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Digital Twins and Energy Management in Smart Greenhouses: An Emerging Bibliometric Landscape (2016–2025).

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INTRODUCTION & AIM

Greenhouse agriculture faces increasing challenges related to food security, sustainability, and energy efficiency, which have driven its transition toward highly technified and industrialized production systems characterized by the intensive use of sensors, automation, and advanced digital technologies [1]. This transformation has led to the emergence of smart, data-driven greenhouses, where processes such as climate control, irrigation, fertigation, lighting, and crop monitoring are managed through digital infrastructures supported by cloud computing, the Internet of Things, big data analytics, and machine learning [2]. Within this context, digital twins have emerged as an enabling technology capable of virtualizing physical assets, replicating their behavior in real time, and simulating operational scenarios to optimize decision-making while enhancing productivity and sustainability across agricultural systems [3]. Nevertheless, despite their considerable potential, the application of digital twins to greenhouse energy management remains incipient and fragmented. Therefore, this study aims to systematically analyze the evolution, trends, and knowledge structure of the scientific literature concerning the use of digital twins and related digital technologies for energy optimization in greenhouses through a bibliometric approach, with the objective of characterizing the state of the art and identifying future research opportunities.

METHOD

A bibliometric analysis was conducted following the PRISMA guidelines for the identification, screening, and selection of scientific literature [4]. The search was performed in the Scopus database, covering the period 2016–2025, using the query: TITLE-ABS-KEY (("digital twin" OR "digital design") AND "greenhouse" AND ("energy system" OR "solar energy")) AND NOT ("greenhouse gas")*. The retrieved records were filtered, standardized, and subsequently analyzed using Bibliometrix (R) to compute scientific performance indicators (production, citations, growth, and collaboration), and VOSviewer to visualize bibliometric networks of keyword co-occurrence and co-authorship. The final dataset comprised 19 documents, whose evaluation enabled the characterization of thematic trends, collaborative structures, and consolidation dynamics within the field, thereby providing a comprehensive overview of the state of the art in digital twins and energy management in smart greenhouses.

RESULTS & DISCUSSION

General Characteristics of the Knowledge Structure

Based on the bibliometric indicators obtained for the period 2016–2025, the field of digital twins applied to energy management in greenhouses exhibits an emerging yet dynamic profile, comprising 19 documents published across 14 sources and produced by 154 authors, with no single-author contributions, reflecting a strongly collaborative research environment (9.63 co-authors per article). Scientific output shows an annual growth rate of 24.14%, accompanied by an international collaboration rate of 10.53%, while an average of 12.21 citations per document and a mean document age of 3.37 years confirm the recent consolidation and increasing scholarly interest in the topic. Overall, these indicators characterize an interdisciplinary and rapidly expanding domain with significant impact potential, driven by the convergence of digitalization, artificial intelligence, and energy efficiency in smart greenhouse systems.

Annual Scientific Production

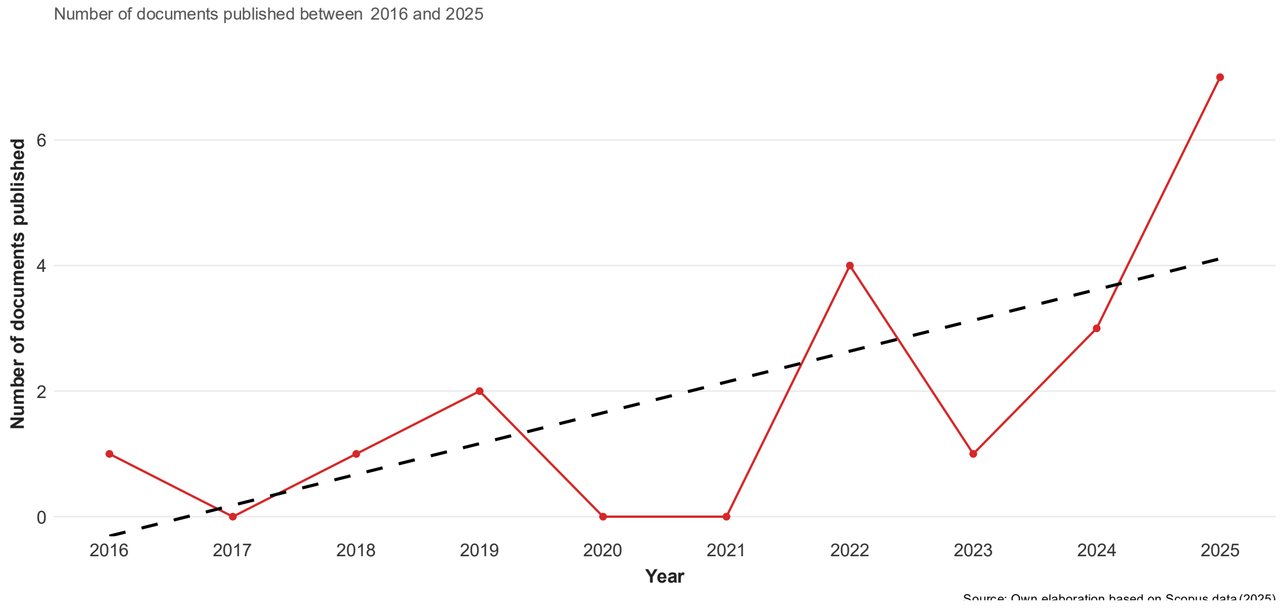
Scientific production displays an incipient and discontinuous pattern between 2016 and 2021, followed by a marked increase from 2022 onward, reaching its peak in 2025. This upward trend confirms the recent consolidation and growing research interest in digital twins for greenhouse energy management.

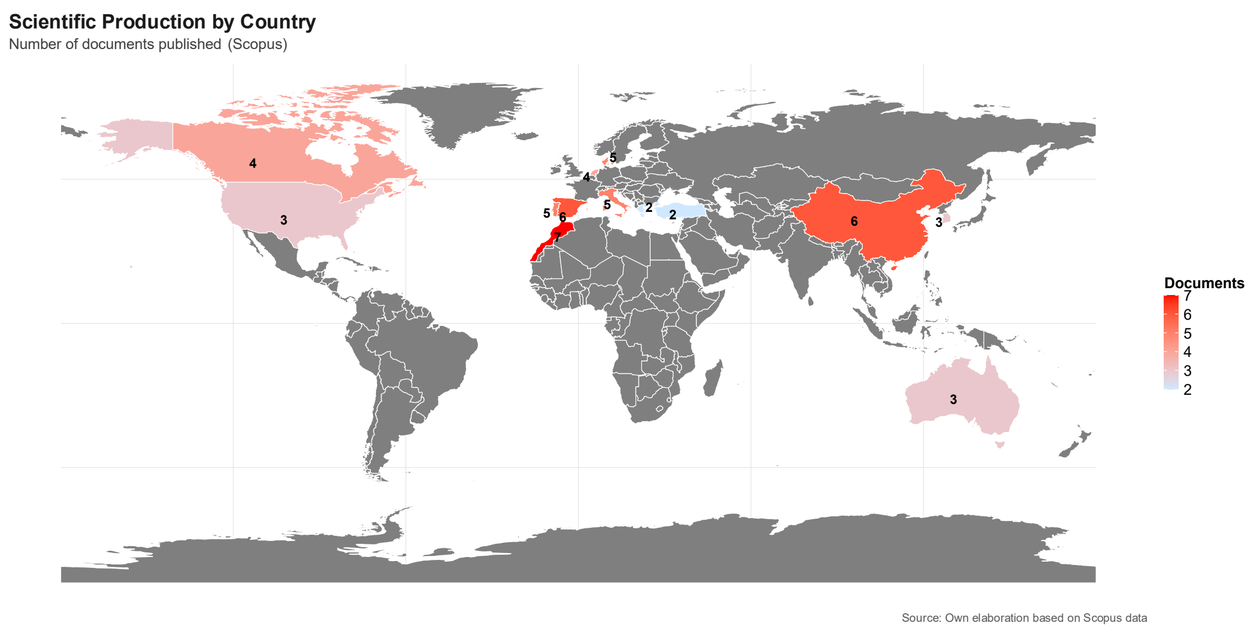
Leading Countries and Institutions in Scientific Production

The geographic distribution of scientific output reveals a concentrated yet collaborative landscape, led by Morocco (7 documents), China and Spain (6 each), followed by Denmark, Italy, and Portugal. Additional contributions from Canada, Netherlands, Australia, South Korea, United States, Greece, and Turkey indicate broad international participation. At the institutional level, Université Moulay Ismaïl, Universidade da Coruña, Syddansk Universitet, and Wageningen University & Research emerge as leading academic hubs driving research in this area.

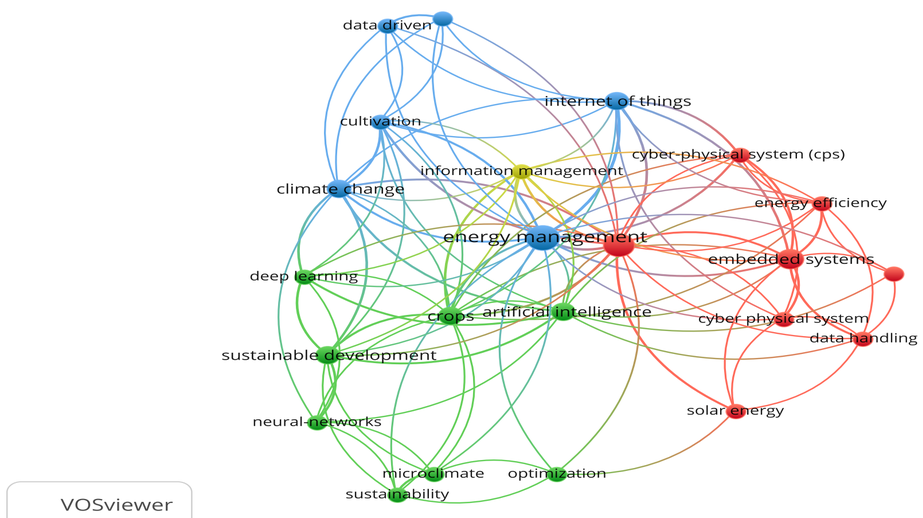
Keyword Co-occurrence Network

Network reveals a thematic architecture centered on the integration of energy management as the node with the highest centrality and link density, strongly connected to artificial intelligence, Internet of Things, and cyber-physical systems, indicating a digital infrastructure oriented toward sensing, predictive modeling, and automated greenhouse control. Clusters associated with optimization, solar energy, embedded systems, and data handling represent the technological implementation layer, whereas crops, sustainability, and microclimate reflect the agroproductive dimension of the system.





Overall, the network topology confirms that digital twins operate as an integrative cyber-physical framework enabling simulation, real-time monitoring, and energy optimization in smart greenhouses, thereby consolidating an emerging and highly interdisciplinary scientific domain.



CONCLUSION AND FUTURE WORK

Overall, the bibliometric analysis demonstrates that research on digital twins and energy management in smart greenhouses constitutes an emerging, interdisciplinary, and rapidly expanding field, in which the convergence of cyber-physical technologies, artificial intelligence, and energy optimization is shaping key digital solutions to enhance the efficiency and sustainability of protected agriculture. As future research directions, it is recommended to advance the implementation of real-time digital twins, strengthen data interoperability and standardization, and empirically validate their application in commercial greenhouses and low-cost contexts, in order to maximize operational efficiency and energy sustainability in protected agriculture.

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