urban agricultural production systems; and (v) to identify knowledge gaps and future research directions related to thermal management in urban agriculture contexts.

2 Material and methods

This study is a scientometric analysis, focusing on identifying the main trends, collaborations, and research themes related to controlled environment agriculture and thermal control in urban agricultural systems, whether in greenhouses or other protected structures, and it aims to understand what has been produced regarding the study of air temperature.

Data collection was carried out using the Scopus and Web of Science databases. Given the rapid advances in science and technology in recent years, such as developments in neural networks that have introduced several changes in the sector, articles published between 2020 and 2025 were considered, aiming to capture the most recent research on the topic. The search strategy used the title, abstract, and keywords fields, with the following combination of descriptors:

((“urban greenhouse” OR “city greenhouse” OR “rooftop greenhouse” OR “urban farming” OR “urban agriculture” OR “plant factory”) AND (“environmental conditions” OR “microclimate” OR “thermal comfort” OR “ambience” OR “environmental control”))

The Scopus results were exported in.csv format, while the Web of Science data were exported in.txt format and subsequently integrated into RStudio (version 2025.09.1 Build 401) for analysis. Duplicate records across the databases were identified and removed prior to processing, ensuring the integrity of the dataset.

The analyses were conducted using the Bibliometrix package and its graphical interface, Biblioshiny, both available in the R environment. VOSviewer was also used for the analysis.

The descriptive analysis included identifying relevant keywords, author, country, and institutional collaboration patterns; the most prominent journals by publication volume, affiliations and influential works in the field. This step made it possible to observe the temporal evolution and geographic distribution of scientific production. Graphical representations were generated using Bibliometrix network functions, with parameters adjusted to ensure clarity and readability of the relationships. Based on the keyword co-occurrence matrix, thematic clusters were identified, representing groups of terms that recurrently appear in the literature. This approach helped identify consolidated topics and the expansion frontiers of the research field.

The initial scientometric analysis established the macro-structure of the research field, including the identification of N = 244 articles in the database. To complement the quantitative analysis and gain a deeper understanding of the most influential works on temperature in urban agriculture, a qualitative stage of the study was conducted.

To this end, the database was refined to select a manageable subset of documents most closely aligned with the topic. The thematic selection was carried out through a targeted search within the metadata columns that showed the greatest conceptual density, namely: Abstract, Keywords and Indexer Keywords. Thus, articles containing terms semantically related to the topic of temperature were identified. This purposive selection was not intended solely to identify the most cited studies, but rather those presenting the greatest conceptual relevance to the object of study. The application of this filtering process resulted in a subset of 20 studies, selected based on their thematic affinity with the study of temperature. These studies are presented in descending order of citations, as indicated in the Rank column, which organizes the publications from the most cited to the least cited according to their Total Citations (TC).

The procedure involved a full-text reading of the selected articles, aiming to extract the main findings and gaps in the field. The manual analysis focused on mapping the approaches and results related to the study of temperature in association with urban agriculture. Subsequently, the results were discussed and synthesized around emerging themes, enabling a contextualized and qualitative discussion of the findings and thereby complementing the quantitative data obtained through scientometrics.

The analysis was conducted to ensure reproducibility and transparency, allowing future studies to replicate or update the procedures described here. Figure 1 presents the methodological workflow of the study.

3 Results

3.1 Scientometric data analysis

The final documentary corpus, resulting from the search strategy and the refinement stages of the scientometric investigation, totaled 244 documents. The analysis of the distribution by document type revealed a clear predominance of Articles (152 documents), indicating that most of the analyzed literature consists of empirical, original research subjected to peer review. The corpus also included 23 Reviews (which play a crucial role in synthesizing previous research and defining the state of the art), as well as 30 Conference Papers and 16 Proceedings Papers (documents that often disseminate findings at the forefront of scientific research). The inclusion of Book Chapters (15 documents) and other minor formats ensures that the documentary base for the subsequent qualitative

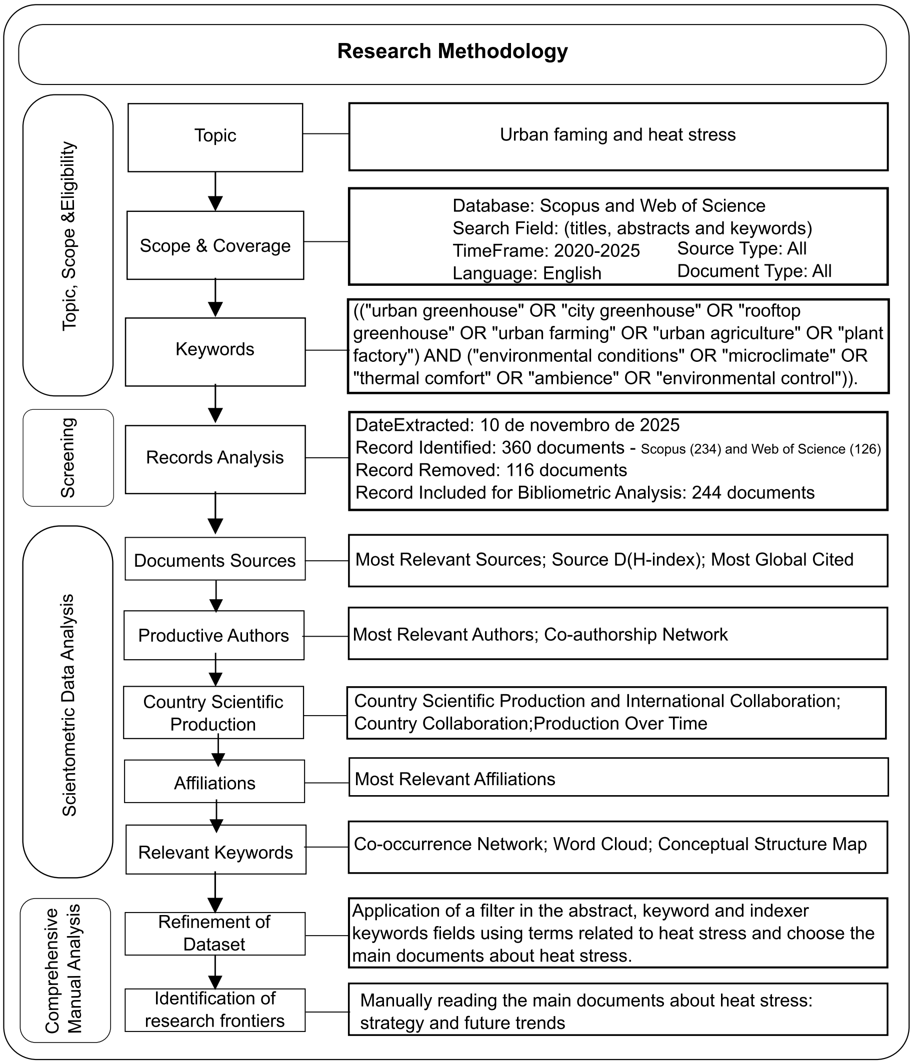

Fig. 1 Research Methodology. *Source:* "Authors"

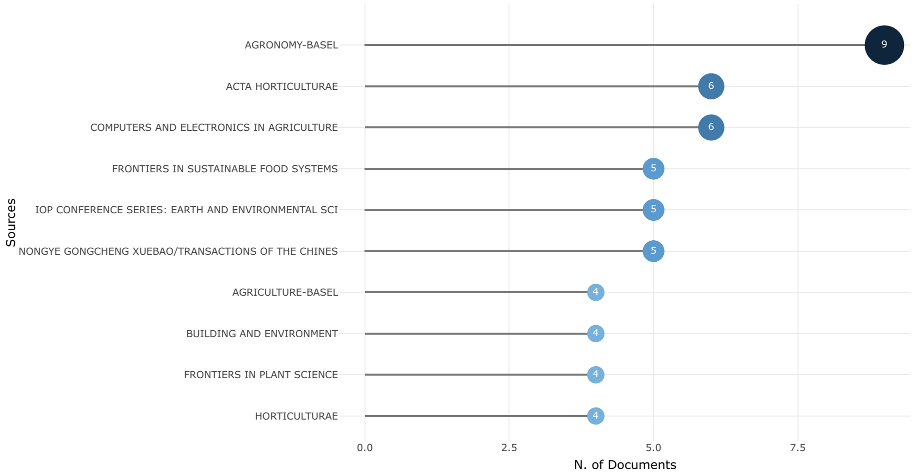

Fig. 2 Most Relevant Sources. *Source:* "Authors"

Table 1 Most Productive Journals in Urban Agriculture Research. *Source:* "Authors"

Rank	Source (Journal)	Number of documents
1	Agronomy-Basel	9
2	Acta Horticulturae	6
3	Computers and Eletronics in Agriculture	6
4	Frontiers in Sustainable Food Systems	5
5	IOP Conference Series: Earth and Environmental Science	5
6	Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering	5
7	Agriculture-Basel	4
8	Building and Environment	4
9	Frontiers in Plant Science	4
10	Horticulturae	4

content analysis is robust and diverse, covering both primary sources and knowledge-consolidation works.

As shown in Fig. 2, the distribution of publications by source reveals a concentration of scientific output in a limited number of journals. Agronomy-Basel presents the highest number of publications (n = 9), followed by Acta Horticulturae and Computers and Electronics in Agriculture, with six articles each. Additional contributions are observed in journals such as Frontiers in Sustainable Food Systems and Building and Environment, each with five publications. Overall, the results show that a small group of journals accounts for a significant share of the publications in the dataset.

The analysis of publication sources, presented in Table 1, highlights a clear concentration of scientific output in a limited number of journals, confirming the classic pattern described by Bradford's Law. Agronomy-Basel stands out as the leading journal, with the highest number of publications (n = 9), consolidating its role as the main outlet for research on temperature in urban agriculture.

This is followed by Acta Horticulturae and Computers and Electronics in Agriculture, each with 6 publications, reinforcing their relevance as core journals in the field. Additional contributions are observed in journals such as Frontiers in Sustainable Food Systems and IOP Conference Series: Earth and Environmental Science, each with 5 documents.

Overall, this distribution demonstrates the existence of a core group of specialized journals that concentrate the dissemination of knowledge on the topic, indicating both thematic consolidation and the interdisciplinary nature of research in urban agriculture and environmental control.

Figure 3 presents the most globally cited documents in the field, indicating the references with the greatest impact and relevance to the scientific community. At the top of the list, with a significantly higher number of global citations (268), is [11] article "Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic", published in the journal Food Security. Although thermal control is the main focus of this study, the prominence of this paper suggests a strong thematic intersection with broader concerns in the field, such as the resilience of urban food systems in the face of environmental and social shocks. In addition, the article emphasizes that food cultivation in urban environments helps regulate and improve local climatic conditions, counteracting the excessive heat inherent to large cities (microclimate improvement and the urban heat island effect).

The co-authorship network (Fig. 4), generated using VOSviewer illustrates the collaborative structure among the most relevant authors in the field. The size of the nodes represents the number of publications, while the links between nodes correspond to co-authorship relationships.

The network is characterized by a fragmented structure, with several small clusters of authors and limited interconnections between groups. Clusters centered around authors such as Lu, Na; Xu, Wenshuo; and Chung, Sun-ok present stronger internal connections, whereas other authors appear isolated or weakly connected.

Overall, the network consists of multiple disconnected or weakly connected components, indicating a dispersed pattern of collaboration among authors.

In terms of quality and consistency indicators, YU H and HU J, despite having a lower NP (5 articles each), stand out with the highest m_index (1.0), indicating that their publications are relatively more recent yet have managed to sustain a high h_index over a short period since they began publishing (PY_start 2022 and 2023, respectively), demonstrating a very rapid rate of high-impact output. The g_index further reinforces relevance, with ZHANG Y and LU N tied at the maximum value (8), indicating that they each have a concentrated set of highly cited works. Finally, it is noteworthy that the

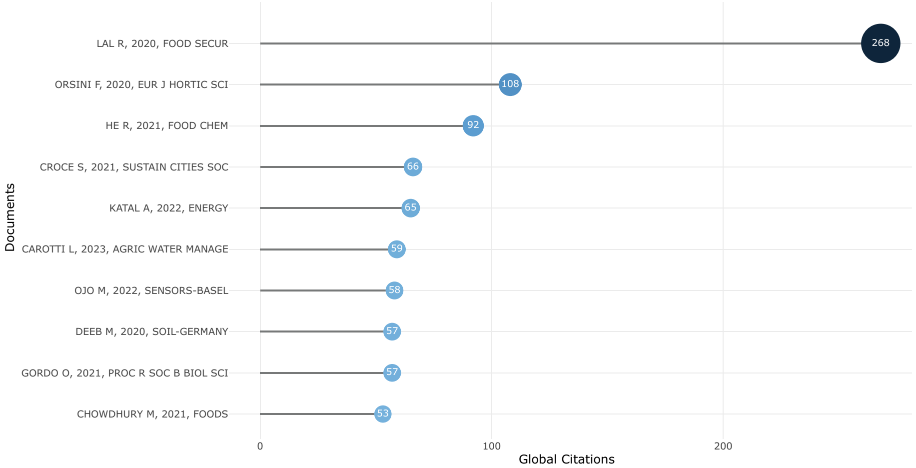

Fig. 3 Most Global Cited Documents. *Source:* "Authors"

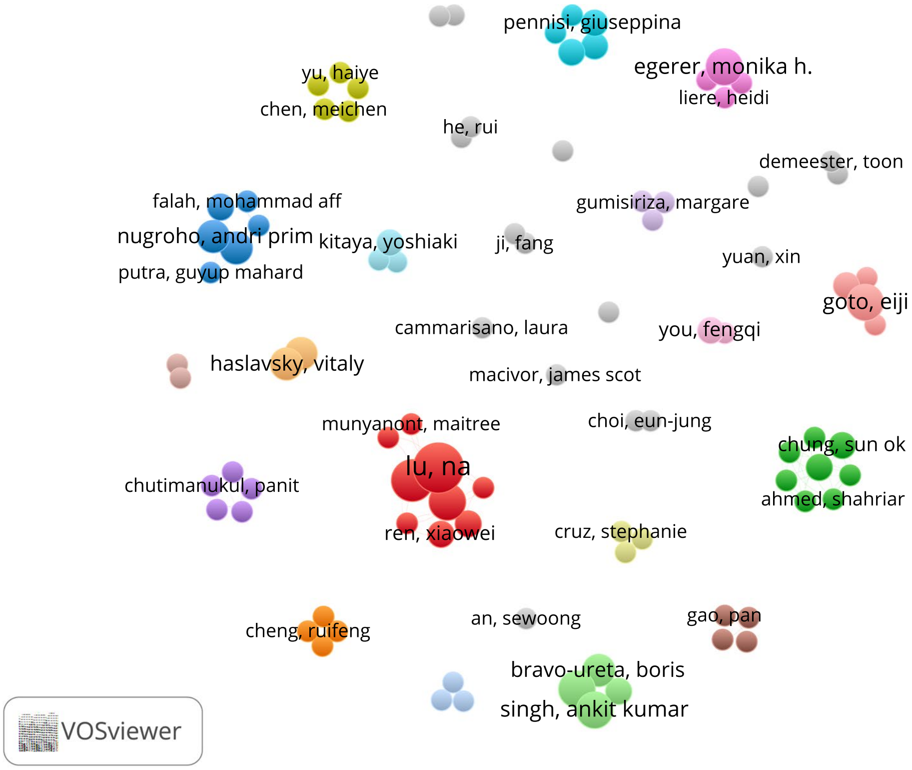

Fig. 4 Co-authorship Network. *Source:* "Authors"

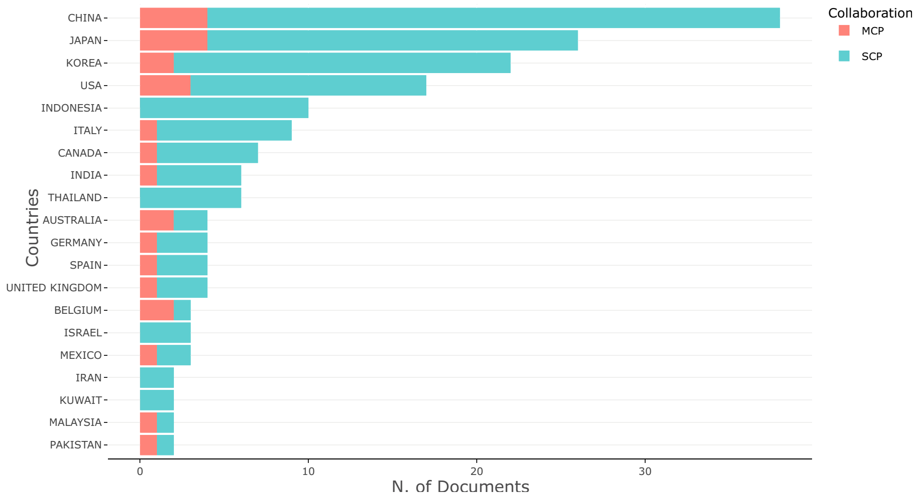

Fig. 5 Corresponding Author's Countries. *Source:* "Authors"

analysis period is recent, with the first recorded publication (PY_start) for the group occurring from 2020 onward, which emphasizes the dynamism and rapid evolution of this research subfield.

The analysis of the geographic distribution of corresponding authors' countries (Fig. 5) shows a clear polarization of scientific output in this area, with strong leadership from East Asia. China clearly dominates, with the highest total number of documents, followed closely by Japan and Korea (as identified in the previous authorship section). Together, these three Asian countries account for most of the literature, reinforcing the importance of research on urban agriculture and thermal control in contexts of high population density and rapid urbanization. At a second tier, the United States and Indonesia emerge as relevant contributors.

Regarding collaboration patterns, the vast majority of publications are classified as Single-Country Publications (SCP) (represented in blue), indicating that research is still predominantly conducted by national teams. However, the absolute number of Multiple-Country Publications (MCP) (represented in red) originating from China, Korea, and the USA is noteworthy, signaling that although international collaboration is a minority, more intense cross-border collaboration tends to concentrate among the countries with the highest production volume. This is evidenced by the larger MCP segment for China, suggesting that global leadership also drives transnational partnerships.

Figure 6 presents the temporal evolution of scientific production by country from 2020 onward. China (red line) shows a continuous increase in the number of publications, with a marked acceleration after 2022, reaching the highest output by the end of the period (approximately 70 articles). Korea (purple line) and Japan (green line) also exhibit consistent growth over time, with Korea showing a pronounced increase between 2022 and 2023.

In contrast, the United States (blue line) shows a gradual and linear increase in publications, while Italy (gold line) maintains a relatively stable and lower output throughout the period. Overall, the data indicate a substantial increase in publication volume after 2022, with higher concentrations of output observed in Asian countries.

Figure 7 graphically depicts the intensity of scientific production and the flows of international partnerships. The darker blue shading of countries reflects publication volume, confirming the prominence of China and the United States as the largest centers of knowledge production, with Korea and Japan also showing significant contributions, in line with the previous analyses. The dashed lines, representing collaboration links, indicate that most international partnerships are established among these dominant hubs.

A notable pattern is the significant transcontinental collaboration flow between North America (USA) and Asia (China), as well as links between Asia and Oceania (Australia).

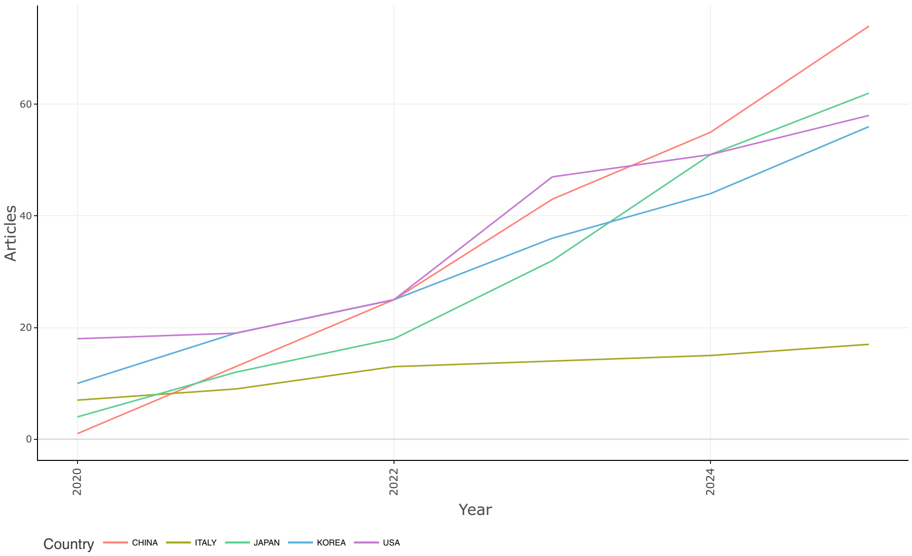

Fig. 6 Country Production over Time. *Source:* "Authors"

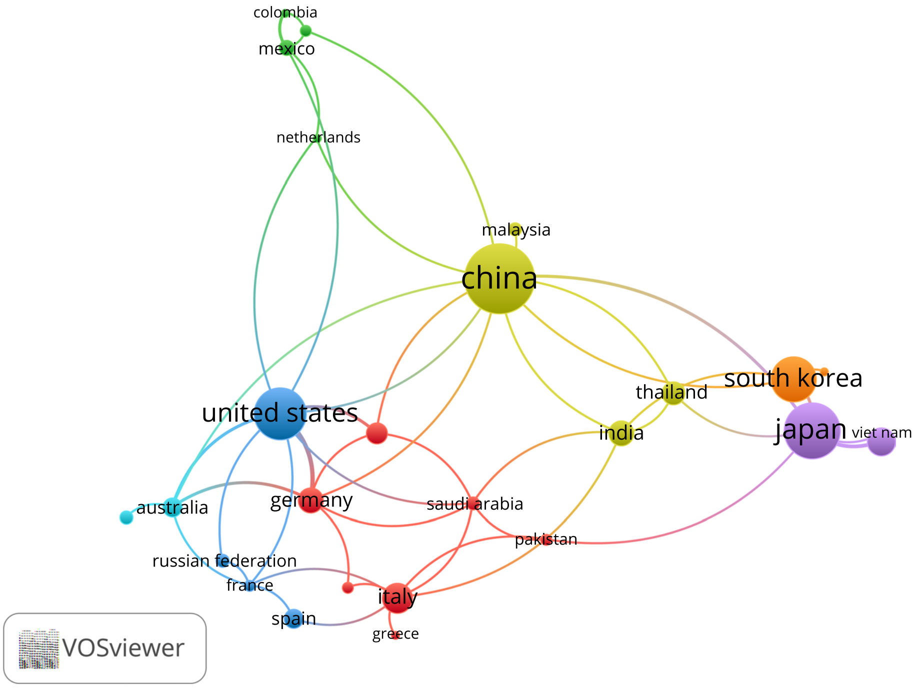

Fig. 7 Country Collaboration Network. *Source:* "Authors"

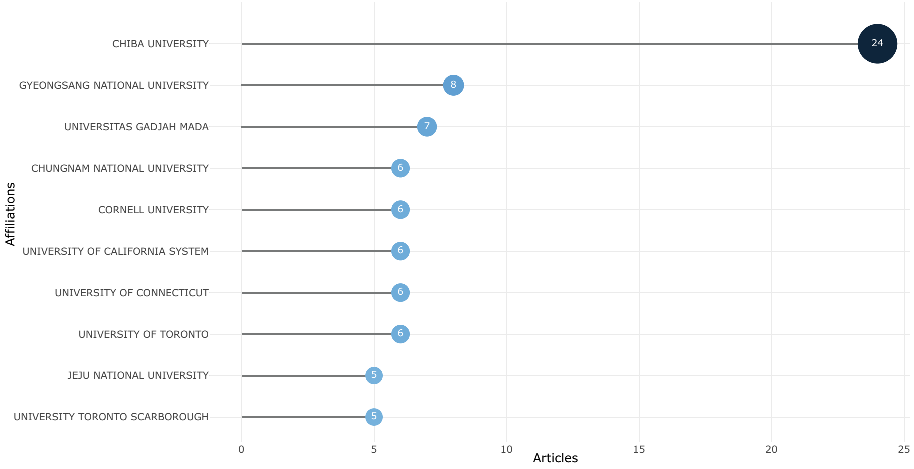

Fig. 8 Most Productive Affiliations in Urban Agriculture Temperature Research. *Source:* "Authors"

This suggests that although research remains largely localized (as indicated by SCPs), the leading producers by volume are actively engaged in forming global research networks that are essential for exchanging data and advanced methodologies, such as those related to climate modeling and the impact of urban agriculture on heat mitigation at a planetary scale.

The affiliation analysis reveals a concentration of institutional expertise driving research on urban agriculture and thermal control. The chart in Fig. 8 shows the dominance of Asian institutions; notably, Chiba University (Japan) emerges as the clear leader, with 24 published articles, an output three times higher than that of the second-ranked institution. This substantial volume suggests that Chiba University acts as a global knowledge hub and hosts highly consolidated research programs within this niche.

Subsequent affiliations, including Gyeongsang National University (South Korea) and Universitas Gadjah Mada (Indonesia), along with Chungnam National University (South Korea) and Jeju National University (South Korea), reinforce Asia's prominence in the field, representing most of the most productive institutions. Although Asian affiliations dominate, North American and Canadian institutions, such as Cornell University, the University of California System, the University of Connecticut, and the University of Toronto, show a consistent contribution, indicating a secondary distribution of expertise in the West. Asia–Pacific institutional leadership directly reflects the concentration of authors and country-level output observed in the previous scientometric analyses.

Figure 9 presents the temporal distribution of keywords related to temperature in urban agriculture. Earlier studies (blue tones) are associated with terms such as urban agriculture, climate change, and environmental conditions. Intermediate studies (green tones) include terms related to environmental management, crops, and hydroponics. More recent studies (yellow tones) are associated with keywords such as controlled environment agriculture, Internet of Things, and machine learning.

Figure 10 complements the network analysis by highlighting the most frequent terms in the dataset, reinforcing the prominence of keywords such as "urban agriculture" and "plant factory." While the network visualization reveals the relationships and temporal evolution among research topics, the word cloud provides a simplified overview of term frequency. Together, these results confirm the central role of controlled environment systems and technology-driven approaches in the current research landscape.

The center of the Conceptual Structure Map (Fig. 11), where the axes intersect, defines the research core: plant growth management, food security, and controlled environment agriculture. The map shows that the field is fundamentally divided between precision engineering to maximize yield (left side) and analysis of the impacts of urban agriculture on the urban climate and city sustainability (right side).

The scientometric results demonstrate a dynamic and technologically oriented research field, with a higher concentration of scientific production in the Asia–Pacific

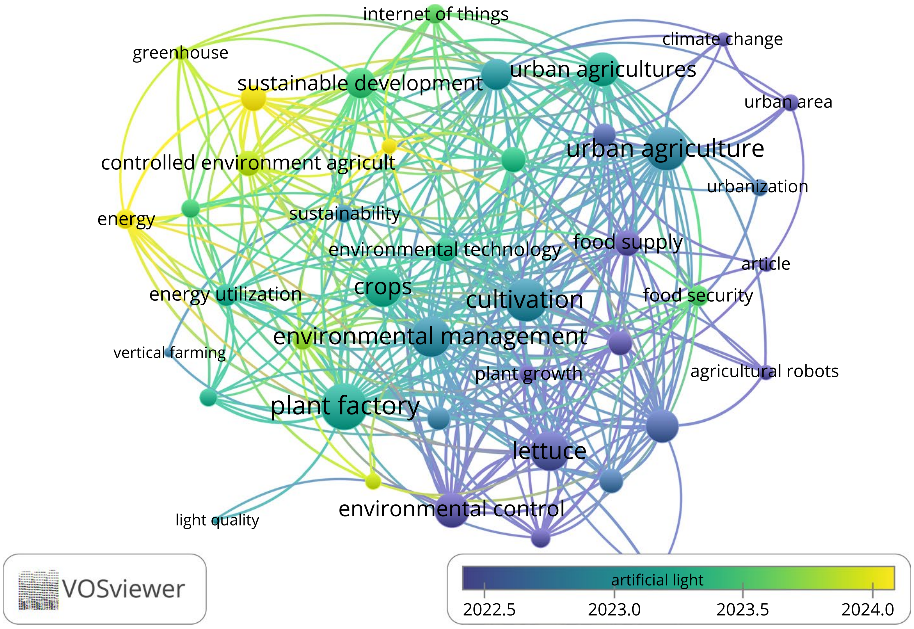

Fig. 9 Keyword Co-occurrence Network. *Source:* "Authors"

Fig. 10 Word Cloud. *Source:* "Authors"

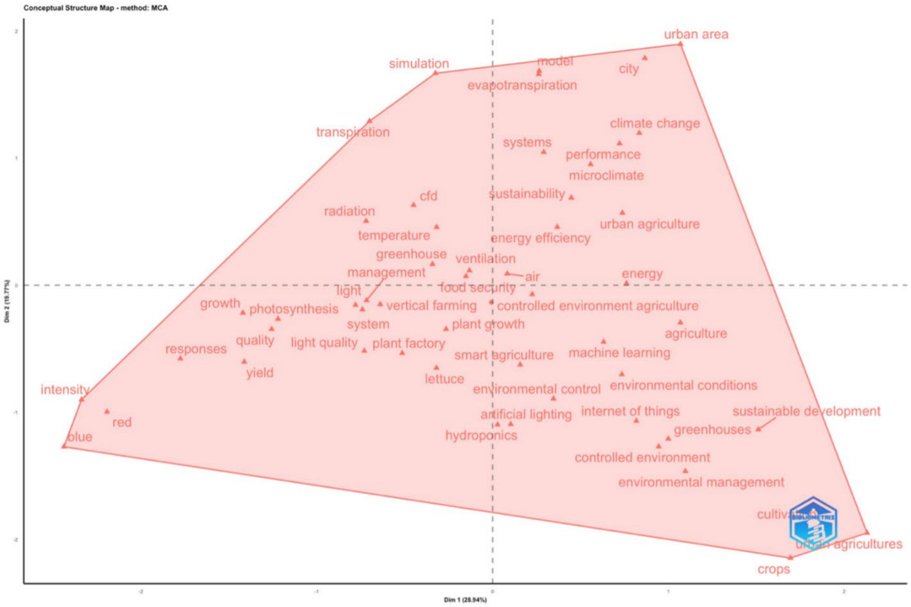

Fig. 11 Conceptual Structure Map. *Source:* "Authors"

region. The distribution of authors, affiliations, and country-level output shows that China, Korea, and Japan present the highest number of publications, while institutions such as Chiba University stand out with the greatest institutional productivity.

The conceptual structure of the literature, based on keyword co-occurrence and mapping analysis, identifies two main thematic orientations. One is associated with applied research in environmental and agricultural engineering, focusing on plant factory systems, hydroponics, and temperature control. The other is related to macro-scale approaches, including microclimate, urban agriculture, and climate change.

These results collectively demonstrate that the field is structurally organized around a dual research paradigm, combining high-precision technological systems with urban-scale environmental approaches. This pattern confirms the consolidation of controlled environment agriculture as a dominant research axis, while also revealing the persistence of fragmented and underexplored domains, particularly in open urban systems.

3.2 Qualitative thermal-focus analysis

A comprehensive analysis filtered the Title, Keywords, and Keywords Plus columns, selecting the terms most closely related to the thermal control theme: analysis of thermal, temporal, air temperature, climate control, thermal comfort, and temperature. Applying these filters resulted in twenty (20) documents, which were ranked by Total Citations (TC) and are presented in this order in Table 2.

It was observed that the articles selected for the qualitative analysis mostly do not correspond to the most influential authors, documents, or institutions identified in the scientometric analysis. Only a small portion shows any degree of overlap. This divergence indicates that, although there is consolidated scientific production on urban agriculture, the "thermal control" subtheme still occupies a peripheral space within the field. Studies directly focused on thermal control show lower accumulated impact and weaker integration into the most-cited networks, suggesting that it is an emerging and still underexplored topic. This contrast reinforces the relevance of the qualitative analysis adopted here, which enables a deeper examination of a thematic niche that does not appear prominently in traditional metrics of scientific influence.

Urban agriculture is widely recognized as an essential multifunctional strategy to address challenges posed by urbanization, notably food security, energy efficiency, and the mitigation of the urban heat island (UHI) effect [33]. The study of temperature ranges from microclimatic regulation mechanisms in open environments to precision control in closed systems, aiming to optimize crop performance and human thermal comfort [33]. The following section presents a comprehensive analysis of the results found in the literature (Table 2), exploring different research contexts and identifying the main gaps.

In analyzing the 20 filtered articles on temperature in urban agriculture, it was possible to identify and categorize three main groups of cultivation systems, which vary according to the level of protection and environmental control. Figure 12 illustrates this relationship, showing a significant concentration of studies in high-technology settings. The articles were divided into groups as shown in Table 2. Group C (Fully Controlled Indoor Environments) focuses on Plant Factories (PFs) and on precision temperature control to optimize productivity and energy efficiency (using, for example, nonlinear adaptive control), and represents the majority of the sample. Group B (Protected and Building-Integrated Systems–BIA), which includes rooftop greenhouses and thermal symbiosis with buildings, corresponds to 30% of the studies. Finally, Group A (Open and Semi-open Systems) investigates microclimatic regulation, Urban Heat Island (UHI) mitigation, and outdoor thermal comfort in urban gardens and farmland, representing 15% of the total.

Group A – Urban Agriculture Systems in Open and Semi-open Environments (Urban Gardens and Farmland) focuses on the microclimatic effects of vegetation in urban areas, where temperature is strongly influenced by external conditions and the composition of the surrounding landscape. Findings from urban gardens show that temperature variability (in the Berlin metropolitan region) is mediated by local ground cover and broader landscape characteristics [34]. A negative correlation was observed between nocturnal thermal amplitude and the imperviousness of the surrounding landscape within a 500 m radius, indicating that sealed surfaces act as nighttime warming factors

Table 2 Top 20 Articles on Thermal Control in Urban Agriculture. *Source:* "Authors"

Rank	Ref	Title	Year	Main Methodological Approach	Group
1	[33]	Co-simulation for thermodynamic coupling of crops in buildings. case study of free-running schools in quito, Ecuador	2022	Computational simulation of thermodynamic coupling between crops and buildings (schools)	B
2	[34]	Temporal temperature variation in urban gardens is mediated by local and landscape land cover and is linked to environmental justice	2022	Field measurements and spatial analysis of temperature variation in urban gardens	A
3	[35]	The impact of planting scenarios on agricultural productivity and thermal comfort in urban agriculture land (case study: Tabriz, Iran)	2023	Computational simulation of thermal comfort under different planting scenarios	A
4	[36]	Thermal analysis and climate control of experimental two level hydroponic growth cell	2020	Microclimate monitoring and Leaf thermal performance under selective lighting (RB/W)	C
5	[37]	Energy-efficient technologies and strategies for feasible and sustainable plant factory systems	2025	Systematic literature review. Energy efficiency (HVAC, LEDs) and circular economy	C
6	[38]	Passive climate control innovations in hunan courtyard dwellings: enhancing indoor environmental and energy efficiency through integrated systems	2025	Microclimate monitoring. Passive strategies (EAT) and greenhouse as a solarium	B
7	[39]	High-order neural-network-based multi-model nonlinear adaptive decoupling control for microclimate environment of plant factory	2023	Computational simulation, Mathematical modeling and AI	C
8	[40]	Analysis of thermal energy loads of a building-integrated rooftop greenhouse (birtg) for urban agriculture	2022	Computational Simulation. Thermal loads in building-integrated rooftop greenhouse	B
9	[41]	Advance of environmental control in plant factory based on computational fluid dynamics	2021	Computational Simulation. Advance of environmental control (PFs) based on CFD	C
10	[42]	Effects of environmental conditions for inducing flower bud initiation on plant growth and flowering of june-bearing strawberry grown under led lighting	2024	Microclimate monitoring and controlled environment experiment. Crossed conditions of EC, dark period temperature, and time	C
11	[43]	Environmental and Social Dynamics of Urban Rooftop Agriculture (URTA) and Their Impacts on Microclimate Change	2021	Field study and evaluation. Dynamics of Urban Rooftop Agriculture	A
12	[44]	Comparative analysis of the performance and energy consumption of air-conditioning systems in a plant factory during a cooling season	2025	Computational Simulation. Crop model with Penman-Monteith equations	C
13	[45]	Urban Agriculture: Climate-Responsive Design Strategies for Blue Infrastructure in the Context of Singapore	2023	Computational Simulation. Climate-responsive design in urban agriculture	B
14	[46]	Experimental Modeling and Thermal Analysis of Closed Hydroponic System Microclimate	2021	Microclimate monitoring and Multi-level monitoring. Growth cell validating LED light interactions	C
15	[47]	Effects of air temperature in the light period on the fruit yield and quality of June-bearing strawberry grown in a controlled environment with artificial lighting	2021	Long-term experimental study. Continuous harvest evaluation (30 weeks) under artificial light	C
16	[48]	Environmental Control in the Plant Factory System Influences Year-Round Production of Allium hookeri Leaves	2023	Controlled environment experiment. Indoor experimental study	C

Table 2 (continued)

Rank	Ref	Title	Year	Main Methodological Approach	Group
17	[49]	Environmental control of PFALs	2022	Controlled environment experiment. Airflow uniformity in Plant Factories	C
18	[50]	Forecasting the vapor pressure deficit in vertical farming facilities aiming to provide optimal indoor conditions	2025	Computational simulation. Machine learning modeling	C
19	[51]	Recent developments of thermal energy storage applications in the greenhouse environment: A comprehensive review	2025	Bibliometric review: Thermal energy storage in greenhouses	B
20	[52]	Current Trends in Research on Temperature Control in Rooftop Greenhouses	2025	Bibliometric review:Temperature control in rooftop greenhouses	B

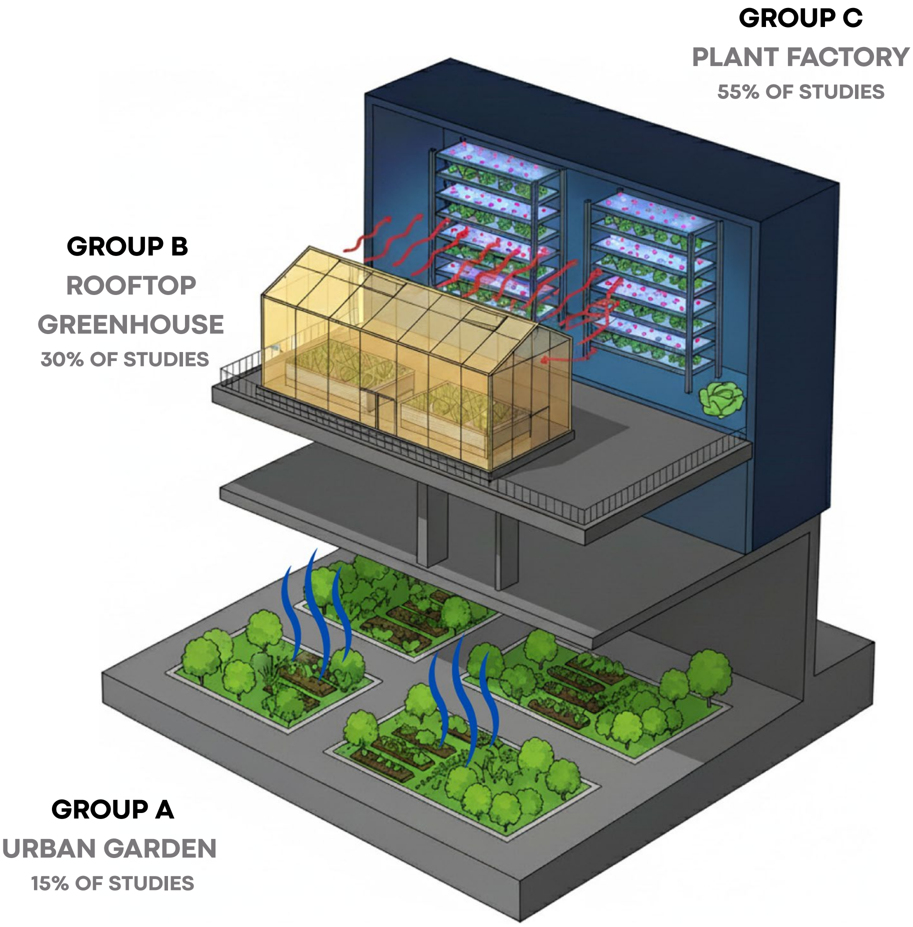

Fig. 12 Main Categories of Urban Agriculture. *Source:* "Authors"

by releasing heat absorbed during the day. Regarding local factors, increased grass cover correlates with greater daytime thermal amplitude and lower minimum nighttime temperatures [34].

For applications in farmland rehabilitation, simulations in urban agricultural land (Tabriz, Iran) showed that planting scenarios with edible deciduous trees – especially when combined with crops – significantly improve outdoor thermal comfort [35]. These scenarios led to an average reduction of 1.42 in the PMV index and 5.2 °C in PET compared to the baseline scenario, with deciduous trees being more effective at reducing air temperature than evergreen trees. Therefore, tree planting in urban agriculture reduces temperature and improves thermal comfort [35].

Group B – Protected and Building-Integrated Systems (Rooftop Greenhouses) focuses on Building-Integrated Agriculture (BIA) systems, such as rooftop greenhouses and edible green roofs, where the main objective is energy symbiosis and improving the thermal performance of the host building. The study shows that rooftop farms are suitable for improving indoor thermal comfort conditions and air quality in buildings, in addition to reducing thermal demand. Crops, through evapotranspiration–the key mechanism for energy dissipation–can divert up to 86% of net solar radiation [33].

The temperature effects in rooftop greenhouses show that crops mitigate peak temperatures, reducing greenhouse air temperature by 1.8 °C during the day and increasing it by 1.3 °C at night [33]. Thermal integration (iRTGs), which uses exhaust air, increases the average greenhouse air temperature by 0.11 °C, which is favorable for crops such as lettuce (with an optimum between 14 and 18 °C) [33, 53].

Regarding energy efficiency, iRTGs achieve the best overall performance, with a 42% reduction in the building's thermal load. The leaf area index (LAI) proved to be a crucial parameter in the crops' energy balance, with an increase of one unit causing significant changes in weekly heating loads [33].

Group C was categorized as Fully Controlled Indoor Environments (Plant Factories). This group addresses vertical cultivation systems (PFs) that use high-precision control of all environmental factors (temperature, humidity, light, and CO_2) to maximize productivity and energy efficiency [37, 39]. Regarding the impact of temperature and optimization, the ideal temperature range for crops (such as lettuce) is generally between 20 and 26 °C [54]. High temperatures can cause heat stress, negatively affecting the photosynthetic rate and crop weight [41].

The energy and control challenges for plant factories are substantial: they use 2 to 20 times more energy than open-ventilated greenhouses [55]. The lighting system is the largest energy consumer, accounting for more than 70% of total use. Heat generated by LED lighting increases the demand for cooling/air conditioning (HVAC) [37].

In high-precision control, the temperature and humidity system in PFs is inherently complex, exhibiting strong coupling, nonlinearity, and multiple disturbances [39]. Nonlinear adaptive decoupling control strategies based on high-order neural networks have been proposed to achieve accurate tracking. Compared with traditional PID control, this advanced strategy reduced the mean temperature error from 0.3615 to 0.1655 [39].

In light of the above, it is clear that temperature control in urban agriculture is essential. Figure 13 illustrates how temperature is investigated across the main groups of urban agriculture.

3.3 Research gaps in the literature on temperature in urban agriculture

Despite the advances identified through the analyses (scientometrics and manual interpretation), they reveal crucial gaps in the association between temperature and urban agriculture, which are essential for future high-impact research.

One of these gaps relates to the Empirical Validation of Complex Models: there is a limitation in the availability of empirical data from real rooftop farms for calibrating and validating thermodynamic co-simulation models [33].

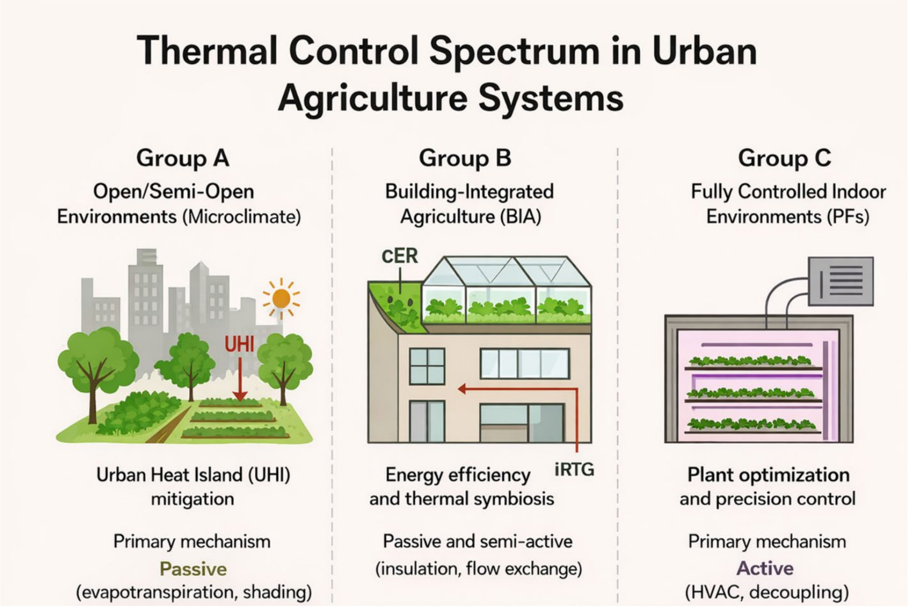

Fig. 13 Thermal control in Urban Agriculture. *Source:* "Authors"

Integrated Flow Modeling in PFs is also identified as a gap. Future studies could integrate the carbon dioxide concentration field simultaneously with airflow, temperature, and humidity fields to achieve a more comprehensive environmental assessment – an approach that is still limited in the current literature [41].

Location optimization and thermal comfort in open environments is another gap. Studies on urban gardens suggest the need to optimize the placement of urban agriculture using spatially explicit temperature data to maximize cooling benefits for vulnerable populations [34].

Regarding the development of crops and complex cultivation systems, there is a need to develop more advanced crop growth models and to diversify crop types and cultivation systems (beyond lettuce) [33, 56]. In addition, the retrofit potential of rooftop farms for educational building stock under different climates (such as in Spain) is still under development [33].

Regarding cost–benefit analysis of cooling in PFs, although water-based cooling has been proposed to remove generated heat, there is a lack of empirical data on its cost–benefit performance in controlled agriculture environments [37].

In summary, the literature demonstrates the fundamental role of temperature in urban agriculture, both as a factor in microclimatic regulation (in greenhouses and gardens) and as a complex systems-engineering challenge in fully controlled environments (PFs). The future of research lies in the empirical validation of complex models and in integrating environmental and social factors to maximize sustainability and environmental justice benefits.

4 Discussion

The analysis of recent literature on temperature control in urban agriculture reveals a clear technological transition, marked by the increasing incorporation of Controlled Environment Agriculture (CEA) systems, including urban greenhouses and, more recently, Plant Factories (PFs). In this context, thermal regulation is no longer limited to mitigating climatic variability but has become a structuring factor in determining agricultural productivity, energy efficiency, and the operational feasibility of these systems, as also highlighted in studies on highly technified production systems [37]. This finding is consistent with the results of the present study, which demonstrate a predominance of research conducted in fully controlled environments (Group C), indicating a strong orientation of the field toward high-precision technological solutions.

Despite the central role of temperature, only 15% of the studies identified in this dataset focus on open and semi-open systems. This distribution may be partially influenced by the study's focus on urban agriculture production systems, whereas open-environment studies are often associated with urban landscaping and green infrastructure. Nevertheless, the results indicate a relative underrepresentation of agricultural-oriented research addressing temperature at the urban scale.

The consolidation of this technological landscape is strongly supported by recent review studies and bibliometric analyses, which outline the evolutionary trends and major bottlenecks in the field. Global literature mapping conducted by [51, 52] indicates a clear transition in research focus, shifting from empirical studies centered on natural ventilation and basic structural design toward energy efficiency, sustainability, and predictive numerical simulation, establishing Computational Fluid Dynamics (CFD) as a key methodological tool. In the context of indoor systems (plant factories), reviews by [37, 41] indicate that, although strict control of artificial lighting and climate conditions enhances plant physiological performance, the high energy demand–particularly associated with HVAC systems–remains a major constraint on large-scale economic viability. In response, the literature consistently points to the need for integrated and hybrid solutions, including the adoption of thermal energy storage systems and renewable energy sources, combined with emerging technologies such as the Internet of Things (IoT) and artificial intelligence, to enable more efficient and integrated climate control.

In fully controlled indoor systems, which represent the state of the art in urban agricultural production, high-precision thermal control is a critical requirement. Minimal thermal deviations can significantly affect plant physiology, influencing processes such as growth, photosynthesis, and reproductive development. Experimental studies, such as that conducted by [42], demonstrate that flower bud initiation in strawberry is associated with an optimal temperature range between 17 and 20 °C during the dark period, highlighting the sensitivity of these systems to environmental variations. These findings reinforce the central role of temperature as a control variable in intensive production systems, as also emphasized by [41], who link crop performance to the integrated management of microclimatic variables.

Within this context, a consistent methodological trend emerges involving the use of artificial intelligence and computational modeling for environmental monitoring and control. The study by [39] demonstrates significant advances through the application of high-order neural networks for decoupled microclimate control in plant factories, substantially reducing temperature tracking errors compared to conventional control strategies. Similarly, machine learning approaches have been applied to predict complex microclimatic variables, such as vapor pressure deficit (VPD), enhancing predictive capabilities and enabling real-time control. These developments confirm the consolidation of a data-driven paradigm in high-technology urban agriculture systems.

Despite these advances, a critical limitation of fully controlled systems lies in their high energy demand, which may compromise economic feasibility, particularly for low-value crops. Studies such as that of [44] demonstrate that optimization strategies–such as separating sensible and latent loads in climate control systems–can lead to significant energy savings. However, the predominance of simulation-based studies, particularly those relying on Computational Fluid Dynamics (CFD), highlights an important gap related to empirical validation under real operating conditions. This underscores the need for long-term experimental studies at commercial scale.

As an alternative to highly energy-intensive systems, building-integrated agriculture (Group B), such as rooftop greenhouses, emerges as an intermediate solution that combines food production with urban energy performance. Studies such as [33] demonstrate that the integration of crops and buildings can generate mutual benefits, including reductions in building thermal loads through processes such as evapotranspiration and convective heat exchange. Similar findings are reported by [40], who observed reductions in annual energy consumption in buildings incorporating rooftop greenhouses. These results reinforce the role of urban agriculture as an active component of the urban energy metabolism, extending its function beyond food production.

In contrast, open and semi-open systems (Group A) operate at a different scale, in which temperature is strongly influenced by urban morphology and land-use characteristics. Studies such as [34, 35] demonstrate that urban agriculture can act as an effective mechanism for microclimate regulation, contributing to the mitigation of the Urban Heat Island (UHI) effect and improving thermal comfort. These findings highlight the multifunctional role of urban agriculture, particularly within the context of sustainable urban planning and environmental justice. However, the dependence on external climatic conditions limits production control and yield stability throughout the year.

The integrated analysis of these systems reveals a structural dichotomy within the field: while highly controlled environments prioritize productivity and precision, open systems emphasize environmental and social benefits at the urban scale. This duality is also reflected in the geographical distribution of scientific production, with Asian countries leading the development of advanced technologies, whereas studies conducted in European and developing countries tend to focus on sustainability, thermal comfort, and socio-environmental dynamics.

Overall, the results of this study confirm that temperature constitutes a key element in urban agriculture, although its investigation remains fragmented and largely concentrated in high-technology systems. Future progress in the field will depend on bridging this imbalance through the integration of different approaches, combining high-precision environmental control, passive thermal regulation strategies, and agronomic innovations. In this sense, the development of hybrid systems emerges as a critical pathway to reconcile productivity, energy efficiency, and climate adaptation, positioning thermal management as a central component of sustainable urban agriculture.

5 Conclusions

5.1 Main findings

This study demonstrated that temperature is a structuring variable in urban agriculture systems, directly influencing productivity, energy efficiency, and environmental performance. The scientometric analysis revealed a strong concentration of research in

Asia–Pacific countries and a predominance of studies focused on high-technology systems, particularly plant factories. The qualitative analysis further identified three main research groups: (i) open and semi-open systems, where temperature is associated with urban microclimate and heat island mitigation; (ii) building-integrated systems, where temperature mediates energy exchanges between crops and buildings; and (iii) fully controlled environments, where temperature is treated as a high-precision variable linked to plant physiological performance and energy optimization. These findings highlight a clear technological shift toward controlled environment agriculture and data-driven approaches.

5.2 Limitations of the study

Despite its contributions, this study presents some limitations. The scientometric analysis was restricted to the Scopus and Web of Science databases and to the period between 2020 and 2025, which may have excluded relevant earlier studies or publications indexed in other databases. In addition, the qualitative analysis was based on a selected subset of studies, which, although carefully chosen based on thematic relevance, may not fully represent the diversity of approaches within the field. Furthermore, the reliance on published literature limits the ability to capture practical challenges and operational constraints observed in real-world applications.

5.3 Future research directions

Future research should focus on bridging the gap between high-precision controlled systems and urban-scale environmental dynamics. There is a need for more empirical studies conducted under real operating conditions, particularly to validate simulation-based models and optimize energy efficiency in plant factories. Additionally, expanding research beyond model crops such as lettuce and incorporating a wider diversity of species is essential. Integrative approaches combining passive design strategies, advanced control technologies, and urban planning perspectives are also recommended to enhance the multifunctional role of urban agriculture. Finally, greater attention should be given to the social and environmental dimensions of temperature management, including its implications for urban resilience and environmental justice.

Acknowledgements
The authors acknowledge the Goiano Federal Institute of Education, Science and Technology (IF Goiano) for providing institutional support and research infrastructure. Special thanks are extended to the University of Rio Verde (UNIRV), the State University of Campinas (UNICAMP), through the Faculty of Agricultural Engineering (FEAGRI), and the Brazilian Agricultural Research Corporation (EMBRAPA) for academic collaboration, technical–scientific support, and institutional contributions that were fundamental to the development of this study, to the Pro-Rector for Research, Graduate Studies and Innovation (PROPII) for administrative and scientific support, and to the Coordination for the Improvement of Higher Education Personnel (CAPES) for support in academic training.

Author contributions
Taline Carvalho Martins performed data collection, database organization, and contributed to the scientometric analysis and interpretation of results. Thais Queiroz Zorzeto Cesar contributed to the methodological framework, critical discussion of thermal control in urban agriculture systems, and manuscript revision. Fábia Barbosa da Silva assisted in data interpretation, thematic categorization, and supported the discussion of controlled environment agriculture systems. Ítalo Moraes Rocha Guedes contributed to the analysis of technological and agronomic aspects of controlled environments and critically reviewed the manuscript. Edson Luiz Souchie contributed to the conceptual discussion, validation of results, and scientific consistency of the manuscript. Caíke da Rocha Damke supported data processing, visualization of scientometric outputs, and manuscript editing. Vinício da Cunha Doro contributed to data analysis, interpretation of scientometric indicators, and manuscript writing, with emphasis on methodological rigor and sustainability implications. Fabiano Guimarães Silva conceptualized the study, coordinated the research design, supervised the scientometric and qualitative analyses, and led the manuscript preparation. All authors reviewed and approved the final version of the manuscript.

Funding
The authors declare that this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study was conducted exclusively through bibliographic review and scientometric analysis of documents indexed in scientific databases. It did not involve human participants, animals, clinical procedures, or personal data collection. Therefore, ethical approval was not required. This study did not involve human participants.

Consent to publication
Not applicable. This manuscript does not contain any identifiable personal data, individual records, or images requiring consent for publication.

Declaration of artificial intelligence use
The authors declare that artificial intelligence tools were used exclusively to support language refinement, grammar correction, and stylistic improvement of the manuscript. No AI systems were employed in data collection, data analysis, interpretation of results, or generation of scientific content. All scientific decisions, analyses, and conclusions remain the sole responsibility of the authors.

Competing interests
The authors declare no competing interests.

Author details
[1]Laboratory of Advanced Studies in Vertical Agriculture, Goiano Federal Institute of Education, Science and Technology (IF Goiano), Campus Rio Verde, Rio Verde, Goiás 75901-970, Brazil
[2]School of Agricultural Engineering (FEAGRI), University of Campinas (UNICAMP), Av. Cândido Rondon, 501 - Cidade Universitária, Campinas, São Paulo 13083-875, Brazil
[3]Brazilian Agricultural Research Corporation (EMBRAPA), Embrapa Hortaliças, Brasília, Distrito Federal 70770-901, Brazil
[4]Center of Excellence in Bioinputs (CEBIO), Goiano Federal Institute of Education, Science and Technology (IF Goiano), Campus Rio Verde, Rio Verde, Goiás 75901-970, Brazil

Received: 20 February 2026 / Accepted: 23 April 2026

References

1. United Nations.: Transforming our world: the 2030 Agenda for Sustainable Development. United Nations. Accessed online. Available from: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf.
2. Picca G, Goñi-Urtiaga A, Lozano de Sosa L, Colombo Rodriguez MV, Navarro IF, Plaza C, et al. Sustainability in urban agriculture: the role of biochar in enhancing the productive capacity of compost-based growing media for rooftop farming. Urban Forest Urban Green. 2025;107:128774. https://doi.org/10.1016/j.ufug.2025.128774.
3. Stutte GW, Parrish CH, Bunchek JM, Ashton WS, Waller RE, Liotta M, et al. Controlled Environment Agriculture Design Standards (CEADS): Purpose, Development, and Implementation. In: 2023 ASABE Annual International Meeting. Omaha, Nebraska, USA; 2023. ASABE Paper No. 2300135.
4. Zhao X, Peng J, Zhang L, Yang X, Qiu Y, Cai C, et al. Optimizing the quality of horticultural crop: insights into pre-harvest practices in controlled environment agriculture. Front Plant Sci. 2024;15:1427471. https://doi.org/10.3389/fpls.2024.1427471.
5. Food and Agriculture Organization of the United Nations (FAO).: How to Feed the World in 2050. Rome: Food and Agriculture Organization of the United Nations. Expert paper / report. Available from: https://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf.
6. OECD, FAO. OECD-FAO Agricultural Outlook 2024–2033. Paris / Rome: OECD Publishing / Food and Agriculture Organization of the United Nations; 2024. Available from: https://www.oecd.org/en/publications/2024/07/oecd-fao-agricultural-outlook-2024-2033_e173f332.html.
7. Trost L, et al. Vertical farming: productivity, environmental impact, and resource use: a review. Agron Sustain Dev. 2025;45(2):1–25. https://doi.org/10.1007/s13593-025-01055-w.
8. Lima CEP, Fontenelle MR, Braga MB, Suinaga FA, Guedes ÍMR, da Silva J. Thermal severity on Brazilian lettuce crops under two global climate change scenarios. Caderno Pedagógico. 2025, 22(11), pp. 1–34. Curitiba. https://doi.org/10.54033/cadpedv22n11-105
9. Righini I, Stanghellini C, Hemming S, Graamans L, Marcelis LFM. Resources for plant-based food: Estimating resource use to meet the requirements of urban and peri-urban diets. Food and Energy Security. 2023;12(3):e462. https://doi.org/10.1002/fes3.462.
10. Stanghellini C, Katzin D. The dark side of lighting: A critical analysis of vertical farms' environmental impact. J Clean Prod. 2024;458:142359. https://doi.org/10.1016/j.jclepro.2024.142359.
11. Lal R. Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Security. 2020;12:871–6. https://doi.org/10.1007/s12571-020-01058-3.

12. Gu X, Goto E. Evaluation of plant canopy microclimates with realistic plants in plant factories with artificial light using a computational fluid dynamics model. Build Environ. 2024;264:111876. https://doi.org/10.1016/j.buildenv.2024.111876.
13. Shamshiri RR, Kalantari F, Ting KC, Thorp KR, Hameed IA, Weltzien C. Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. Int J Agricult Biol Eng. 2018;11(1):1–22. https://doi.org/10.25165/j.ijabe.20181101.3210.
14. Fei S, Wu R, Liu H, Yang F, Wang N. Technological Innovations in Urban and Peri-Urban Agriculture: Pathways to Sustainable Food Systems in Metropolises. Horticulturae. 2025;11(2):212. https://doi.org/10.3390/horticulturae11020212.
15. Takva Ç, Cudzik J, İlerisoy ZY. Digitalization of building site management in the construction industry. Int J Sustain Constr Eng Technol. 2023;14(4):171–93. https://doi.org/10.30880/ijscet.2023.14.04.014.
16. Wang S, Wang P, Cebula R, Foley M, Liang C. Scientometric analysis of development and opportunities for research in digital agriculture innovation management. Environ Modell Softw. 2025;188:106392. https://doi.org/10.1016/j.envsoft.2025.106392.
17. He D, Li H, Zhou P, Guo J, Yuan J, Wang J, et al. Leaf plasticity responses of four urban garden plants to low-light environments under viaducts. Forests. 2025;16(4):651. https://doi.org/10.3390/f16040651.
18. Carfora A, Lucibelli F, Di Lillo P, Mazzucchiello SM, Saccone G, Salvemini M, et al. Genetic responses of plants to urban environmental challenges. Planta. 2025;261:102. https://doi.org/10.1007/s00425-025-04678-1.
19. Lin ZE, Lin YC, Lee M, Chiueh PT, Wu CW, Chang YS. An integrated quantitative framework for exploring sustainable scenarios in urban agriculture planning. Sustain Environ Res. 2025;35:7. https://doi.org/10.1186/s42834-025-00241-5.
20. Moslinger L, Streit E, Korjenic A, Sulejmanoski A. Microclimatic Effects of Retrofitting a Green Roof Beneath an East-West PV Array: A Two-Year Field Study in Austria. Sustainability. 2025;17(16):7495. https://doi.org/10.3390/su17167495.
21. Yuan X, Hu J, Marcelis LFM, Heuvelink E, Peng J, Yang X, et al. Advanced technologies in plant factories: exploring current and future economic and environmental benefits in urban horticulture. Horticult Res. 2025;12(5):uhaf024. https://doi.org/10.1093/hr/uhaf024.
22. Zhang Y, Li J, Xu Q, Chen C, Nie S, Lei J, et al. Cytokinin modulates the inhibitory effect of shade stress on photosynthesis, antioxidant capacity and hormone homeostasis to regulate the grain yield in wheat. Front Plant Sci. 2024;15:1498123. https://doi.org/10.3389/fpls.2024.1498123.
23. Moore CE, et al. The effect of increasing temperature on crop photosynthesis: from enzymes to ecosystems. J Exp Bot. 2021;72(8):2822–39. https://doi.org/10.1093/jxb/eraa081.
24. Sun F, Zhang J, Takeda S, Cui J, Yang R. Vertical plant configuration: its impact on microclimate and thermal comfort in urban small green spaces. Land. 2024;13(10):1715. https://doi.org/10.3390/land13101715.
25. Vox G, Oliveira H, Vasconcelos M, Fonseca P, Cotta R, Pereira C. Green façades to control wall surface temperature in urban buildings. Build Environ. 2018;143:634–45. https://doi.org/10.1016/S0360-1323(17)30560-7.
26. Silva T, Lopes A, Vasconcelos J, Chokhachian A, Wagenfeld M, Santucci D. Thermal stress and comfort assessment in urban areas using Copernicus Climate Change Service Era 5 reanalysis and collected microclimatic data. Int J Biometeorol. 2024;68(5):949–63. https://doi.org/10.1007/s00484-024-02639-z.
27. Al-Hajri S, Al-Ramadan B, Shafiullah M, Rahman SM. Microclimate performance analysis of urban vegetation: evidence from hot humid middle eastern cities. Plants. 2025;14(4):521. https://doi.org/10.3390/plants14040521.
28. Zezzo LV, Coltri PP, Dubreuil V, Torres GAL, Amorim MCdCT. Exploring the urban heat island phenomenon in a tropical medium-sized city: insights for sustainable urban development. Environmental Monitoring and Assessment. 2025;197:445. Article number 445; Published 20 March 2025. https://doi.org/10.1007/s10661-025-13890-1.
29. Calfapietra C, Peñuelas J, Niinemets Ü. Urban plant physiology: adaptation-mitigation strategies under permanent stress. Trends Plant Sci. 2015;20(2):72–5. https://doi.org/10.1016/j.tplants.2014.11.001.
30. Schmidt K, Lima MJ, Haase D. Urban greening as a response to climate-related heat risk: A social-geographical review. Sustainability. 2023;15(6):4996. https://doi.org/10.3390/su15064996.
31. Saha S, Kumar R, Jain P. A review of adaptation strategies to increased urban temperatures and heat island effect. Discover Sustain. 2025;5(1):64. https://doi.org/10.1007/s44327-025-00064-4.
32. Sheikhnejad Y, Yigitcanlar T. Scientific landscape of sustainable urban and rural areas research: a systematic scientometric analysis. Sustainability. 2020;12(4):1293. https://doi.org/10.3390/su12041293.
33. Ledesma G, Nikolic J, Pons-Valladares O. Co-simulation for thermodynamic coupling of crops in buildings. Case study of free-running schools in Quito, Ecuador. Building and Environment. 2022;207:108407. Barcelona. https://doi.org/10.1016/j.buildenv.2021.108407.
34. Nolte AC, et al. Temporal temperature variation in urban gardens is mediated by local and landscape land cover and is linked to environmental justice. Front Sustain Food Syst. 2022;6:826437. https://doi.org/10.3389/fsufs.2022.826437.
35. Rahimi A, Nobar Z. The impact of planting scenarios on agricultural productivity and thermal comfort in urban agriculture land (case study: Tabriz, Iran). Front Ecol Evol. 2023;11:1048092. https://doi.org/10.3389/fevo.2023.1048092.
36. Vitoshkin H, Haslavsky V. Thermal Analysis and Climate Control of Experimental Two-Level Hydroponic Growth Cell. In: Proceedings of the 6th World Congress on Mechanical, Chemical, and Material Engineering (MCM'20). Prague, Czech Republic; 2020. p. HTFF 136. Paper HTFF 136. Available from: https://doi.org/10.11159/htff20.136.
37. Mun HS, et al. Energy-Efficient Technologies and Strategies for Feasible and Sustainable Plant Factory Systems. Sustainability. 2025;17(7):3259. Basel. https://doi.org/10.3390/su17073259.
38. Xie L, et al. Passive climate control innovations in Hunan courtyard dwellings: Enhancing indoor environmental and energy efficiency through integrated systems. Ain Shams Eng J. 2025;16:103442. https://doi.org/10.1016/j.asej.2025.103442.
39. Wang Y, et al. High-Order Neural-Network-Based Multi-Model Nonlinear Adaptive Decoupling Control for Microclimate Environment of Plant Factory. Sensors. 2023;23(19):8323. Basel. https://doi.org/10.3390/s23198323.
40. Yeo UH, Lee SY, Park SJ, Kim JG, Cho JH, Decano-Valentin C, et al. Rooftop Greenhouse: (2) Analysis of Thermal Energy Loads of a Building-Integrated Rooftop Greenhouse (BiRTG) for Urban Agriculture. Agriculture. 2022;12(6):787. https://doi.org/10.3390/agriculture12060787.
41. Lin Z, Yang Q, et al. Advance of environmental control in plant factory based on computational fluid dynamics. Fresenius Environ Bull. 2021;30(12):12708–13.

42. Wada T, Goto M, Furukawa H, Kitaya Y, Tojo M, Hirai N. Effects of environmental conditions for inducing flower bud initiation on plant growth and flowering of June-bearing strawberry grown under LED lighting. Acta Horticulturae. 2024;1404:1221–1228. IV Asian Horticultural Congress (AHC2023). https://doi.org/10.17660/ActaHortic.2024.1404.169.
43. Begum MS, Bala SK, Islam AKMS, Roy D. Environmental and Social Dynamics of Urban Rooftop Agriculture (URTA) and Their Impacts on Microclimate Change. Sustainability. 2021;13(16). https://doi.org/10.3390/su13169053.
44. Choi EJ, Lee D, Lee SM. Comparative analysis of the performance and energy consumption of air-conditioning systems in a plant factory during a cooling season. Energy Build. 2025;335:115483. https://doi.org/10.1016/j.enbuild.2025.115483.
45. Xu M, Fricker P. Urban Agriculture: Climate-Responsive Design Strategies for Blue Infrastructure in the Context of Singapore. J Digit Landsc Archit. 2023;8:292–300. https://doi.org/10.14627/537740031.
46. Vitoshkin H, Grinshpun J, Haslavsky V. Experimental modeling and thermal analysis of closed hydroponic system microclimate. J Fluid Flow Heat Mass Transfer. 2021;8:1–5. https://doi.org/10.11159/jffhmt.2021.001.
47. Wada T, Nishiura Y, Yamamoto T, Fujito H, Furukawa H, Ikeda H. Effects of air temperature in the light period on the fruit yield and quality of June-bearing strawberry grown in a controlled environment with artificial lighting. Eco-Eng. 2021;33:93–9. https://doi.org/10.11450/seitaikogaku.33.93.
48. Heo JW, Baek JH, Lee SH, Kim MJ, Shim CK. Environmental control in the plant factory system influences year-round production of allium hookeri leaves. Korean J Environ Agricult. 2023;42(4):279–85. https://doi.org/10.5338/KJEA.2023.42.4.32.
49. Zhang Y, Kacira M. Environmental control of PFALs. In: Plant Factory Basics, Applications and Advances. Elsevier; 2022. p. 391–400. https://doi.org/10.1016/B978-0-323-85152-7.00021-5.
50. Perez Garcia CA, Avgoustaki DD, Santolini E, Torreggiani D, Bartzanas T, Tassinari P, et al. Forecasting the vapor pressure deficit in vertical farming facilities aiming to provide optimal indoor conditions. J Agricult Eng. 2025;56(1):1793. https://doi.org/10.4081/jae.2025.1793.
51. Lu J, Li H, Zong C, Wang C, Song W, Yang D. Recent developments of thermal energy storage applications in the greenhouse environment: A comprehensive review. Energy Build. 2025;347:116342. https://doi.org/10.1016/j.enbuild.2025.116342.
52. Popa M, Balas VE, Alexuta D, Balas MM. Current Trends in Research on Temperature Control in Rooftop Greenhouses. In: 2025 18th International Conference on Engineering of Modern Electric Systems (EMES). IEEE; 2025. p. 1–6. https://doi.org/10.1109/EMES65692.2025.11045579.
53. Medina F. Necesidades nutricionales y de riego de la lechuga. Granja Revista Agropecuaria. 2017;22:104–11.
54. Carotti L, et al. Plant Factories Are Heating Up: Hunting for the Best Combination of Light Intensity, Air Temperature and Root-Zone Temperature in Lettuce Production. Front Plant Sci. 2021;11:592171. https://doi.org/10.3389/fpls.2020.592171.
55. Weidner T, et al. Energy optimisation of plant factories and greenhouses for different climatic conditions. Energy Convers Manage. 2021;243:114336. https://doi.org/10.1016/j.enconman.2021.114336.
56. Graamans L, et al. Plant factories; crop transpiration and energy balance. Agric Syst. 2017;153:138–47. https://doi.org/10.1016/j.agsy.2017.01.003.

Publisher's Note