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RESEARCH ARTICLE
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Plant Factory Perspectives in Support of Fruit: Bibliometric Analysis

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ABSTRACT

This study presents a bibliometric analysis of Plant Factory (PF) research in fruit crop production, mapping global trends, key contributors, and emerging topics from 2020 to 2024. Using Scopus as the primary data source, 13,593 initial documents were refined to 2,142 relevant studies based on inclusion criteria. Findings identify China as the leading contributor, with significant outputs on topics such as LED lighting, environmental control, postharvest quality, and productivity in fruit crops. Major journals include Scientia Horticulturae and Frontiers in Plant Science. Keyword co-occurrence analysis highlights key research clusters, including antioxidant capacity, yield optimization, and postharvest management, while emerging areas such as bioactive compounds and vertical farming suggest promising directions for future studies. The application of advanced technologies, such as IoT and AI, is identified as pivotal in improving PF systems' efficiency and sustainability. This study fills a critical gap in the literature, providing a comprehensive framework to understand PF research trends and its implications for sustainable agriculture. By emphasizing innovative technologies and sustainability, the findings aim to guide researchers and policymakers in addressing global challenges in food security and environmental resilience.

Keywords: Bibliometric analysis, Fruit crop production, Precision farming.

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INTRODUCTION

Over the last five decades, global food production has nearly tripled, significantly contributing to global economic growth (Bodirsky et al., 2015). However, projections by the United Nations estimate that the world population will reach approximately 8.5 billion by 2030 (Siregar et al., 2022). This population growth underscores the urgent need to enhance food production, distribution, and accessibility to ensure global stability. On the other hand, major challenges such as limited freshwater resources, unpredictable climate change, and population displacement further complicate efforts to meet the increasing demand for food. Open-field agricultural systems cannot fully address these challenges due to long supply chains, high operational costs and imbalances in freshwater resource availability.

Conventional agriculture also faces limitations caused by uncertain weather patterns, soil degradation, and inefficient use of water and fertilizers, all of which are exacerbated by the impacts of climate change (Kaya, 2025). In low- and middle-income countries, rising incomes have shifted food consumption patterns, with households allocating more of their spending to grains over fruits and vegetables due to affordability factors (FAO, 2017). However, the growing trend toward healthier eating habits is driving increased demand for sustainable farming practices among farmers (Rachma et al., 2024). This highlights the importance of agricultural innovations that support food production diversification, especially under varying environmental conditions.

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One promising and sustainable solution for improving crop yields with economic efficiency is the Plant Factory (PF) system. PF utilizes three core elements: light-emitting diode (LED) lighting, efficient crop growth management, and strict environmental control (Kozai et al., 2022). The advantages of PF systems include high crop yields, efficient water and nutrient usage, reduced pesticide requirements, shorter supply chains, and the ability to produce crops year-round. These features promote the sustainability of water and other resources (Cai et al., 2025). PF technologies have enabled the development of more efficient cultivation methods for seasonal crops such as tomatoes, strawberries, and melons, yielding higher harvests with improved quality (Oh & Lu, 2023).

Additionally, the controlled environment in PF systems enhances the concentration of health-beneficial bioactive compounds such as phenolics, anthocyanins, and ascorbic acid (de Sá Mendes & Branco de Andrade Gonçalves, 2020; Frías-Moreno et al., 2021). Advanced technologies such as the Internet of Things (IoT), automated sensors, and LED lighting are employed to precisely manage environmental parameters, including light, temperature, humidity, and nutrients. PF systems also enable year-round production, independent of seasonal or weather variations, ensuring a stable supply of fresh produce (Gargaro et al., 2023). However, further research is required to optimize energy efficiency, reduce operational costs, and minimize the environmental footprint of these systems in the long term.

Based on the latest developments in research, this study aims to analyze recent trends in PF research on fruit crops, identify key articles, authors, journals, and countries contributing to the field, and explore the development of research topics on PF for fruit crops. Additionally, this study investigates PF applications in the cultivation of fruit crops such as tomatoes and strawberries. By focusing on optimizing environmental conditions to improve crop yields, this study seeks to fill gaps in the literature on PF. The bibliometric approach employed also aims to identify key research keywords, providing new insights for researchers and future technological advancements.

MATERIALS & METHODS

Research Design

In this study, bibliometric analysis began with data mining by conducting a focused search of literature within the relevant subject area as recommended by Anshori et al. (2023). This systematic method was structured into clear stages, enabling reproducibility for future researchers. Dirpan et al. (2023) described that bibliometric analysis utilizes mind-mapping techniques to illustrate the boundaries of existing knowledge, which enhances the understanding of research trends and gaps. The bibliometric data were obtained from the Scopus database, renowned for its extensive collection of curated abstracts and citations, thus serving as a pivotal resource for bibliometric research (Rahmani et al., 2024).

This method is commonly applied across multiple fields and emphasizes quantitative analysis of journal articles, books, and other forms of written publications. In this study, the bibliometric analysis was divided into five stages: (1) defining search keywords, (2) obtaining preliminary search results, (3) refining these results, (4) compiling initial statistical data, and (5) analyzing the data (Fig. 1).

Data Source

This research was executed on 15 March 2024, employing a structured set of keywords as search strings relevant to Plant Factory (PF) technology. The keywords were strategically applied to search the titles, keywords, and abstracts of articles using the following criteria: TITLE-ABS-KEY ("Plant Factory") OR TITLE-ABS-KEY ("fruit and LED") OR TITLE-ABS-KEY ("Plant Factory and fruit").

These specified keywords enabled a focused and comprehensive retrieval of scholarly articles within the defined scope of the study. For the data source, the Scopus database was chosen due to its status as a leading, reputable repository of peer-reviewed scientific literature. Scopus provides access to a vast array of high-quality journal articles, ensuring the credibility and academic rigor of the articles gathered, which supports the reliability of the research outcomes.

Initial Search Result

The initial search using the specified keywords yielded a total of 13,593 documents from the Scopus database. No restrictions were imposed on the publication period to allow for a comprehensive mapping of the development and current state of research on the Plant Factory (PF) theme. The analysis revealed that the earliest relevant publication on PF appeared in early 2009, marking the beginning of scholarly interest in this field. Examples of key publications, including their authors, titles, sources, and publication years, are summarized in Table 1. Publications from as early as 1991 were identified; however, they were deemed less relevant to the focus of this study.

Refinement of Results

A systematic filtering process was applied to refine the initial search results from the Scopus database, focusing on literature published between 2020 and 2024. This selection was guided by two inclusion criteria: the articles had to be original research written in English, and the sources were restricted to peer-reviewed journal articles. Other sources, such as conference proceedings, book chapters, books, newspapers, letters, and editorials, were excluded to ensure

Fig. 1: Phases of the bibliometric analysis.

Table 1: Historical and Recent Publications on Plant Factory (PF) Studies

Author	Title	Source	Year of Publication
Iwao, K., Ikeda, A., & Nakayama, S.,	Control Application for PF	IFAC Symposia Series - Proceedings of a Triennial World Congress, 6, pp. 269-275.	1990
Kato, K., Yoshida, R., Kikuzaki, A., Hirai, T., Kuroda, H., Hiwasa-Tanase, K., Takane, K., Ezura, H., & Mizoguchi, T.	Molecular breeding of tomato lines for mass production of miraculin in a PF	Journal of Agricultural and Food Chemistry, 58(17), pp. 9505-9510	2010
Noh, A. M., Tahir, M. A. M., Mat, S., & Dzulkipli, M. H.	CFD simulation of temperature and airflow inside a shipping container size plant factory for optimal lettuce production	Food Research, 4, pp. 54-59	2020

that only high-quality scientific contributions were included.Additionally, duplicate articles were removed during the screening process to maintain data accuracy. The final results of this process were saved in RIS file format for further data analysis. Relevant keywords were identified by analyzing terms extracted from the database and incorporating prior knowledge of the research topic.

The final search keywords were constructed using the following Boolean combination:((TITLE-ABS-KEY ("Plant Factory") OR TITLE-ABS-KEY ("Plant Factory" AND "fruit") OR TITLE-ABS-KEY ("fruit" AND "LED") OR TITLE-ABS-KEY ("Plant Factory" AND "LED")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))). The use of Boolean operators enhanced the precision of the search, ensuring that the retrieved literature aligned with the study's inclusion criteria and was relevant for further analysis.

Data Analysis

Del-Aguila-Arcentales et al. (2024) explain that Scopus provides data export options, enabling researchers to export search results and citation data for further analysis using external tools. After the filtering process was completed, the search results were stored in RIS file format to support subsequent processing stages. According to Akhiruyanto and Yudhistira (2024), Mendeley was employed to enhance article metadata, including author names, titles, keywords, abstracts, and journal details such as publication year, volume, and page numbers. Aria and Cuccurullo (2017) emphasized that the dataset underwent verification, with additional information incorporated as needed to complete any incomplete records. The processed data were then systematically analyzed and categorized based on critical aspects, such as the annual number of publications, publication sources (journals), contributing authors, and subject areas. Furthermore, co-authorship and co-occurrence relationships were evaluated using VOSviewer software, as highlighted by Jia et al. (2025).

RESULTS & DISCUSSION

Plant Factory Research Trends in Fruit

Bibliometric analysis highlights the influence of Plant Factory (PF) technology on fruit crop research by analyzing metrics such as the number of publications per country, trends over time, inter-country collaborations, and international research efforts. The results show that publications related to PF in fruit crops are predominantly concentrated in Asia, with China leading in total outputs (4,146 documents), followed by Brazil (809), the USA (789), Spain (690), and Italy (694). This aligns with findings by Ares et al. (2021), Zhou et al. (2022), and Wang et al. (2023) who emphasized China and Brazil as major contributors to PF research in fruit crops. Asia dominates globally, accounting for 5,869 documents, while Africa shows minimal development in this field (Fig. 2).

The research gained significant momentum starting in 2020, driven by the growing global demand for sustainable agricultural solutions. Recent technological advancements, such as artificial intelligence (AI), the Internet of Things (IoT), and renewable energy integration, have further propelled PF research. AI and IoT are increasingly utilized to enhance operational efficiency, optimize resource use, and improve agricultural resilience (Puri et al., 2019; Mellit & Kalogirou, 2021).

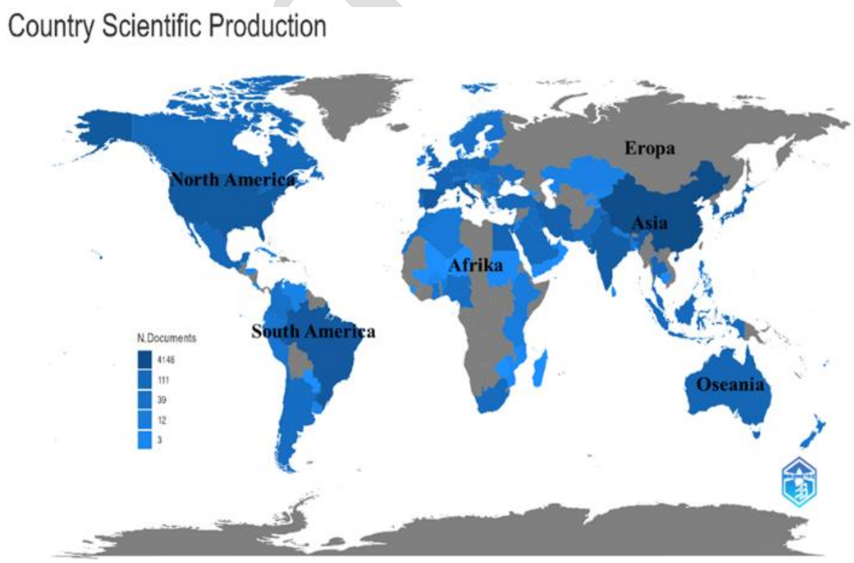

Fig. 2: Map of research distribution of PF in fruit crops in different regions of the world with bibliometrix.

For instance, IoT-enabled systems paired with AI models can significantly enhance monitoring and automation in PF systems, reducing resource waste and increasing yield efficiency (Rathor et al., 2024; Usigbe et al., 2024). These technologies address critical challenges such as climate change, food security, and energy efficiency by leveraging renewable resources and smart farming techniques. As highlighted by Kuldeep et al. (2024), AI-driven nutrient management systems have improved fruit yields by up to 20% under controlled environments. Such advancements underscore the evolving role of PF systems in meeting global agricultural demands and establishing sustainable practices.

China's dominance in annual publication output is particularly evident from 2022 to 2024, reflecting a substantial increase in studies and highlighting its leadership in Plant Factory (PF) research. This growth signifies China's focus on addressing food security challenges through advanced agricultural technologies, making PF research a pivotal area of interest in bibliometric analysis (Fig. 3). The number of publications related to PF in fruit crops has shown consistent growth, with the sharpest increase observed between 2022 and 2023. As of April 2024, preliminary data recorded 176 publications. However, a slight decline from 2021 to 2022 can likely be attributed to disruptions caused by the COVID-19 pandemic, such as research delays, labor shortages and restricted access to facilities, all of which adversely impacted publication rates (Alsharef et al., 2021).

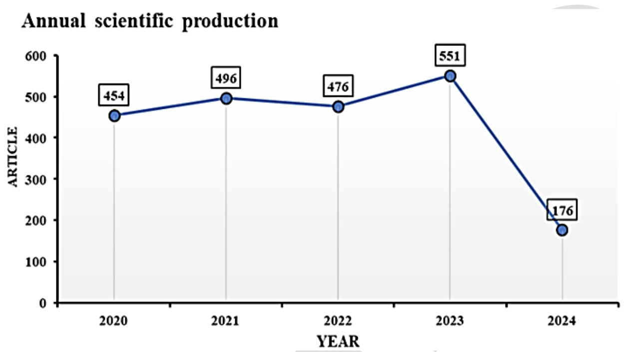

Fig. 3: Number of publications of PF journal articles on fruit crops from 2020-2024.

In addition to tracking publication trends, bibliometric analysis identifies emerging patterns and innovations in PF systems. Recent studies highlight the transformative role of artificial intelligence (AI) and the Internet of Things (IoT) in enhancing agricultural productivity, optimizing resource use and increasing resilience (Alreshidi, 2019; Hamed et al., 2024). Adaptive AI systems, capable of self-learning from real-time data, are now widely used in precision agriculture to optimize operations and decision-making (Akintuyi, 2024). Furthermore, remote sensing technologies and Agriculture 5.0 approaches are being integrated to ensure agricultural sustainability, especially in resource-constrained environments (Martos et al., 2021). In PF systems, the use of AI for energy optimization is increasingly coupled with renewable energy sources, offering sustainable solutions to reduce operational costs and environmental impact (Ukoba et al., 2024). Such advancements position PF research as a critical component in the global shift toward smart and sustainable agricultural practices.

The identification of PF literature trends in fruit crops was conducted using bibliographic coupling analysis, which groups similar works and related research points based on shared citation patterns (Jarneving, 2007). This method, implemented through VOSviewer, visualized relationships between publications, where similar research focuses are represented in the same color groups, and curved links illustrate citation connections (Fig. 4). The proximity of these groups highlights strong bibliographic relationships, providing insights into shared research themes and collaboration patterns. Recent studies emphasize the utility of bibliometric and scientometric tools in uncovering key trends and research connections, particularly in agriculture and allied disciplines (Hamdan & Alsuqaih, 2024; Zhang et al., 2024).

The bibliographic coupling analysis identified 10 clusters, 21 links, and a total link strength of 47 based on Scopus data. Among these, Samkumar (2021) emerged as a central publication with the highest total link strength of 39 and 21 links, reflecting its influence in PF-related research. Other significant contributors include García-Pastor et al. (2024), who explored preharvest and postharvest treatments in fruit quality improvement and Chen et al. (2021), who demonstrated the impact of CO_2 enrichment on lettuce growth in controlled environments.

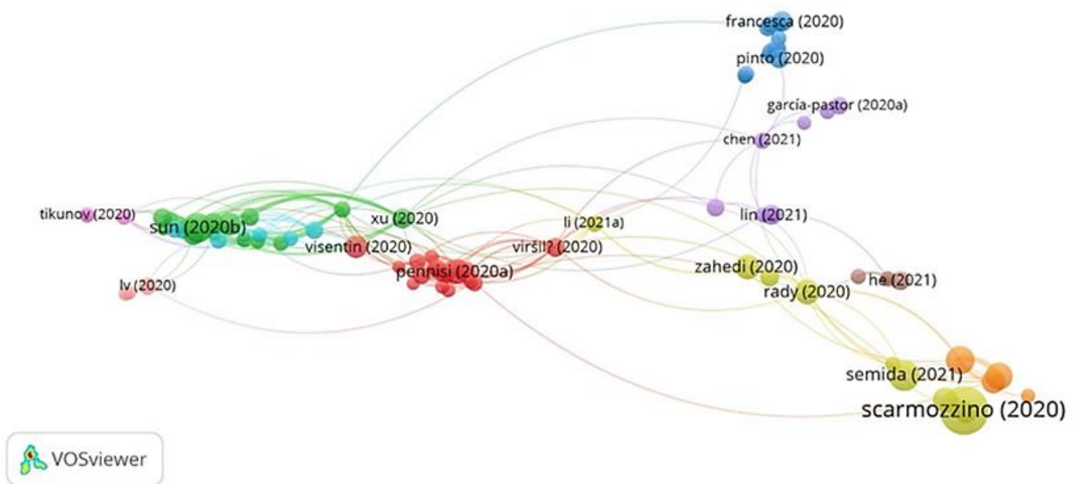

Fig. 4: The results of bibliographic coupling analysis of PF literature on fruit plants based on documents with VOS viewer.

These findings highlight overlapping research themes, such as the role of light quality, preharvest treatments, and CO_2 optimization in enhancing yield and quality in PF systems. Moreover, emerging technologies like artificial intelligence (AI) and the Internet of Things (IoT) have been increasingly integrated into PF research to improve resource efficiency and energy management (Morkūnas et al., 2024; Senoo et al., 2024). Such advancements illustrate the transformative potential of PF systems in addressing sustainability challenges and optimizing agricultural practices.

Lead Author Plant Factory Research in Fruit

Based on the citation analysis presented in Fig. 5, ten authors have significantly contributed to Plant Factory (PF) research on fruit crops, each with more than one publication. Data were analyzed using bibliometric methods from the Scopus Database (or Web of Science, depending on your database). According to the bibliometric analysis performed in this study (Fig. 5), Wang, Y. stands out as the most prolific contributor to Plant Factory (PF) research in fruit crops, with 59 publications. Zhang, Y. and Li, J. follow with 49 and 45 publications, respectively. Zhang, X. has authored 43 articles, while Wang, X. and Li, J. have published 38 and 33 articles, respectively. Other significant contributors include Liu, Y. and Zhang, Z., each with 30 articles, and Liu, X., who has authored 28 articles.

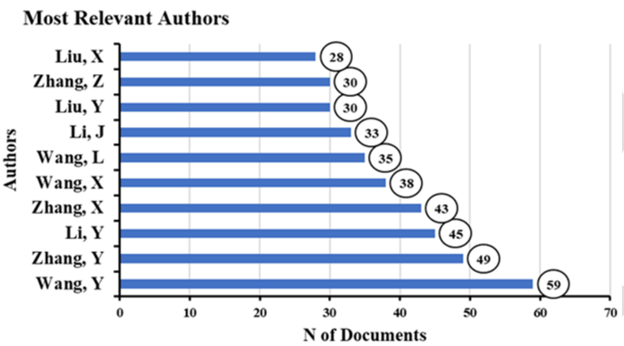

Fig. 5: Citation analysis of PF literature on fruit crops by author.

Recent research highlights the significant contributions of these authors in advancing PF technology and its applications. For instance, Zhang and Kacira (2022) explored climate uniformity in PF systems using computational fluid dynamics (CFD), providing insights for improving environmental control in indoor systems. Similarly, previous studies have extensively studied the effects of environmental lighting on crop growth and quality, emphasizing its role in optimizing photosynthesis and energy efficiency (Zou et al., 2024; Zhang et al., 2018). Meanwhile, Liu, Y.'s work on speed breeding in PF systems demonstrates how these technologies can enhance metabolic diversity and accelerate rice generation time, offering breakthroughs in agricultural productivity (Liu et al., 2024). Additionally, Liu et al. (2021) highlighted the integration of industrial communication and computing in PF, transforming it into a smart and efficient agricultural system. The collaborative and innovative work of these authors underscores their pivotal role in driving PF research forward. Their contributions not only advance knowledge in optimizing environmental conditions but also address broader challenges such as reducing energy loss, increasing yield, and enhancing sustainability in PF systems. The integration of advanced technologies, as reflected in these studies, continues to shape the future of controlled-environment agriculture.

Main Articles on Plant Factory Research in Fruit

To identify the key articles used as main references in Plant Factory (PF) research on fruit crops, co-citation and citation analyses were conducted. Based on the co-citation network analysis (Fig. 6a, b), the most globally cited document, with 376 citations, is Scarmozzino et al. (2020), titled "Covid-19 and the Subsequent Lockdown Modified the Dietary Habits of Almost Half the Population in an Italian Sample." This article highlights the broader implications of food security and nutrition, themes that are increasingly relevant in PF research. Another highly cited document is Rodríguez-Pérez et al. (2020), which has received 366 citations and explores nutrient optimization, a crucial focus in PF studies.

The co-citation analysis revealed two distinct knowledge groups in PF literature on fruit crops, as visualized in Fig. 6a. Group 1 (red) contains five articles that primarily discuss PF applications in fruit plants, with the main article authored by Abdelraouf et al. (2020). This group emphasizes agronomic practices, environmental controls, and energy-efficient strategies in PF systems. Group 2 (blue) contains one article focusing on PF's role in sustainable agricultural practices, with Abbasi et al. (2023) as the primary reference. The clear distinction between these groups reflects the thematic evolution of PF research, highlighting both its technical and sustainability-oriented aspects.

These results demonstrate that PF research integrates multidisciplinary approaches, from technical advancements in controlled-environment systems to addressing global challenges in food security and sustainability. The highly cited articles indicate the pivotal role of PF in developing innovative solutions for future agricultural practices.

Main Countries of Research Publications on plant Factory in Fruit

Based on citation analysis, China leads in the production of Plant Factory (PF) research on fruit crops, with an impressive total of 570 documents. The United States follows with 132 documents, and Brazil ranks third with 122 documents (Fig. 7). Other notable contributors include Spain (119 documents), India (101 documents), and Italy (93 documents). Asian countries dominate this field, reflecting a strong regional focus on sustainable agricultural development and advanced controlled-environment agriculture systems.

The integration of cutting-edge technologies and practices, such as vertical farming, AI-driven optimization, and energy-efficient solutions, has propelled PF research to address global challenges like climate change and food security (Erekath et al., 2024; Benedek et al., 2023). China's leadership in PF research reflects its significant investment in precision agriculture and water -saving technologies to

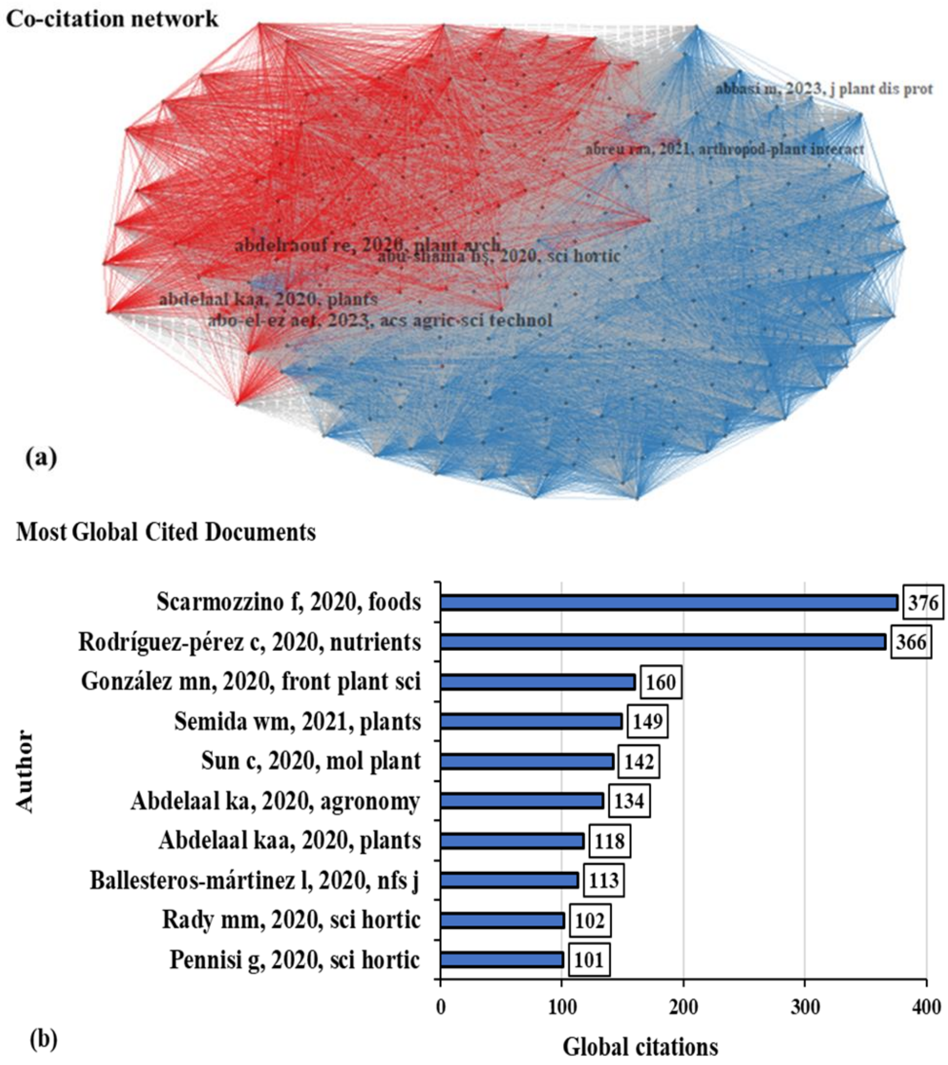

Fig. 6: Co-citation analysis (a) co-citation network with bibliometrix and (b) PF literature on fruit plants by author.

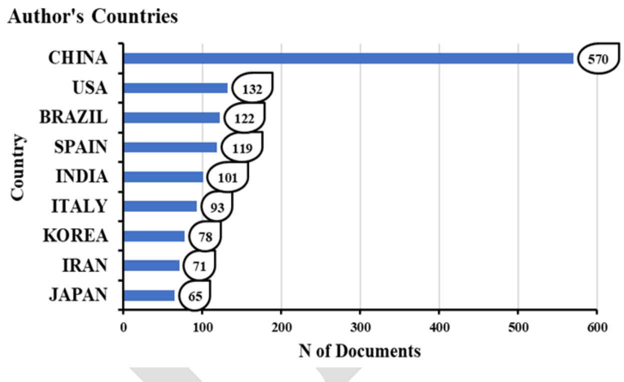

Fig. 7: Citation analysis of PF literature on fruit crops by author.

enhance crop yields while reducing environmental footprints (Lakhiar et al., 2024). Similarly, the United States and Brazil contribute through sustainable agricultural practices, focusing on nutrition-sensitive agriculture and energy security (Tedesco et al., 2023). These advancements align with the growing need for AI integration and resource-based approaches to optimize agricultural sustainability (Petcu et al., 2024). The trends identified in PF research illustrate a global collaboration to innovate controlled-environment agriculture. From vertical farming technologies to smart irrigation systems, the contributions from leading countries demonstrate the transformative potential of PF systems to support sustainable food production, enhance resource efficiency, and minimize environmental impacts (Ragaveena et al., 2021).

Main Journal of Research Plant Factory in Fruit

Based on citation analysis, the journal Scientia Horticulturae, published by Elsevier, stands out as the most productive and influential journal in Plant Factory (PF) research on fruit crops, with a total of 101 articles (Fig. 8).

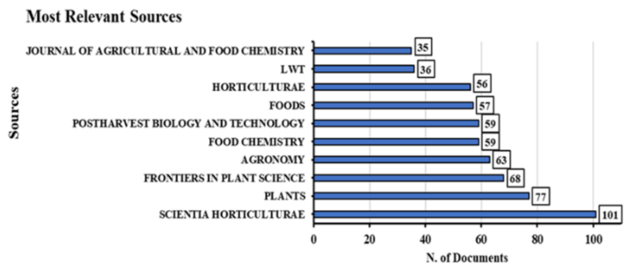

Fig. 8: Citation analysis of PF literature on fruit crops based on journals.

This journal plays a pivotal role in advancing PF research, particularly in optimizing vertical farming practices, controlled-environment agriculture, and light management strategies. For instance, Chen et al. (2022) proposed a dry weight-based model for regulating light intensity in tomato cultivation, providing valuable insights into optimal growth conditions. Similarly, Yamaura et al. (2023) demonstrated how day-night temperature variations and high light intensity under elevated CO_2 conditions improve carbohydrate utilization and seedling growth in tomato plants. These findings underscore the journal's contribution to advancing knowledge in light optimization and crop physiology in PF systems.

The integration of advanced technologies in postharvest management is another critical area of research published in leading journals like Postharvest Biology and Technology. Mastilović et al. (2024) highlighted the role of sensor technologies in improving storage conditions and reducing postharvest losses, while Liu et al. (2023) demonstrated how intense pulsed light treatments can stabilize strawberry flavor by modulating the lipoxygenase pathway. These innovations align with the growing focus on enhancing crop quality and sustainability in PF systems. Furthermore, the application of Internet of Things (IoT) technologies in agricultural systems has been explored in journals like Computers in Industry. Jagtap et al. (2021) emphasized how IoT solutions can optimize resource efficiency in food manufacturing, which has significant implications for controlled-environment agriculture. These contributions highlight the multidisciplinary nature of PF research, bridging horticulture, postharvest technologies, and engineering to address global challenges in food security and sustainability.

Main Topics on Plant Factory in Fruit

The main topics in Plant Factory (PF) research on fruit crops were determined using co-occurrence analysis with VOSviewer software (Fig. 9). From 2,142 documents retrieved from the Scopus database, a total of 7,436 author keywords were extracted. To ensure consistency and eliminate redundancy, a thesaurus program was applied to unify similar keywords differing only in singular/plural forms or synonyms (e.g., "amino acid" and "amino acids"; "antioxidant" and "antioxidants"). Applying a threshold of at least 12 occurrences per keyword, the analysis identified 50 final keywords representing the primary topics in PF research.

The co-occurrence analysis revealed six distinct clusters representing thematic focuses in PF research. Cluster 1 emphasizes tomato and yield, focusing on growth optimization under controlled environments. Yamaura et al. (2023) demonstrated that high light intensity and day-night temperature variations under elevated CO_2 conditions improve carbohydrate utilization and seedling development in tomatoes. Similarly, Ahmed et al. (2024) highlighted the role of greenhouse cultivation in enhancing productivity and crop quality, reflecting the importance of advanced cultivation techniques. Cluster 2 revolves around fruit quality and postharvest management, with studies exploring storage optimization and sensory improvement. For instance, Liu et al. (2023) investigated the use of intense pulsed light treatments to stabilize strawberry flavor postharvest, while Mastilović et al. (2024) highlighted the growing role of sensors in improving storage efficiency and reducing losses.

Cluster 3 addresses antioxidant capacity and nutritional value, particularly through the study of polyphenols and phenolic compounds. Noreen et al. (2024) discussed the nutritional benefits and industrial applications of bioactive compounds in sweet potatoes, contributing to innovations in functional food development. Postharvest biochemical mechanisms, particularly those addressing chilling injury, dominate Cluster 4. Zhang et al. (2021) reviewed advancements in control technologies to mitigate chilling injuries in fruits and vegetables, providing key insights into improving storage stability. Cluster 5 explores the integration of PF systems and photosynthesis optimization through advanced technologies such as IoT and automation. Fatima et al. (2022) demonstrated how IoT enhances operational efficiency and automates production processes, aligning with the goals of Industry 5.0. Furthermore, Lakhiar et al. (2024) reviewed precision irrigation technologies that improve water use efficiency and reduce environmental footprints, highlighting their critical role in sustainability.

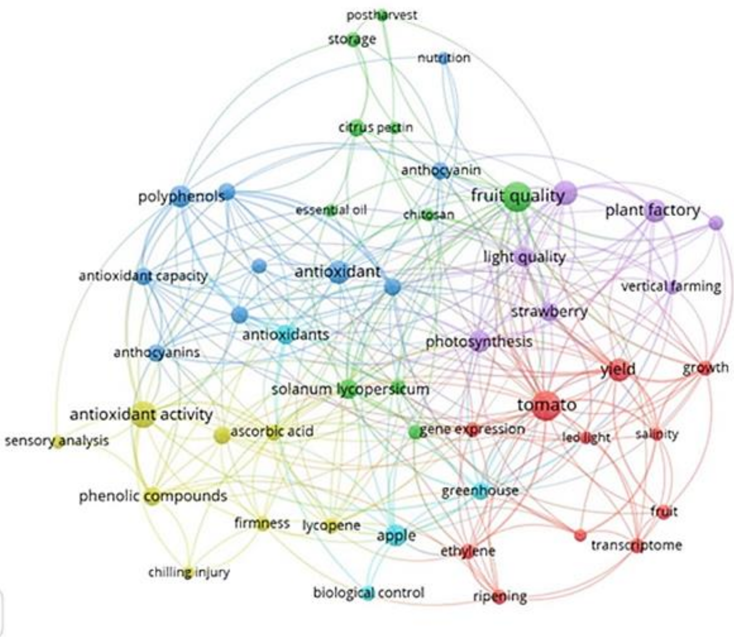

Fig. 9: The final result of network visualisation of PF literature in fruit crops in VOS viewer.

Cluster 6 focuses on greenhouse systems and energy efficiency, addressing the increasing demand for sustainable agricultural practices. Corigliano and Algieri (2024) examined energy consumption challenges in the food industry, emphasizing the need for energy-efficient solutions in PF systems. Additionally, Mastilović et al. (2024) highlighted the role of sensors and smart technologies in optimizing energy usage and maintaining consistent environmental conditions in greenhouses, contributing to both productivity and sustainability. These findings illustrate the multidisciplinary nature of PF research, bridging horticulture, food science, and engineering to address critical aspects of crop production, postharvest quality, and environmental sustainability. By identifying these clusters, this analysis provides valuable insights into emerging trends and future directions for PF systems in fruit crop research.

The main topics in Plant Factory (PF) research on fruit crops were determined using co-occurrence analysis with VOSviewer software (Fig. 10 and 11). From 2,142 documents analyzed, a total of 7,436 author keywords were extracted, with 50 prominent keywords identified based on their frequency and relationships within the dataset. The visualization revealed frequent keywords like "fruit quality," "antioxidants," and "yield," reflecting high research interest, while less frequent terms like "nutrition" and "vertical farming" indicate emerging areas requiring further exploration.

Environmental control emerges as a dominant theme in PF research, particularly in optimizing growth and yield. Studies such as Yamaura et al. (2023) demonstrate that controlling CO_2 levels and high light intensity significantly improves carbohydrate utilization and seedling growth in tomatoes. Similarly, Chen et al. (2022) highlights the importance of light intensity regulation in enhancing tomato dry weight, while Zou et al. (2024) explores strategies to reduce energy loss in PF systems. These findings align with the increasing focus on sustainable agricultural practices. Ahmed et al. (2024) also emphasizes the role of vertical farming and greenhouse cultivation in

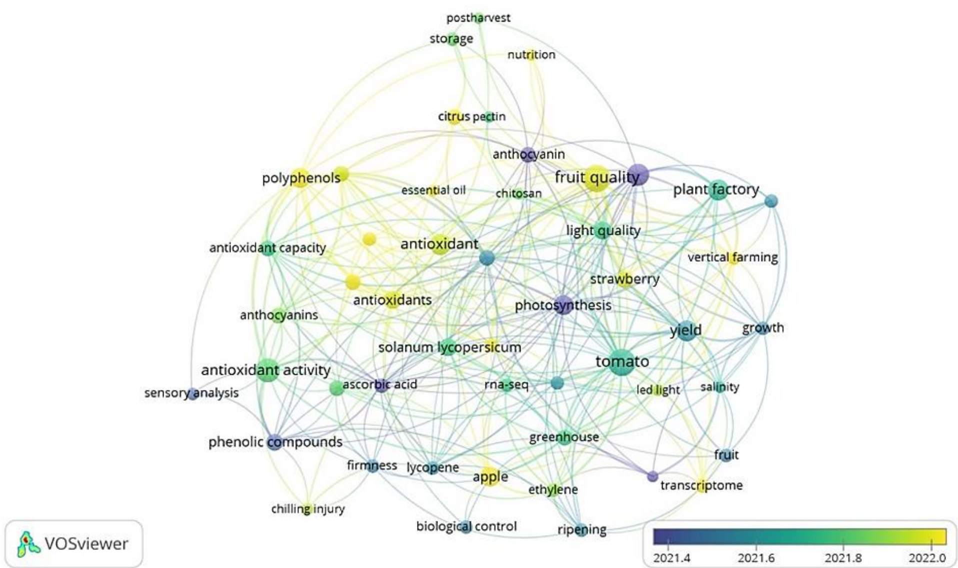

Fig. 10: Final result of overlay visualisation of PF literature on fruit plants in VOS viewer.

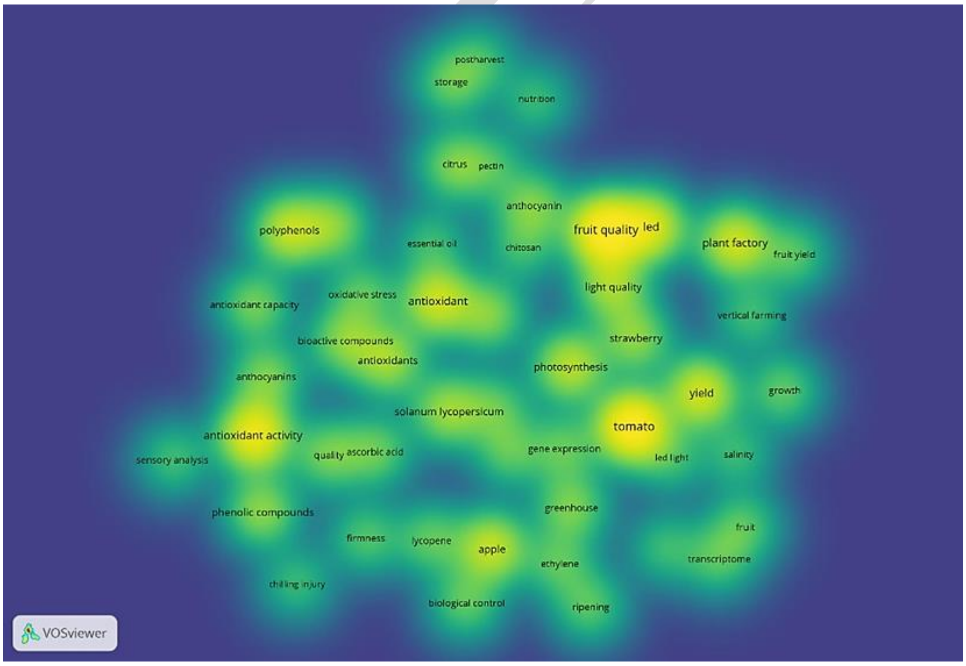

Fig. 11: Final results of density visualisations of PF literature on fruit plants in VOS viewer.

boosting crop productivity and quality. Another critical area in PF research involves the nutritional and antioxidant value of crops. Keywords like "polyphenols" and "bioactive compounds" underscore the significance of these components in enhancing food quality. Noreen et al. (2024) reviewed the industrial applications of bioactive compounds in sweet potatoes, contributing to innovations in functional foods. Similarly, Zhang et al. (2022) explored biochemical mechanisms to mitigate chilling injury in postharvest fruits and vegetables, providing solutions to maintain storage stability.

Postharvest technologies are another key area of interest, with a focus on improving storage conditions and reducing postharvest losses. Liu et al. (2023) investigated the application of intense pulsed light to stabilize strawberry flavor postharvest, while Mastilović et al. (2024) highlighted the role of sensors in optimizing storage efficiency. García-Pastor et al. (2020) demonstrated the effectiveness of pre- and postharvest treatments in reducing chilling injury and maintaining phenolic content, further showcasing advancements in this domain. IoT and AI are increasingly being integrated into PF systems to enhance operational efficiency and sustainability. Fatima et al. (2022) discussed how IoT-based automation aligns with the principles of Industry 5.0, enabling smarter production systems. Similarly, Senoo et al. (2024) and Martos et al. (2021) emphasized the role of IoT and AI in optimizing precision agriculture and environmental control. Usman and Yusuf (2024) reviewed the integration of smart logistics and precision farming techniques to optimize transportation systems, demonstrating their relevance in enhancing supply chain efficiency while maintaining environmental sustainability.

Energy efficiency and sustainability are also pivotal in PF research. Corigliano and Algieri (2024) analyzed energy consumption challenges in the food industry, emphasizing the importance of adopting energy-efficient solutions in controlled-environment agriculture. These findings are supported by Erekath et al. (2024), who explored innovative energy-saving practices in vertical farming, ensuring resource optimization and cost reduction. These insights illustrate the multidisciplinary nature of PF research, bridging horticulture, food science, and engineering to address critical aspects of crop production, postharvest quality, and environmental sustainability. By leveraging advanced technologies and integrating sustainable practices, PF systems hold the potential to transform fruit crop research and contribute to global food security.

Conclusion

This study provides a comprehensive bibliometric analysis of Plant Factory (PF) research based on peer-reviewed journals from the Scopus database, highlighting the rapid growth and emerging trends in this field over the past four years (2020–2024). The analysis underscores the increasing influence of ICT integration in plant factory systems and identifies key trends in publication outlets, contributing authors, productive countries, influential articles, and core research topics. The findings reveal that while PF research has expanded significantly, it remains in a developmental stage, providing ample opportunities for further exploration. Through the refinement process, an initial dataset of 13,593 documents was reduced to 2,142 datasets that met predetermined inclusion criteria. The cluster analysis identified major research topics based on keyword associations, such as environmental control, postharvest management, antioxidant capacity, and sustainability. Furthermore, the identification of infrequently occurring keywords, such as "bioactive compounds" and "vertical farming," highlights potential research areas for future studies, marking a key contribution of this research to the field. This study fills a critical gap in the literature, as no bibliometric analysis has been conducted on Plant Factory research in the past five years, thereby providing an updated overview of its progress and emerging areas. Another contribution of this study lies in its application of VOSviewer for mapping and visualizing bibliometric data. The use of this tool has demonstrated its effectiveness in identifying research trends and visualizing keyword co-occurrence, which is particularly valuable given the limited application of VOSviewer in previous PF bibliometric studies. The analysis enriches the understanding of PF literature and offers a framework for future bibliometric studies.

Despite its contributions, this study has certain limitations. The dataset was exclusively derived from the Scopus database, focusing solely on peer-reviewed journals. Future research should incorporate additional electronic databases, such as IEEE Xplore, Web of Science (WoS), Springer, and Crossref, to ensure a broader and more diverse dataset. Moreover, comparative analyses using alternative bibliometric tools, such as Hitscite and BibExcel, are recommended to minimize subjective bias and enhance the robustness of the findings. In conclusion, this study provides an essential foundation for understanding the current state of PF research and identifies key areas for future exploration, including interdisciplinary approaches, advanced technologies like IoT and AI, and sustainable practices. The insights presented in this study aim to guide researchers and policymakers in advancing PF systems to address global challenges in food security, environmental sustainability, and agricultural innovation.

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