Journal of Biological and Environmental Sciences

e-ISSN 1308-2019
https://dergipark.org.tr/en/pub/jbes
http://www.uludag.edu.tr/jbes

2026, 58, 18327431

Received: 02 October 2025
Accepted: 22 January 2026

RESEARCH ARTICLE
https://doi.org/10.5281/zenodo.18327431

Agriculture 4.0 Research (2018–2025): Bibliometric Insights into Trends, Gaps, and Global Inequalities[A]

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Abstract: This study provides a global bibliometric assessment of Agriculture 4.0 research from 2018 to 2025, analyzing 156 Web of Science–indexed publications to identify major thematic trends, research gaps, and geographical imbalances. The results show that scholarship in this field is predominantly driven by technological innovations—such as IoT, artificial intelligence, and big data-while social justice, data governance, and digital accessibility remain marginal, particularly for smallholder farmers and low-income contexts. Significant regional inequalities are evident, with Sub-Saharan Africa, Central Asia, and parts of Latin America receiving limited scholarly attention and participating weakly in collaborative networks. The study highlights the need for interdisciplinary, equity-oriented frameworks that incorporate ethical data practices and local knowledge systems. These insights can guide researchers and policymakers in advancing more inclusive and resilient pathways for digital agricultural transformation.

Keywords: Agriculture 4.0, digital inequality, sustainable development, bibliometric analysis, data governance

[A] The study does not require approval from an ethics committee. The article has been prepared according to research and publication ethics.

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Atıf/Citation: Kirmikil, M. 2026. Agriculture 4.0 research (2018–2025): Bibliometric insights into trends, gaps, and global inequalities. *Journal of Biological and Environmental Sciences*, 58, 18327431.

Introduction

In the 21st century, global agriculture is facing challenges from climate change, biodiversity loss, soil degradation, rural depopulation, and widening inequalities in food access. With the world population expected to surpass 9.7 billion by 2050, agricultural systems must simultaneously ensure food provision, economic viability, and ecological sustainability (Satterthwaite 2009; United Nations, 2019). Urbanization further exacerbates labor shortages, farmland fragmentation, and the erosion of traditional knowledge in many rural regions (Carolan, 2020; Wolfert et al., 2017).

In response, digital technologies—commonly referred to as Agriculture 4.0—have emerged as a transformative pathway for agricultural production. Innovations such as IoT, artificial intelligence, robotics, big data analytics, drone imaging, and blockchain-based traceability aim to optimize resource use, strengthen decision-making, and improve productivity while reducing environmental impacts (Bezas and Filippidou, 2023; Eashwar and Chawla, 2021; Kamilaris et al., 2017; Lezoche et al., 2020; Liu et al., 2021; Mutalemwa, 2023). Empirical studies demonstrate their transformative potential: AI-driven precision irrigation has reduced water consumption in India and Morocco (Kumar et al., 2021; Zhai et al., 2020), smart farming programs in Indonesia have enhanced smallholder productivity (Sudaryanto et al., 2022), IoT-based monitoring tools are being tested in Sub-Saharan Africa (Mutalemwa, 2023). Deep learning–powered robotic systems support automated weeding and harvesting in Europe (Milioto et al., 2018; Zambon et al., 2019).

Despite these advances, access to smart farming technologies remains highly uneven, reinforcing existing social and spatial inequalities (Klerkx and Rose, 2020; Rose and Chilvers, 2018). Rural and low-income regions often lack adequate connectivity, digital tools, and institutional support, creating a "technology trap" in which digital exclusion amplifies longstanding disparities in land ownership, gender, and education (Abbasi et al., 2022; Carolan 2020; Jakku et al., 2019; Klerkx et al., 2019; Rotz et al. 2019). Data governance poses additional challenges, as privately controlled sensor- and drone-generated data raises concerns about autonomy, privacy, and algorithmic transparency (Carolan, 2020; Crawford and Calo, 2016). Unregulated AI-based decision-support systems may further embed biases or marginalize non-commercial farming models, while concentrated digital infrastructure limits innovation in marginal environments and overlooks traditional knowledge essential for local adaptation (Carone et al., 2025; Y. Xu et al., 2022).

Although Agriculture 4.0 research has expanded rapidly since 2018, structural imbalances persist. Scholarly output is concentrated in Brazil, India, China, and Italy, while contributions from Sub-Saharan Africa, Central Asia, and the Middle East remain limited (Carmo-Filho and Ribas, 2024; Kushartadi et al., 2023). Collaboration networks are also uneven, with most partnerships occurring within national or regional boundaries and few cross-continental initiatives (Hu et al., 2024). The literature continues to prioritize technical optimization, whereas themes related to social justice, gender, and governance remain marginal (Aria and Cuccurullo, 2017; Klerkx et al., 2019; Rose et al., 2021).

This study aims to systematically map global Agriculture 4.0 research published between 2018 and early 2025 using bibliometric analysis. Beyond identifying technological trends, it highlights underexplored dimensions such as digital inequality, data governance, and the limited representation of low-income regions in global research networks. The goal is to provide evidence-based insights for fostering more equitable, participatory, and resilient digital agricultural systems worldwide.

Materials and Methods

Research Design and Scope

This study employs a quantitative bibliometric approach to examine evolution, thematic structure, and knowledge gaps within the field of Agriculture 4.0. Bibliometric analysis is a widely accepted method for evaluating large volumes of scientific literature by using statistical and network-based techniques to uncover publication trends, collaboration patterns, and emerging research areas (Aria and Cuccurullo, 2017; Cobo et al., 2011).

The scope of the analysis was defined as all peer-reviewed academic publications indexed in the Web of Science Core Collection (WoS) that include the phrase "Agriculture 4.0" in their title field. This specific query ensures a focused dataset that directly reflects the central theme of the study, though it may exclude related research using alternative terms such as "smart farming" or "digital agriculture." The time period considered spans January 2018 to April 2025, reflecting the years during which the term "Agriculture 4.0" gained substantial academic traction.

It should be noted that the deliberate restriction to the exact term "Agriculture 4.0" may influence the observed geographical distribution of publications. In some regions—particularly in parts of Africa, Latin America, and Asia—researchers may prefer alternative labels such as "precision agriculture," "smart farming," or "digital agriculture" when addressing Industry 4.0–related transformations. Therefore, the underrepresentation of certain regions in this dataset does not necessarily indicate a lack of relevant research activity, but rather reflects differences in terminological preferences within scholarly communication.

Bibliometric Indicators and Analysis Techniques

In this study, several bibliometric indicators and analysis techniques were employed to systematically examine the Agriculture 4.0 research landscape. The analysis began by evaluating publication trends over time between 2018 and 2025, followed by an assessment of the distribution of publications by type, including journal articles, conference papers, and book chapters. The study identified the most prolific authors, institutions, and countries contributing to the field, while citation analysis was conducted to highlight the most cited publications and calculate citation averages. Keyword co-occurrence networks were generated to reveal dominant research themes, and co-authorship and country collaboration networks were constructed to assess patterns of scientific interaction. Beyond mapping the volume and distribution of research activity, the analysis also aimed to uncover structural gaps—such as the underrepresentation of certain geographical regions, the lack of attention to governance-related topics, and the predominance of technically focused narratives within the existing literature.

Country-level publication counts were calculated using the full counting method. In this approach, each country listed in the author affiliation field of a publication receives one full credit, regardless of the number of co-authors from that country. Therefore, the sum of country totals may exceed the number of unique publications in the dataset.

Limitations

This study focuses exclusively on publications that contain the exact term "Agriculture 4.0" in their title, resulting in a deliberately restricted dataset. While this approach ensures thematic precision and allows for a focused examination of how the Agriculture 4.0 label has evolved in scholarly communication, it excludes relevant research using alternative terminology such as smart farming, digital agriculture, precision agriculture, and climate-smart agriculture. Consequently, the findings should not be generalized to the broader digital agriculture

domain. Future research should incorporate additional related terms, expand searches to abstracts and keywords, and construct larger datasets for a more comprehensive mapping of digital agriculture research (Cobo et al., 2011; X. Xu et al., 2022; Y. Xu et al., 2022).

The analysis is further limited to publications indexed in the Web of Science Core Collection and written in the English language. Although WoS is a leading source for high-quality, peer-reviewed literature, this focus may underrepresent contributions from non-English-speaking regions or local academic communities. Expanding the dataset to include Scopus, regional indices, and non-English publications would enhance global representativeness.

Additionally, country-level publication counts were calculated using the full counting method, in which each country listed in a multi-country publication receives full credit. As a result, country totals may exceed the number of unique records in the dataset. While this method accurately reflects collaborative activity, it may overemphasize productivity in highly connected research systems.

Results

The study presents a bibliometric analysis of academic research on the subject of "Agriculture 4.0" in the article title, included in the Science Citation Index, Science Citation Index Expanded (SCI, SCI-Expanded), and Social Sciences Citation Index (SSCI) in the Web of Science database until the first months of 2025. The results reveal the academic interest in this field, basic studies, and topics that need to be focused on in the future.

Number of Publications by Year

Academic publications on Agriculture 4.0 have shown a steady increase in the period under review. The first publication appeared in 2018 (Figure 1). While only 3 publications were identified in this field in 2018, the annual number of publications increased to 14 in 2019 and 23 in 2020. The increase continued with 27 publications in both 2021 and 2022, and a similar level was maintained in 2023 with 26 publications. The highest number of publications was reached in 2024, when 30 articles were published. The 6 publications listed as of the first months of 2025 indicate that this number will increase with the addition of studies to be published by the end of the year. These data reveal that academic interest in the field of Agriculture 4.0 has gained significant momentum, especially after 2018. The increase in the number of publications throughout the process indicates that Agriculture 4.0 is becoming an increasingly established research field.

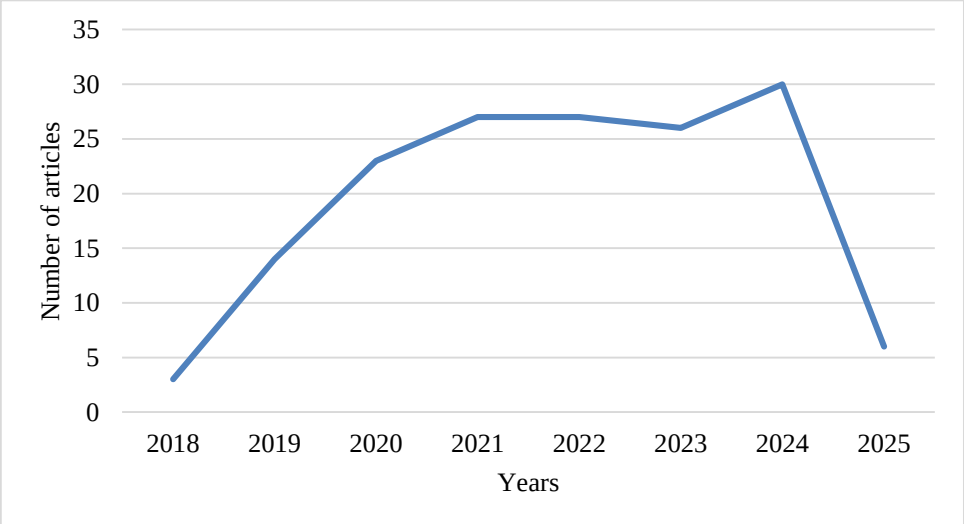

Figure 1. Increase in the number of publications on Agriculture 4.0 by year (2018–2025)

However, this upward trend in publication volume, while indicative of growing scholarly attention, does not necessarily correspond to a diversification of research themes or a broadening of geographical representation. As subsequent analyses in this study demonstrate, the majority of the publications are concentrated in a limited number of countries, with research largely focused on technological aspects such as automation, AI, and data analytics. Critical dimensions, including governance, data ownership, socio-political implications, and equitable digital transformation, remain considerably underexplored.

Distribution by Publication Types

A total of 126 articles were published as journal articles (J–Journal Article), indicating that a large portion of academic studies are disseminated through peer-reviewed scientific journals (Figure 2). In addition, 22 publications appeared as conference proceedings (C–Conference Paper), emphasizing the role of conferences as dynamic venues for sharing emerging ideas and fostering scholarly dialogue. Moreover, 8 studies were published as book chapters (B–Book Chapter), suggesting that Agriculture 4.0 is also being explored in interdisciplinary compilations where deeper conceptual, policy, or regional insights can be developed.

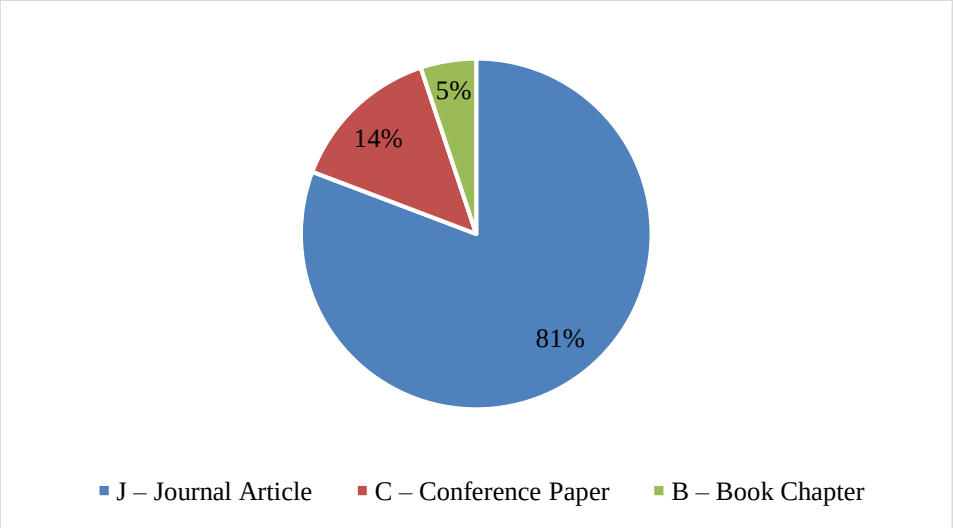

Figure 2. The distribution by publication type

This distribution shows that while journal articles remain the dominant medium for scientific communication, conference papers and book chapters also contribute significantly to the visibility and diversification of the field. Notably, conference papers may reflect experimental or work-in-progress studies, particularly from early-career researchers or institutions with limited access to high-impact journals. Similarly, book chapters often emerge from international collaborative projects or edited volumes that bring together region-specific knowledge and alternative framings.

Therefore, the diversity in publication types not only reflects the maturation of Agriculture 4.0 as an academic field but also highlights the importance of broadening epistemic inclusion across different platforms of scientific exchange, especially in regions where journal publishing opportunities are less accessible.

Most Published Authors

In the bibliometric analysis of authorship, two complementary perspectives were adopted: first-author analysis and all-author analysis (Figures 3 and 4). While the first author analysis highlights the researchers who generally lead the conceptual and methodological design of studies, the all-author analysis reflects the broader scientific participation contributing to collaborative knowledge production in Agriculture 4.0.

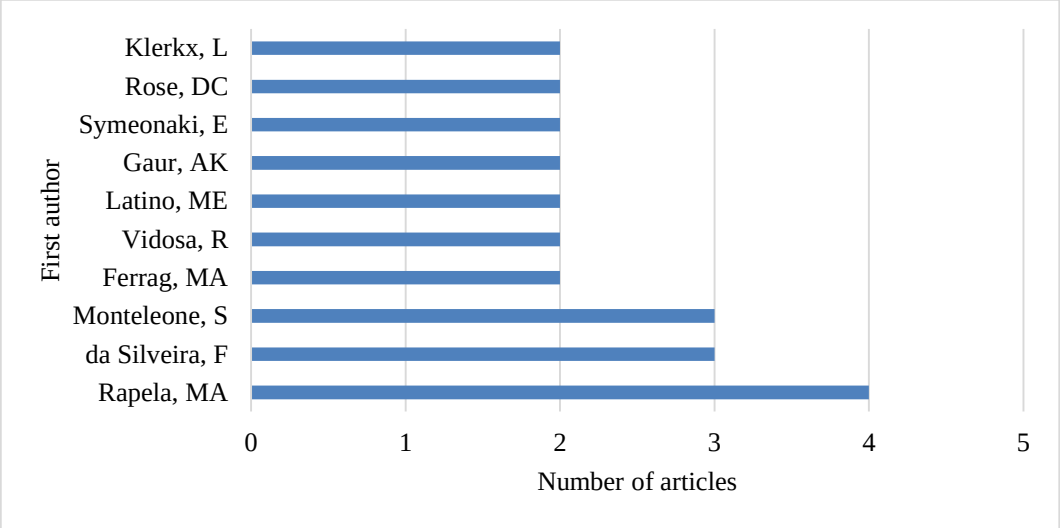

Figure 3. Top 10 Authors with the Most Publications (As the First Author)

The results of the first author's analysis reveal a concentration of leadership among a small group of scholars. Rapela, MA (4 articles), Monteleone, S (3 articles), da Silveira, F (3 articles), Ferrag, MA (2 articles), and Vidosa, R (2 articles) stand out as prolific first authors. These individuals appear to play a pivotal role in shaping the field, suggesting the emergence of specialized research hubs. The presence of recurring authors may also indicate regionally or thematically focused clusters, where expertise and institutional support are concentrated. While this reflects a degree of consolidation, it also raises questions about the representation and visibility of scholars from underfunded or underrepresented regions.

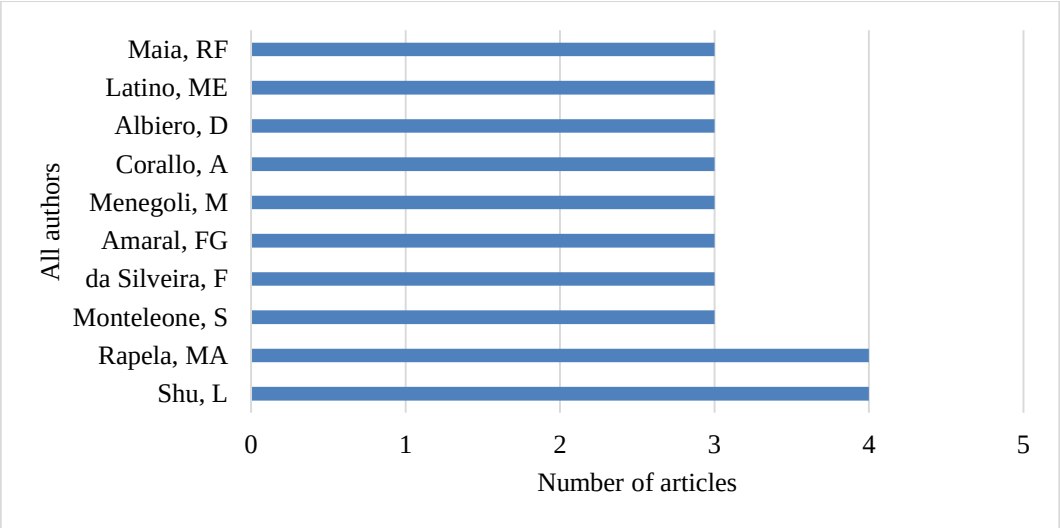

Figure 4.Top 10 Authors with the Most Publications (All Authors)

When analyzing all contributing authors, a pattern of multi-authored publications emerges. Scholars such as Shu, L (4 articles), Rapela, MA (4 articles), and Amaral, FG (3 articles) frequently appear as co-authors, highlighting the collaborative and interdisciplinary nature of Agriculture 4.0 research. These findings point to a growing reliance on teamwork rather than isolated contributions and reinforce the notion that digital agriculture is a complex domain requiring integrated expertise from computer science, agronomy, environmental studies, and data governance.

Most Published Journals

When analyzing the journals and sources publishing Agriculture 4.0 research, it becomes clear that the field spans multiple disciplines. Figure 5 presents the top 20 sources by publication volume. Revista Ciencia Agronomica leads with 11 articles, followed by interdisciplinary journals at the intersection of agriculture, engineering, and digital technologies—such as Computers and Electronics in Agriculture (6 articles), Sensors (5 articles), and Sustainability (5 articles). Open-access platforms like Agriculture (Basel), Agronomy (Basel), and Applied Sciences (Basel) also feature prominently, each hosting four publications.

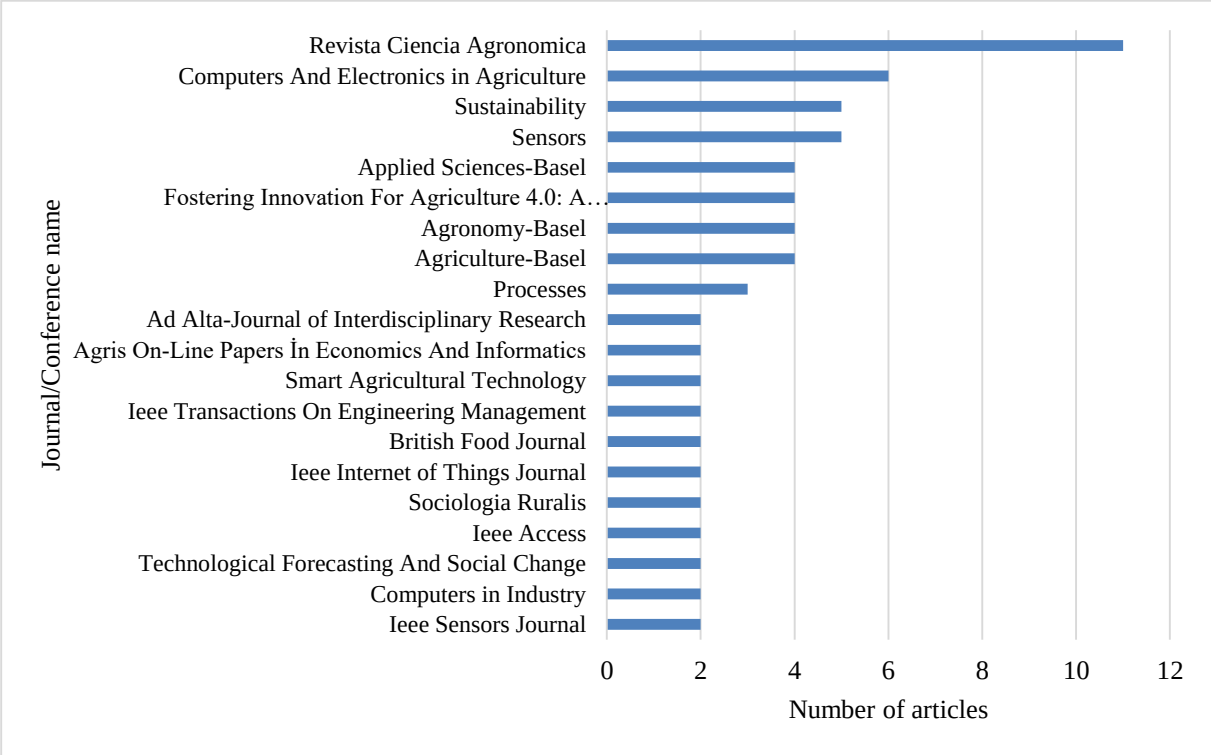

Figure 5. The 20 most published journals/conferences

This distribution illustrates the strong alignment of Agriculture 4.0 with technical and engineering-driven domains, while policy-focused or social science journals appear largely absent. This suggests a dominant technocentric narrative in the field, with less emphasis placed on governance, labor, or socioeconomic implications. The notable presence of open-access journals reflects attempts to broaden the reach of scientific knowledge; however, the financial burden of article processing charges (APCs) may still restrict participation from researchers in low- and middle-income countries.

Countries with the Most Publications

The geographical distribution of publications in the field of Agriculture 4.0 reveals a notable concentration in a limited number of countries. Based on the authors' affiliations, Brazil leads the list with 63 publications, followed by India with 54 and Italy with 42. These three countries alone account for a substantial share of the literature, indicating that they are key drivers of scientific output in this domain. China ranks fourth with 28 publications, followed by the United Kingdom and Greece, each contributing 21. The United States and Australia follow with 15 and 14 publications, respectively, while Türkiye and Germany round out the top ten with 13 and 12 publications (Figure 6).

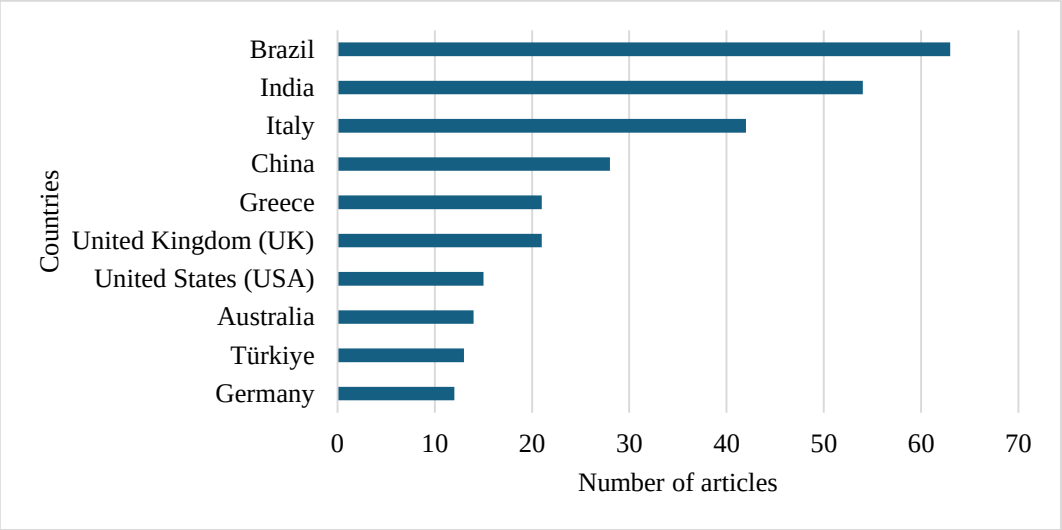

Figure 6. Top 10 Countries with the Most Publications

This distribution highlights that both developed countries (e.g., Italy, the United Kingdom, the United States, Germany) and emerging economies (e.g., Brazil, India, China, Türkiye) are actively engaged in Agriculture 4.0 research. However, the high concentration in a handful of nations also signals a potential imbalance in the global production of knowledge. The near absence of contributions from large parts of Sub-Saharan Africa, Central Asia, and the Middle East reflects persistent structural inequalities in digital infrastructure, research funding, and access to advanced technologies. However, this geographical imbalance should be interpreted with caution. The low visibility of certain regions—particularly Sub-Saharan Africa—may partly result from the limited use of the term "Agriculture 4.0" in article titles, rather than an absence of digital agriculture–related research. Studies from these regions often address similar technological transformations under alternative conceptual frameworks, which fall outside the strict search criteria of this analysis.

Institutions with the Most Publications

When analyzed at the institutional level, Agriculture 4.0 research appears to be concentrated in a limited number of universities and research centers. Universidade Estadual de Campinas (UNICAMP) in Brazil leads with five publications, followed by the University of Reading (United Kingdom) and Nanjing Agricultural University (China), each contributing four articles (Figure 7). These findings mirror the national publication trends, highlighting how institutional productivity aligns with broader country-level leadership in the field.

A third tier of institutions—each with three publications—includes Universidade Estadual Paulista (UNESP) and Centro Universitário da FEI (Brazil), Austral University (Argentina), the University of Lincoln (UK), Universitat Politècnica de València (Spain), Agricultural University of Athens (Greece), and the University of Salento (Italy). These universities not only contribute to the growing literature on Agriculture 4.0 but also reflect a degree of thematic and regional diversity.

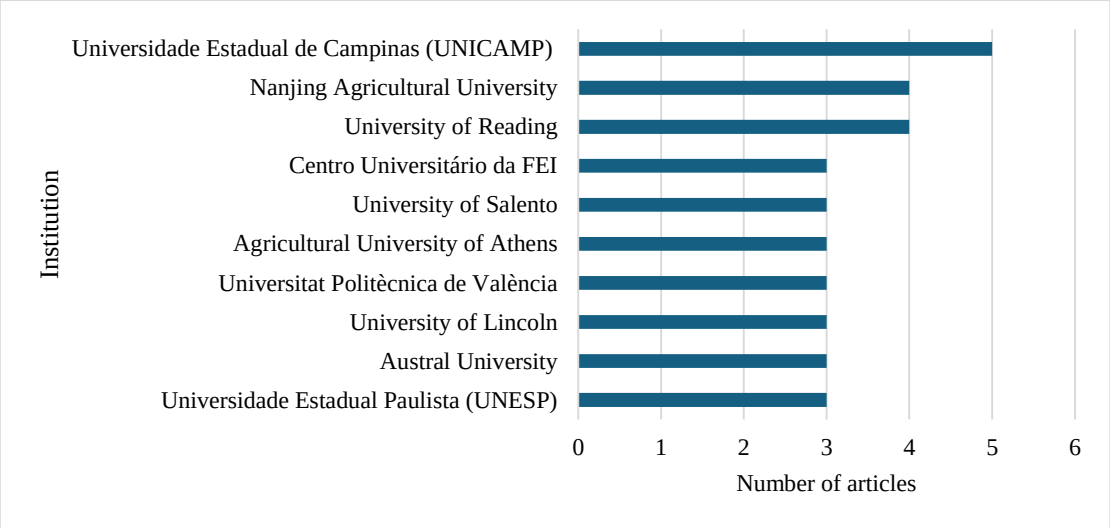

Figure 7. Top 10 Institutions with the Most Publications

The concentration of publications in a relatively small group of institutions suggests that Agriculture 4.0 research is shaped by academic centers with strong ties to agri-tech innovation, access to funding, and established international networks. Brazilian universities, in particular, appear to play a leading role, likely driven by state-level investment in precision agriculture and digital farming systems.

Most Cited Articles

The ten most cited articles between 2018 and 2025 are presented in Table 1. Among them, the most influential is the review by Klerkx et al. (2019) titled "A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda", which has received 615 citations. This article is widely regarded as a foundational work for its effort to bridge technological change with social science insights, particularly emphasizing governance, stakeholder engagement, and conceptual clarity in digital agriculture. Another key contribution Lezoche et al. (2020) with 416 citations, it presents a comprehensive review of smart supply chain technologies and has become a major reference point for technological infrastructure in Agriculture 4.0. Zhai et al. (2020) followed by 379 citations, providing a systematic overview of decision support systems and their digital transformation. These three studies, in particular, have set the research agenda by moving the conversation from mere automation toward integrated, intelligent systems with strategic decision-making capabilities.

Several other highly cited publications have further enriched the field from different angles. Liu et al. (2021) (377 citations) explored the transition from Industry 4.0 to Agriculture 4.0 by identifying enabling technologies and current research challenges. (Rose and Chilvers, 2018) and Klerkx and Rose (2020), both cited over 300 times, contributed critical perspectives on responsible innovation, ethics, and sustainability in the age of smart farming. Articles such as (Kumar et al., 2021) focused on integration barriers to Industry 4.0 and circular economy in

agricultural supply chains, while (Zambon et al., 2019) highlighted the implications of digital transformation for SMEs. (Rose et al., 2021) addressed the human, environmental, and productivity dimensions of Agriculture 4.0, and (Abbasi et al., 2022) offered a comprehensive literature review of digitalization trends in the agricultural industry. Together, these articles represent the technological, managerial, and ethical pillars of the field.

Table 1. Top 10 Most Cited Articles in Agriculture 4.0

Article Title	Authors	Publication Year	Number of Citations
A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda	Klerkx, L; Jakku, E; Labarthe, P	2019	615
Agri-food 4.0: A survey of the supply chains and technologies for the future agriculture	Lezoche, M; Hernandez, JE; Díaz, MDEA; Panetto, H; Kacprzyk, J	2020	416
Decision support systems for agriculture 4.0: Survey and challenges	Zhai, ZY; Martínez, JF; Beltran, V; Martínez, NL	2020	379
From Industry 4.0 to Agriculture 4.0: Current Status, Enabling Technologies, and Research Challenges	Liu, Y; Ma, XY; Shu, L; Hancke, GP; Abu-Mahfouz, AM	2021	377
Agriculture 4.0: Broadening Responsible Innovation in an Era of Smart Farming	Rose, DC; Chilvers, J	2018	317
Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?	Klerkx, L; Rose, D	2020	317
To identify industry 4.0 and circular economy adoption barriers in the agriculture supply chain by using ISM-ANP	Kumar, S; Raut, RD; Nayal, K; Kraus, S; Yadav, VS; Narkhede, BE	2021	236
Revolution 4.0: Industry vs. Agriculture in a Future Development for SMEs	Zambon, I; Cecchini, M; Egidi, G; Saporito, MG; Colantoni, A	2019	189
Agriculture 4.0: Making it work for people, production, and the planet	Rose, DC; Wheeler, R; Winter, M; Lobley, M; Chivers, CA	2021	145
The digitization of agricultural industry - a systematic literature review on agriculture 4.0	Abbasi, R; Martinez, P; Ahmad, R	2022	143

A thematic review of these top-cited articles reveals three dominant narratives: (1) the emphasis on digital supply chains and decision-support systems; (2) the growing concern with responsible innovation and inclusion; and (3) the alignment of Agriculture 4.0 with broader industrial transformations such as Industry 4.0 and circular economy principles. Despite this diversity, most of these studies are authored by researchers affiliated with institutions in the Global North, reflecting persistent asymmetries in research visibility and access. Regions such as Sub-Saharan Africa, Central Asia, and parts of Latin America are largely absent from the most-cited literature, indicating a gap in context-sensitive, place-based insights.

Keyword Analysis

The keyword analysis provides valuable insight into the thematic orientation of Agriculture 4.0 research. Figure 8 displays the 20 most frequently used keywords across the literature. The dominant terms include “agriculture,” “industry,” “technologies,” “precision,” “IoT,” “smart,” and “applications,” revealing a strong emphasis on technological innovation and digital transformation. These keywords suggest that the field is primarily shaped by

an engineering and systems-oriented discourse, prioritizing efficiency, automation, and data-driven solutions in agricultural contexts.

A second thematic group focuses on environmental and sustainability issues, with keywords such as "sustainable agriculture," "climate-smart agriculture," and "environmental monitoring." These terms indicate that, alongside its technological foundation, literature also engages with ecological and environmental concerns. However, keywords that reflect social and governance dimensions—such as "equity," "policy," "digital divide," "adoption," and "farmer agency"—are noticeably underrepresented. This underrepresentation reveals a thematic imbalance: while technological progress is central, inclusive innovation, socio-political structures, and local knowledge systems remain on the periphery of scholarly focus.

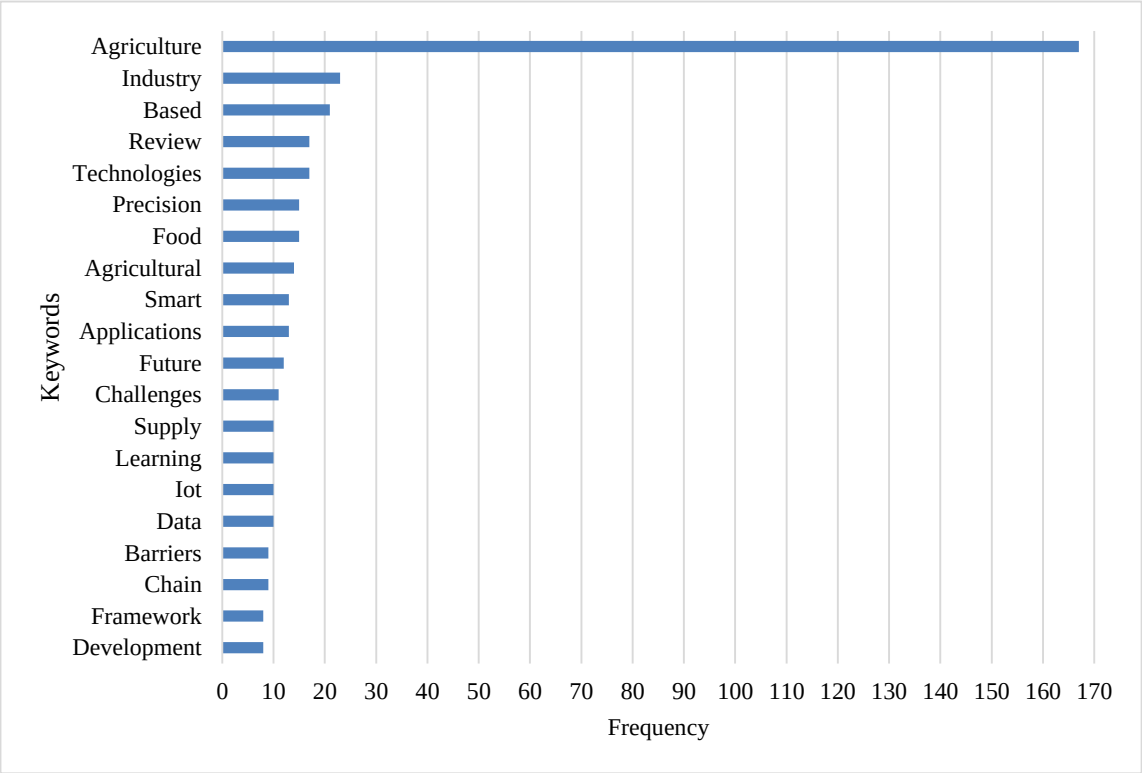

Figure 8. The 20 most frequently used keywords in Agriculture 4.0 publications

Figure 9 further illustrates these patterns through a keyword co-occurrence network. Terms like "smart farming," "IoT," and "precision agriculture" occupy central positions, forming dense clusters that reflect strong interconnections in technological themes. In contrast, socially oriented terms are either weakly connected or absent from the network, visually confirming the lack of attention to governance, participation, and rural equity issues. This confirms that the Agriculture 4.0 literature is still predominantly driven by a technocentric approach.

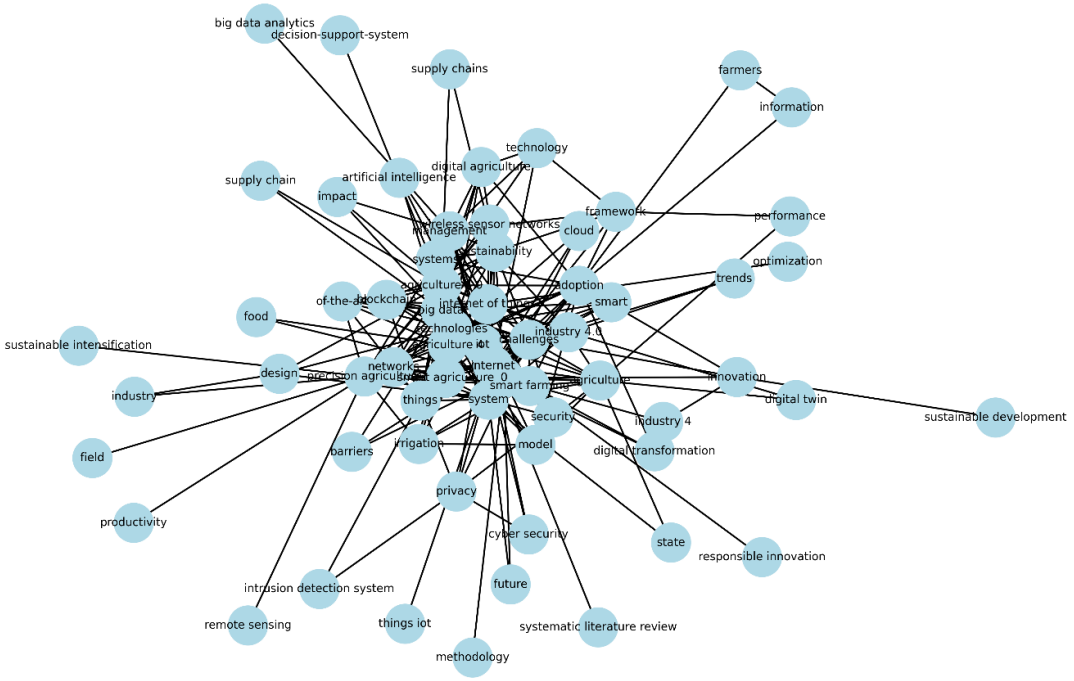

Figure 9. Keyword Co-occurrence Network in Agriculture 4.0 Research

Co-authorship and Country Collaborations

Most publications in the field of Agriculture 4.0 have been prepared through collaboration by more than one author. The average number of authors in the articles examined is approximately four, with one publication including as many as sixteen contributors. These data emphasize that Agriculture 4.0 research is generally built on teamwork and highlights the importance of interdisciplinary collaboration.

When the co-authorship network is analyzed (Figure 10), it is observed that distinct clusters of researchers have formed based on geographical and institutional proximity. A notable cluster consists of Brazilian researchers who have co-authored multiple publications, reflecting strong intra-national cooperation. Similarly, researchers from Italy and the United Kingdom predominantly collaborated within their respective countries or with nearby institutions. However, some authors participated in international collaborations, publishing jointly with colleagues from various countries. For example, Lei Shu—one of the most prolific contributors—co-authored articles with researchers from China, South Africa, and the United Kingdom, exemplifying the global dimension of Agriculture 4.0 research projects.

At the country level, the collaboration network (Figure 11) demonstrates that Agriculture 4.0 research is supported by a wide-ranging international infrastructure. Countries were considered connected if at least one article included authors from both nations. The most frequent collaborations were observed between the United Kingdom and China (3 joint publications), and between Brazil and Spain (3 joint publications). Other notable pairings include England–Poland and France–Spain. Although India is among the top publishing countries, its contributions are largely domestic; international partnerships were less frequent, with a few collaborative studies involving Saudi Arabia and Türkiye. Turkish researchers, for instance, were involved in three publications, some of which were conducted in collaboration with authors from other countries.

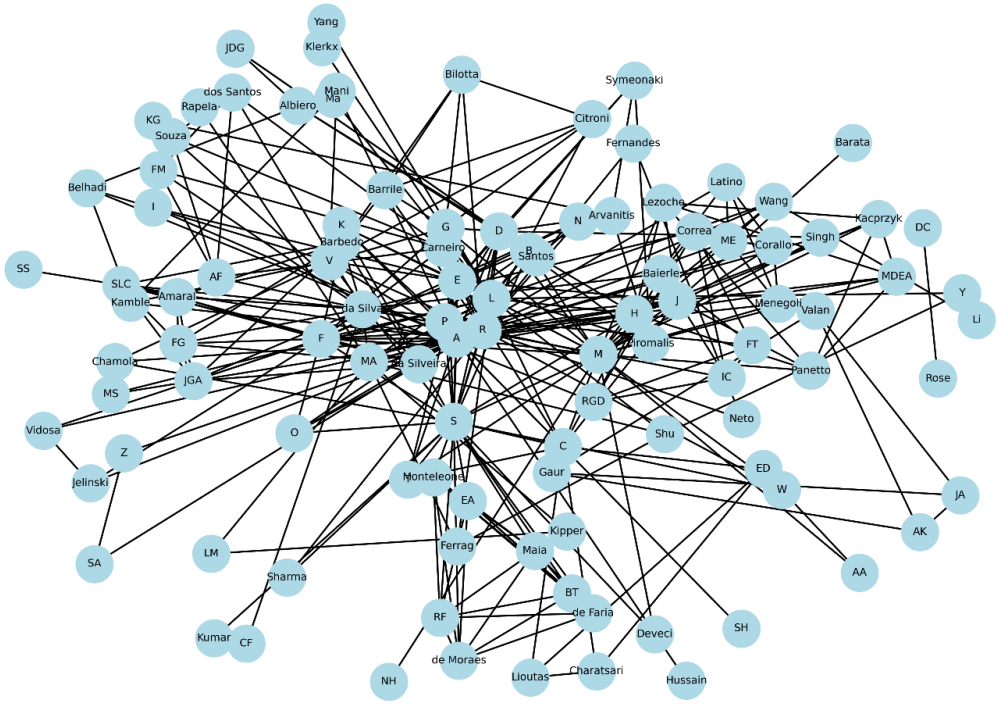

Figure 10. Co-authorship Network in Agriculture 4.0 Research

Importantly, during data cleaning, some entries in the original dataset contained inconsistently recorded institutional affiliations, where individual names or partial addresses were mistakenly classified as countries (e.g., "Heiko," "Francisco Tardelli," or "AL 36849 USA"). To ensure accurate network representation, only verified country names were retained in the final visualization. As a result, Figure 11 includes 20 valid countries that participated in international co-authorships, while countries such as Germany and Argentina appear as isolated nodes, indicating that their publications did not involve authors from other countries.

These findings confirm that Agriculture 4.0 research is progressing within a global and collaborative scientific ecosystem. Diverse geographies, expertise domains, and institutional backgrounds are converging to enrich the knowledge base, underscoring the interdisciplinary and international nature of this rapidly evolving field.

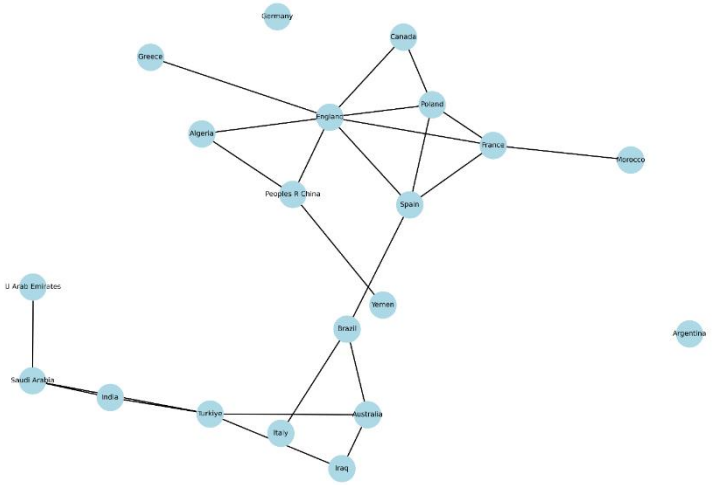

Figure 11. Country Collaboration Network in Agriculture 4.0 Research

Discussion

This study maps the evolution of Agriculture 4.0 research through bibliometric methods, identifying major trends, thematic structures, collaboration patterns, and geographical contributions. Academic output has grown significantly since 2018, driven by interdisciplinary collaborations and technological advancements such as smart agriculture, IoT, artificial intelligence, and big data—reflecting a fundamental transformation of agricultural systems (Kamilaris et al., 2017; Lezoche et al., 2020; Mühl and de Oliveira, 2022).

Importantly, the findings discussed in this section reflect academic production specifically framed under the "Agriculture 4.0" label. They do not represent the full scope of digital agriculture technologies or research streams, such as precision agriculture or smart farming more broadly, but rather illustrate how this particular terminology has been adopted and operationalized within the scientific literature.

However, despite the technological emphasis, social, ethical, and governance-related dimensions remain insufficiently addressed. Issues such as smallholder farmers' access to digital tools, impacts on rural communities, data ownership, and digital inequality are limited in scope (Klerkx and Rose, 2020; Rose and Chilvers, 2018). In developing contexts, more empirical research is needed to understand how digital solutions interact with local knowledge systems (Carolan, 2020).

Geographical analyses reveal that Brazil, India, and China dominate publication output, while emerging economies like Türkiye are expanding their presence. National funding programs, university–industry partnerships, and strategic policies support this growth, though many collaborations remain locally concentrated with limited international integration (Kushartadi et al., 2023; Vahdanjoo et al., 2025). Co-authorship networks further show strong interdisciplinarity, connecting engineering, informatics, environmental, and social sciences. Bilateral collaborations, such as those between England and China, and Brazil and Spain, indicate a gradual increase in global scientific exchange.

Methodologically, the study focuses solely on Web of Science publications with "Agriculture 4.0" in the title, which may exclude related research employing terms such as smart farming, digital agriculture, and precision agriculture. Including abstracts and keywords in future searches could yield a more comprehensive dataset (Cobo et al., 2011).

While much of the literature highlights technical efficiency and productivity, it pays limited attention to digital inequalities. Small-scale farmers in low-income regions continue to face numerous barriers, including inadequate infrastructure, education gaps, and high operational costs. Keywords related to digital divide, socioeconomic inequality, and adoption barriers appeared infrequently, underscoring that digital agriculture represents both a technological and social transformation. Future research should examine its broader effects on rural development and inform policy strategies.

Data governance remains another underdeveloped theme. Control of digital agriculture data by private companies restricts farmers' rights and raises concerns about transparency and fairness. Ethical and governance issues—including data privacy, ownership, algorithmic transparency, and bias—are underrepresented. As AI-based tools increasingly influence decisions related to credit, irrigation, and crop management, opaque algorithms risk reinforcing existing inequalities, particularly for marginalized farmers.

Addressing these gaps requires interdisciplinary research integrating ethical, legal, and participatory governance perspectives. Agriculture 4.0 should be approached not only as a technological paradigm but also as a framework that prioritizes equity, accountability, and inclusion, ensuring that digital transformation aligns with the needs and rights of end-users.

Conclusion

The conclusions drawn in this study are limited to academic production explicitly framed under the "Agriculture 4.0" label and should not be interpreted as representative of the entire digital agriculture landscape.

This bibliometric analysis of 156 publications (2018–2025) demonstrates the rapid expansion and increasing interdisciplinarity of Agriculture 4.0 research. The prevalence of multi-authored studies reflects growing collaboration and knowledge integration across countries and institutions. Brazil, India, Italy, China, and the United Kingdom emerge as leading contributors, indicating strong engagement from both developed and emerging economies. Collaboration networks show that while partnerships often follow geographical proximity, international cooperation is gradually increasing.

The thematic structure of the literature remains dominated by smart agriculture, IoT, artificial intelligence, big data analytics, and sustainability, underscoring the field's strong technological orientation. However, social and ethical issues—including equity, inclusiveness, data governance, and policy integration—are comparatively underexamined. Overall, bibliometric methods prove effective in identifying research trends, collaboration patterns, and thematic gaps, offering valuable insight for shaping more inclusive and sustainable Agriculture 4.0–oriented digital transformation strategies.

Despite notable growth, critical gaps remain in agricultural research for Agriculture 4.0. Socioeconomic disparities—especially those affecting smallholder farmers and low-income communities—are insufficiently explored in regions such as Sub-Saharan Africa, South Asia, and Latin America. Understanding how inequality influences digital technology adoption is crucial for achieving equitable transformation.

The integration of indigenous knowledge and traditional practices with smart technologies also requires greater attention, as hybrid approaches may enhance sustainability, resilience, and cultural relevance. Ethical and governance concerns—including data privacy, ownership, transparency, and accountability—are similarly underrepresented and demand interdisciplinary inquiry to strengthen trust in digital agricultural ecosystems.
Geographical imbalances persist, with limited research from Central Asia, the Middle East, and Sub-Saharan Africa. Broader empirical engagement with these regions is crucial for a more globally representative understanding of digital agriculture research framed under the Agriculture 4.0 concept. Furthermore, despite increasing interdisciplinarity, stronger integration with social sciences and deeper engagement with farmers, civil society, and local institutions are needed. Participatory and user-centered research approaches can help ensure that technological developments align with the needs of end-users and support rural development.

Future bibliometric studies would also benefit from expanding beyond the strict use of "Agriculture 4.0" to include related terms such as "smart farming," "digital agriculture," "precision agriculture," and "climate-smart agriculture," enabling a more comprehensive assessment of digital transformation in agriculture.

This study focuses exclusively on publications that include the exact term "Agriculture 4.0" in their title, and therefore represents a deliberately restricted dataset. While this approach enables a precise examination of how the 'Agriculture 4.0' label has evolved in the scientific literature, it does not encompass the broader digital agriculture landscape, including research on smart farming, digital agriculture, precision agriculture, or climate-smart agriculture. As a result, the findings should not be generalized to the entire domain of digital agricultural technologies.

The use of full counting in country-level analysis may also produce totals exceeding the number of unique publications. Future studies should incorporate broader terminology, examine abstracts and keywords, and construct larger datasets to provide a more comprehensive mapping of digital agriculture research.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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