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Review article

Sustainable agriculture in the digital era: Past, present, and future trends by bibliometric analysis

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ABSTRACT

The digital era is reshaping agricultural practices, opening new avenues for sustainable growth, and proving indispensable in global challenges like food security and environmental conservation. However, a comprehensive understanding of this evolving landscape remains paramount. This research evaluates 344 papers from the Web of Science database to delve into sustainable agriculture's historical and current patterns in the digital era through bibliometric analysis and project future domains. Specifically, citation analysis identified influential papers, journals, institutions, and countries, while co-authorship analysis verified the interactions between authors, affiliations, and countries. Co-citation analysis found four hotspot clusters: prosperity and challenges in agricultural sustainability, digital information and agricultural development, innovations for sustainable agriculture, and geospatial analysis in environmental studies. The co-occurrence of keywords analysis revealed four main clusters for future studies: smart agriculture and biodiversity conservation, digitalization and sustainable agriculture, technologies and agricultural challenge management, and digital intelligence and farmer adoption. The study pioneers the use of bibliometric analysis to explore sustainable agriculture in the digital era. It presents invaluable insights into the evolving landscape of this field, summarizing its hotspots and suggesting future trajectories.

1. Introduction

Sustainable agriculture employs holistic plant and animal production practices to address humanity's long-term food and fiber requirements while enhancing ecosystem health [1]. It is designed to conserve resources, minimize waste, and reduce environmental impact [2]. By adopting sustainable agricultural methods, farmers can enhance soil fertility [3], conserve water resources [4], and protect ecosystems [5], thus safeguarding the natural resources vital for food production [6]. Over the years, sustainable agriculture has evolved in response to changing environmental, social, and economic conditions. Initially focused on organic farming and agroecology [7,8], the concept of sustainable agriculture has expanded to encompass broader principles, including conservation agriculture [9], integrated pest management [10], and climate-smart agriculture [11]. Sustainable agriculture integrates cutting-edge technologies and pioneering practices, such as precision farming and digital agriculture, to optimize productivity while mitigating

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environmental footprints [6,12].

The digital era has ushered in transformative possibilities for sustainable agriculture, reshaping traditional agricultural practices and methodologies [13]. Encompassing a plethora of technologies and innovations, the field of the digital era includes the digital economy [14], digital infrastructure [15], information services [16], and agricultural technologies [17], which hold promise for enhancing the sustainability and resilience of farming systems. By integrating digital solutions, sustainable agriculture increasingly benefits from various digital services and platforms. These include digital technology innovations such as remote sensing technologies, machine learning, geospatial analysis, and the Internet of Things (IoT), enabling farmers to monitor crop health, optimize irrigation, and minimize chemical inputs [18–21]. The integration of digital technology in agricultural extension services bolsters climate-smart practices, thereby enhancing the resilience and sustainability of farming communities [22]. Additionally, digital inclusive finance initiatives provide financial services to smallholder farmers, enabling them to allocate resources to sustainable agricultural methods and adapt to environmental changes [23]. Furthermore, digital platforms for rural household engagement facilitate collaborative decision-making processes and enhance the resilience of rural communities [24].

However, despite the promises of the digital era, sustainable agriculture still faces significant challenges. Data privacy and ownership have gained attention due to the increasing reliance on digital technologies for agricultural operations [25]. Besides, farmers face disparities in access to and adoption of digital tools, known as the digital divide, which can exacerbate inequalities and hinder the widespread implementation of sustainable practices [26]. Additionally, ensuring the longevity and sustainability of digital infrastructure, such as broadband networks and data storage systems, poses a significant challenge, as technological advancements require ongoing investment and maintenance to remain effective [27]. These challenges underscore the need for comprehensive strategies to address the complexities of integrating digital solutions into sustainable agricultural practices.

Under this circumstance, recent examinations into the digital era' sustainable agriculture have transpired. Existing bibliometric analyses have explored various impacts of diverse technologies on agriculture. For example, Bertoglio et al. [28] found five streams in digital agricultural technologies: climate-smart agriculture, site-specific management, remote sensing, IoT, and Artificial Intelligence (AI). Patel et al. [29] revealed the structure of AI and IoT-assisted land and water management research. Abdul-Majid et al. [30] summarized the mixed effect of agricultural technologies on farmers' welfare, influenced by the specific type adopted and the farmers' compatibility with technological proficiency. However, there remains a gap in the literature comprehensively summarizing the effects of the digital era on sustainable agriculture. As the world transitions towards more sustainable practices, it becomes increasingly important to understand the impact of digitization on sustainable agriculture development.

This study represents a pioneering effort to bridge the gap by thoroughly examining the evolving landscape of sustainable agriculture in the digital era. It performs a bibliometric analysis of relevant literature from 1998 to 2024. The study sheds light on the topic's past, present, and future trends by systematically analyzing publication trends and identifying critical thematic constructs. By understanding past research trends and the most influential publications, researchers can build upon existing knowledge and guide the progress of the field. Furthermore, a bibliometric analysis is a roadmap for future research endeavors, guiding researchers toward understudied topics or emerging trends in the digital era' sustainable agriculture. By systematically analyzing the literature and identifying key themes and challenges, this study can inform policy decisions, guide research efforts, and ultimately facilitate the progression of agriculture in the digital era. The research contains four specific objectives.

1. To identify the most influencing publications in sustainable agriculture in the digital era using citation analysis.
2. To verify the interactions of authors, affiliations, and countries in sustainable agriculture in the digital era by co-authorship analysis.
3. To pinpoint impactful historical contributions and current prevalent themes in sustainable agriculture in the digital era through co-citation analysis.
4. To discover burgeoning fields in sustainable agriculture in the digital era, to predict forthcoming trends using co-word analysis.

2. Materials and methods

2.1. Bibliometric analysis

Bibliometric analysis extensively assesses research status within a particular domain by examining existing publications, including keywords, citations, sources, and countries [31,32]. This analysis method enables the evaluation of a specified subject's developmental path and directions [33]. Its primary advantage is converting abstract literature into an organized and controllable format [34,35].

Citation, co-authorship, co-citation, and co-word analyses are typical methods employed in bibliometric research [36]. Citation analysis entails assessing the referenced articles by quantifying the volume of citations and links a publication garners, which is crucial for identifying noteworthy contributions [37]. Co-authorship analysis pertains to the interactions of authors, affiliations, and countries [38]. Co-citation analysis tallies simultaneous citations and employs co-citation counts to gauge reference similarities [32]. Exploring research themes entails structuring academic literature to reveal coherence and evolutionary trends [39,40]. Meanwhile, co-word analysis calculates the prevalence of keywords in papers, examining correlations among keywords to indicate impactful topics [41]. Leveraging information from titles, authors' keywords, or abstracts, the co-occurrence of keywords evaluates future trends and concept connections [42,43].

2.2. Data and research design

Beginning with a meticulous literature selection, the research conducted both quantitative and qualitative analyses. This methodical approach seeks to yield insightful findings and draw pertinent conclusions.

Firstly, data is gathered from the Web of Science (WOS) database. Table 1 delineates the exploration and screening criteria. This database's repository is preferred for bibliometric analysis because of its accuracy and expansiveness [44]. These repositories are the most widely used and dependable academic literature sources, providing access to esteemed research worldwide [45,46]. Nevertheless, Scopus and Google Scholar encompass broader cataloged publications and may yield disparate outcomes [47]. Despite this constraint, exclusive reliance on the WOS database guarantees the inclusion of reputable publications, ensuring overall quality [48].

The "WOS Database" section denoted an exhaustive scrutiny of all WOS repositories. The "Time Period" encompassed publications to March 22, 2024. The "TOPIC" search field covered titles, abstracts, and keywords, ensuring a comprehensive and relevant selection of literature. The "Search Keywords" category revealed that papers containing the keywords ("Green agricultur*" or "Green farming*" or "Sustainable agricultur*" or "Sustainable farming*" or "Environmental agricultur*" or "Environmental farming*" or "Eco-friendly agricultur*" or "Eco-friendly farming*" or "Organic agricultur*" or "Organic farming*" AND Digital*) constituted the focal point. These specific keywords were meticulously chosen to encompass various research domains within the theme of sustainable agriculture in the digital era. The utilization of asterisks (*) facilitated the inclusion of diverse terminologies and phrases falling under these critical themes. Incorporating asterisks (*) enabled encompassing a wide array of terminologies and phrases associated with these core themes. The "Citation Topics Meso" section encompassed all relevant interdisciplinary research intersecting with sustainable agriculture in the digital era. "Document Type" encompassed all categories, ensuring a thorough compilation of research outputs. "Languages" clarified that only English-language articles were considered. This restriction was imposed to ensure the analysis's accessibility to the broadest academic audience despite the potential omission of non-English perspectives. This meticulous process yielded 344 publications.

In the next phase, the bibliometric software VOSviewer 1.6.18 facilitated a quantitative analysis. Density analysis centers on citations, links, and total link strengths, pinpointing notable contributions from documents, sources, organizations, and countries. Concurrently, network analysis delved into co-citation and keyword co-occurrence, unveiling past collaborative research networks and emerging academic trends [36]. Overlay analysis was used to analyze the timeline of the co-occurrence of keywords. VOSviewer provided a rich array of visualization tools, enabling the scientific representation of sustainable agriculture in the digital era literature [34]. Through clustering, it consolidated dispersed knowledge from diverse fields, emphasizing similarities and relevance. Nodes displaying higher similarity were color-coded for visual distinction, while efforts were made to segregate nodes with lower similarity whenever feasible [49].

Finally, a qualitative thematic examination was undertaken, elucidated by tables and narrative synopses. This involved carefully reviewing the publications to understand their main ideas and assigning descriptive labels to the identified clusters [50].

3. Results

This section entails an in-depth examination of publication trends on sustainable agriculture in the digital era literature and conducts citation, co-citation, and co-word analyses.

3.1. Publication trends

From the 344 selected publications, the Web of Science retrieved 4521 citations, with 4445 excluding self-references. The average citation is 14.68 per article, with an H-index of 37. The aggregation of 344 articles reflects an increasing demand for research concerning sustainable agriculture in the digital era. Research in this field began to emerge in 1998, but until 2018, the annual publication count consistently stayed below 10. Starting in 2019, it witnessed a consistent rise in the publication volume annually, reaching 88 in 2023. It is anticipated that scholarly investigations into sustainable agriculture in the digital era will expand in the forthcoming years. The trend in citations generally follows a similar pattern to the publication trend, emerging in 2001 and consistently rising since 2015. There was a substantial surge starting from 2020, reaching 1815 citations by 2023. Fig. 1 illustrates the trend from 1998 to March 22, 2024.

Table 1
Search string.

WOS Database	ALL
Time Period	Up to March 22, 2024
Search field	TOPIC
Search keywords	"Sustainable agricultur*" or "Sustainable farming*" or "Green agricultur*" or "Green farming*" or "Environmental agricultur*" or "Environmental farming*" or "Eco-friendly agricultur*" or "Eco-friendly farming*" or "Organic agricultur*" or "Organic farming*" AND Digital*
Citation Topics Meso	ALL
Document Type	ALL
Languages	English

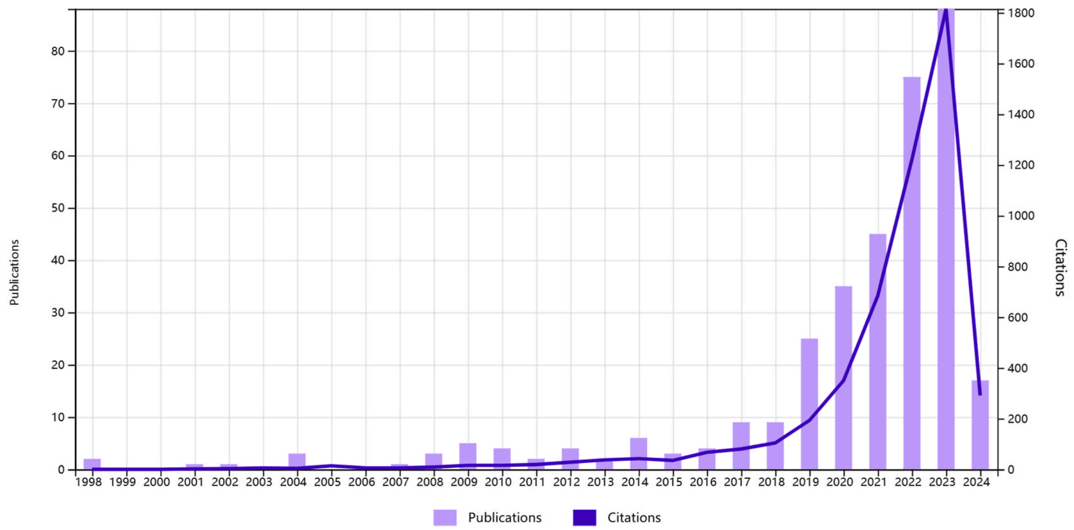

Fig. 1. Publications and citations between 1998 and March 22, 2024.

3.2. Citation analysis

3.2.1. Documents citation

From a threshold of 10 citations, 113 documents from the 344 studies were included in the analysis. The top three articles were Kamble et al. [51] (390 citations), Klerkx and Rose [52] (239 citations), and Pigford et al. [5] (219 citations). The top 10 publications, along with citation and link counts, are detailed in Table 2, providing insight into the most influential works in the field under analysis.

Fig. 2 shows the density analysis visualization of documents ranked by links. Klerkx and Rose [52] ranked 1 with seven links. Then came Pigford et al. [5], Jacquet et al. et al. [56], Hrustek [60], and Schnebelin et al. [61], each with three links, indicating their significant contribution and influence in digital area' sustainable agriculture.

3.2.2. Sources citation

With a criterion of one document and three citations per source, this study identified 136 sources out of the total 216 sources available. Table 3 presents the top 10 sources based on average citations. International Journal of Production Economics from Elsevier ranked 1 (390 average citations). Next came Nature Sustainability from Springer Nature and Global Food Security - Agriculture Policy Economics and Environment from Elsevier, with 166 and 128.5 average citations, respectively.

Fig. 3 shows the density analysis visualization of sources ranked by total link strength. The Sustainability and the Agriculture-basel from MDPI ranked first and second with 37 and 19 total link strengths, respectively. The third came Springer's Environmental Science and Pollution Research (12 total link strength). This ranking underscores the substantial impact of these journals in the academic landscape.

Table 2
Top 10 documents ranked by citation.

No.	Author	Title	Citation	Links
1	Kamble et al. [51]	Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications	390	1
2	Klerkx and Rose [52]	Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?	239	7
3	Pigford et al. [5]	Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions	219	3
4	Basso [53]	Digital agriculture to design sustainable agricultural systems	166	2
5	Le Bissonnais et al. [54]	Mapping erosion risk for cultivated soil in France	158	0
6	Grudpan et al. [55]	Applications of everyday IT and communications devices in modern analytical chemistry: A review	93	0
7	Jacquet et al. [56]	Pesticide-free agriculture as a new paradigm for research	89	3
8	Chen et al. [57]	Mapping dynamics of soil organic matter in croplands with MODIS data and machine learning algorithms	80	0
9	Minervini et al. [58]	Image-based plant phenotyping with incremental learning and active contours	80	1
10	Hank et al. [59]	Spaceborne Imaging Spectroscopy for Sustainable Agriculture: Contributions and Challenges	77	0

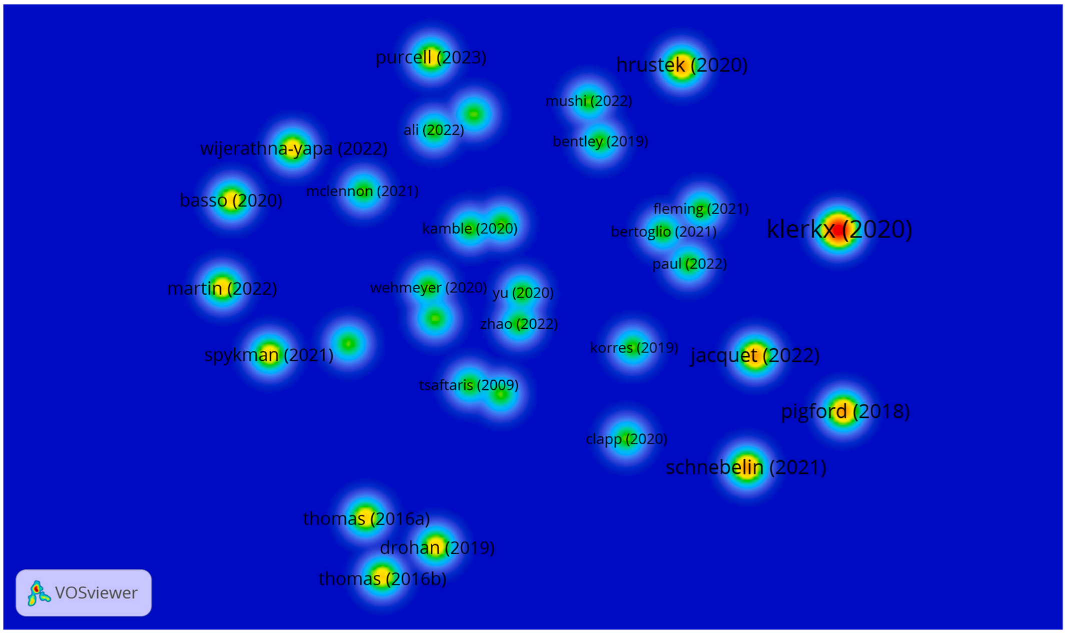

Fig. 2. The density visualization of documents citation analysis.

Table 3
Top 10 sources ranked by average citation.

No.	Source	Publisher	Publication	Citation	Total link strength	Average citation
1	International Journal of Production Economics	Elsevier	1	390	3	390
2	Nature Sustainability	Springer Nature	1	166	9	166
3	Global Food Security - Agriculture Policy Economics and Environment	Elsevier	2	257	10	128.5
4	Talanta	Elsevier	1	93	0	93
5	Ecological Informatics	Elsevier	1	80	1	80
6	Surveys in Geophysics	Springer	1	77	0	77
7	Catena	Elsevier	3	228	0	76
8	Agricultural Systems	Elsevier	4	291	10	72.75
9	Global Environmental Politics	MIT Press	1	72	5	72
10	Technological Forecasting and Social Change	Elsevier	1	71	5	71

3.2.3. Organizations citation

The analysis identified 104 institutions from 709 organizations based on a threshold of at least two publications and two citations per organization. Table 4 showcases the top 10 organizations based on their average citation count. The University of Reading from England leads the list, claiming the top spot with an average citation count of 119.5. Following closely are Wageningen University from the Netherlands and Oregon State University from the USA, with average citations of 102.4 and 97, respectively. This ranking highlights the scholarly impact and recognition garnered by these institutions.

Fig. 4 shows the density analysis visualization of organizations ranked by total link strength. Wageningen University from the Netherlands ranked first (29 total link strength). Next came Oregon State University from the USA and the University of Montpellier from France, with 21 total link strengths. This visualization underscores the collaborative nature of research efforts among these prominent institutions across different geographical regions.

3.2.4. Countries citation

Countries citation analysis included 86 countries published on the digital era' sustainable agriculture. Table 5 provides a ranking of countries based on their average citations, offering insights into the scholarly impact of research from different nations. Israel secured the first position with an impressive average of 77 citations. Wales and the Netherlands ranked second and third, with average citations of 66 and 60.73, respectively. This ranking highlights the significant contributions exhibited by these countries in the global research landscape.

Fig. 5 depicts the ranking of countries based on total link strength, which offers a contrasting perspective. China emerges at the top,

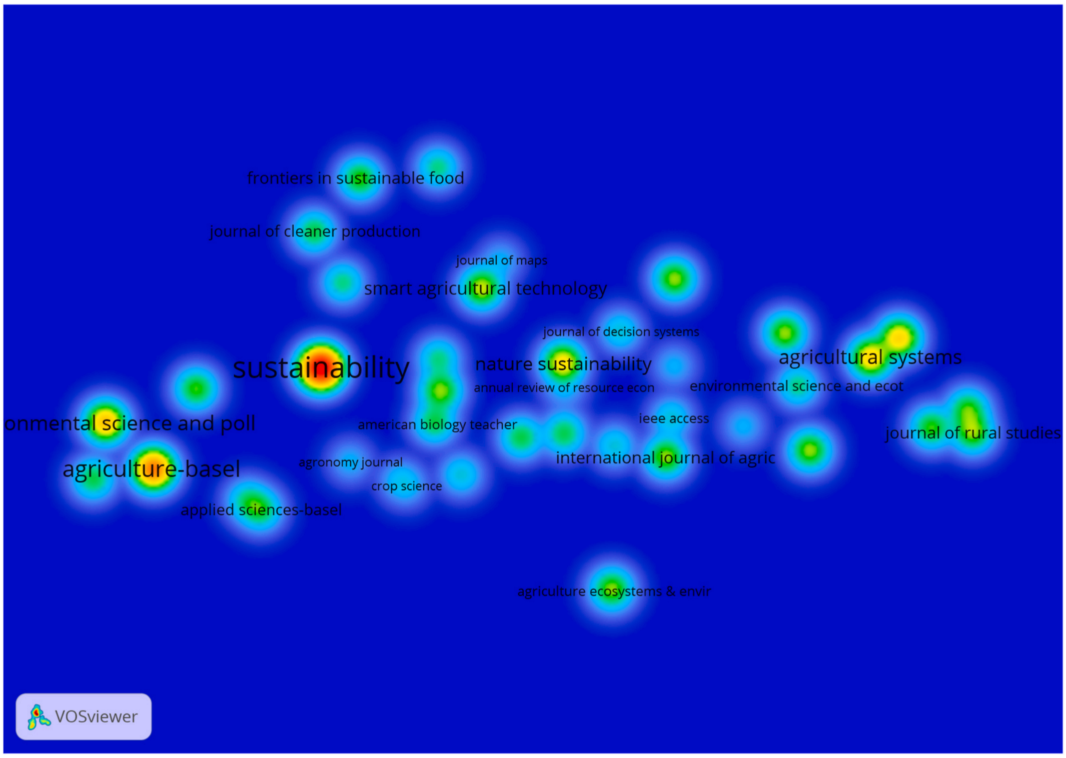

Fig. 3. The density visualization of sources citation analysis.

Table 4
Top 10 institutions ranked by average citation.

No.	Institution	Country	Publication	Citation	Total link strength	Average citation
1	University of Reading	England	2	239	16	119.5
2	Wageningen University	Netherlands	5	512	29	102.4
3	Oregon State University	USA	2	194	21	97
4	Newcastle University	England	2	111	2	55.5
5	University of Padua	Italy	2	111	0	55.5
6	INRAE	France	2	105	9	52.5
7	University of Burgundy Franche-Comté	France	2	105	9	52.5
8	Environmental Systems Research Institute	USA	2	105	0	52.5
9	Institut Agro	France	2	96	12	48
10	University College Dublin	Ireland	2	95	15	47.5

claiming the first position with a total link strength of 60. Then, France and the USA ranked second and third (46 and 45 total link strengths, respectively).

3.3. Co-authorship analysis

3.3.1. Authors co-authorship analysis

Out of the total 1514 authors considered, 122 authors were selected based on having at least one document and an average of 50 citations per author. Table 6 showcases the top 10 authors ranked by their average number of citations, with Gawankar, Gunasekaran, and Kamble topping the list, each boasting an average of 390 citations.

Fig. 6 shows a map of co-authorship based on the authors' names. The largest cluster, with the most authors, comprises 18 and was prevalent in 2019. The second-largest cluster, which was comprised of 11 authors, was also prominent in 2019. Meanwhile, the third-largest cluster, comprised of 10 authors, stood out in 2016.

3.3.2. Organizations Co-authorship analysis

Out of the 104 institutions selected based on the criteria of at least two publications and two citations per organization, some were not connected. Ultimately, 49 groups formed four clusters for the network of organizations. Fig. 7 visualizes the co-authorship network among institutions, with Université de Montpellier and Wageningen University & Research standing out as the two groups with the

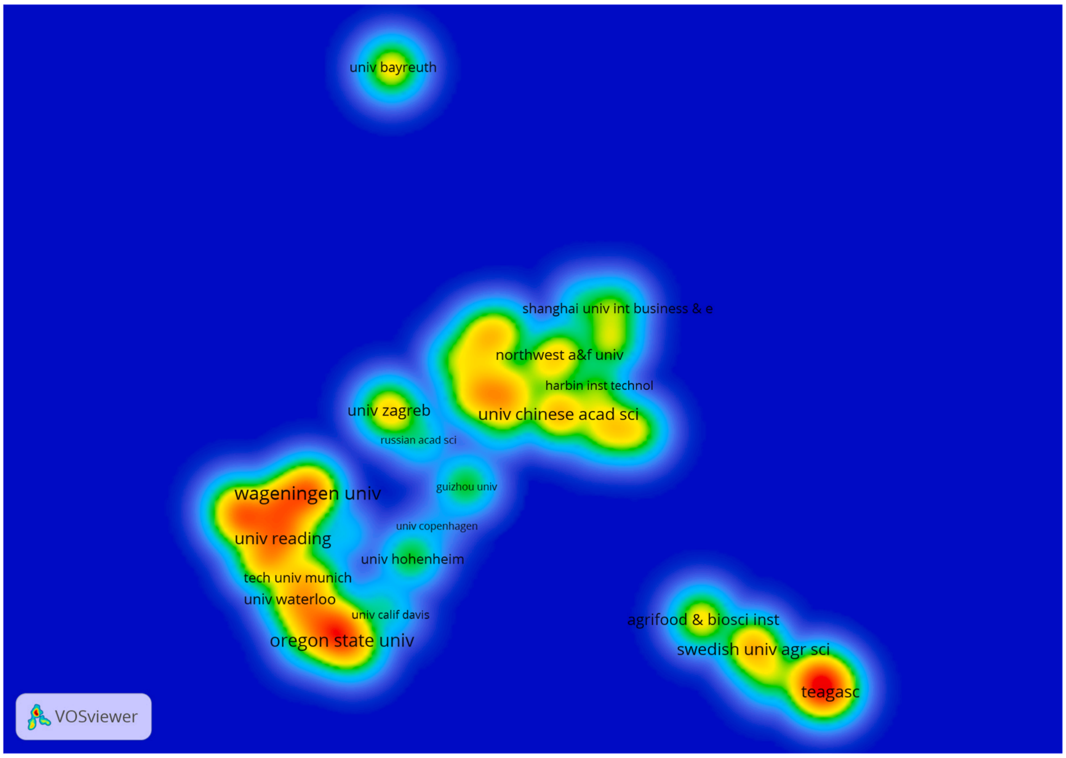

Fig. 4. The density visualization of organizations citation analysis.

Table 5
Top 10 countries ranked by average citation.

No.	Country	Publication	Citation	Total link strength	Average citation
1	Israel	1	77	0	77
2	Wales	1	66	1	66
3	Netherlands	11	668	39	60.73
4	Thailand	2	93	0	46.5
5	Croatia	2	79	26	39.5
6	England	14	514	23	36.71
7	New Zealand	2	66	5	33
8	North Ireland	4	121	27	30.25
9	Canada	11	326	21	29.64
10	USA	46	1302	45	28.3

most collaborations, co-authoring with eight other institutions. Following were the Teagasc and the Chinese Academy of Sciences, both collaborating with seven different organizations. Table 7 presents the affiliations that are encompassed within each of these clusters.

3.3.3. Countries co-authorship analysis

As some countries were not connected with others in sustainable agriculture in the digital era, the final national co-authorship network was comprised of 77 countries, organized into five clusters. As Fig. 8 illustrates, the U.S.A., England, and Italy were the top three countries with the most collaborations, co-authoring with 33, 30, and 26 countries, respectively. Table 8 provides a list of the countries that fall within each of these clusters.

3.4. Co-citation analysis

Document over author co-citation analysis was chosen to minimize potential misinterpretations stemming from authors' involvement in multiple research fields, as noted by Hota et al. [62]. From 19,239 cited references, 63 exceeded the criteria of six minimum citations. One of the items in the network was not connected, making the most extensive set of connected publications 62 items. Table 9 showcases the top ten co-cited references, while Fig. 9 displays network analysis. Wolfert et al. [63] were cited 31 times with 147 total link strengths, Klerkx et al. [64] were cited 29 times with 156 total link strengths, and McBratney et al. [65] were mentioned 21 times with 50 total link strengths.

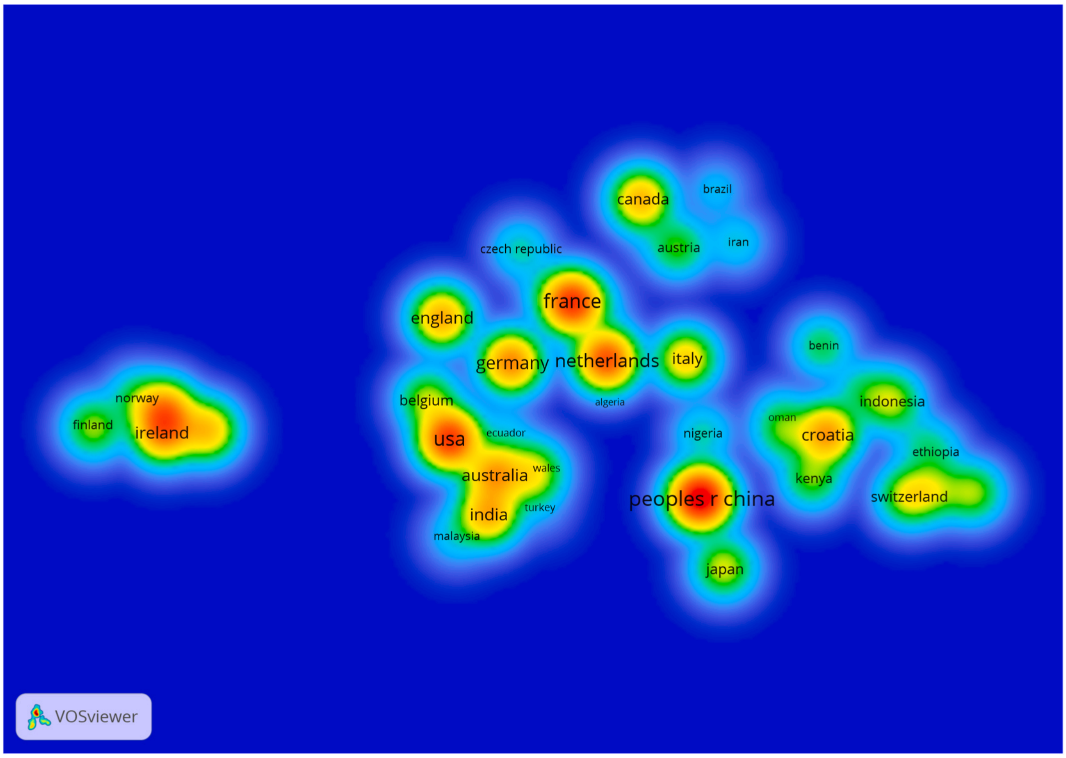

Fig. 5. The density visualization of countries citation analysis.

Table 6
Top 10 authors ranked by average citation.

No.	Author	Publication	Citation	Total link strength	Average citation
1	Gawankar, Shradha A.	1	390	2	390
2	Gunasekaran, Angappa	1	390	2	390
3	Kamble, Sachin s.	1	390	2	390
4	Rose, David	1	239	1	239
5	Hickey, Gordon m.	1	219	2	219
6	Pigford, Ashlee-ann E.	1	219	2	219
7	Antle, John	1	166	1	166
8	Basso, Bruno	1	166	1	166
9	Daroussin, J	1	158	4	158
10	Jamagne, M	1	158	4	158

Co-citation analysis unveils four thematic clusters among references, facilitating the identification of shared topics and thematic connections: nodes of the same color share common issues. Table 10 presents cluster labels, publication counts, and typical publications.

3.5. Co-word analysis

Out of 2068 keywords, 64 were selected for co-word analysis, each appearing at least six times. The co-occurrence of keywords witnessed “Sustainable agriculture” 59 times, making it the keyword with the highest frequency. The second and third most frequently occurring keywords were “Agriculture” and “Precision agriculture,” with 43 and 38 times, respectively. Table 11 displays the top 10 co-occurring keywords. Most of these frequently occurring keywords have an average publication year of 2021. Fig. 10 shows the temporal trends of the top 10 keywords regarding occurences.

Fig. 10 illustrates variations in the frequency of keyword occurrences over different years. In the early years (2001–2010), most keywords appeared infrequently or not. However, starting in 2018, there has been a noticeable increase in the occurrence of keywords. For instance, “Sustainable agriculture” increased from 3 occurrences in 2018 to 19 in 2023, while “Sustainability” has risen threefold in four years. Additionally, “Digital agriculture” peaked at nine occurrences in 2021. In recent years, there has been a surge in research focused on agricultural sustainability and digitalization. As technology develops, these keywords are expected to increase further, fostering innovation and progress in agriculture.

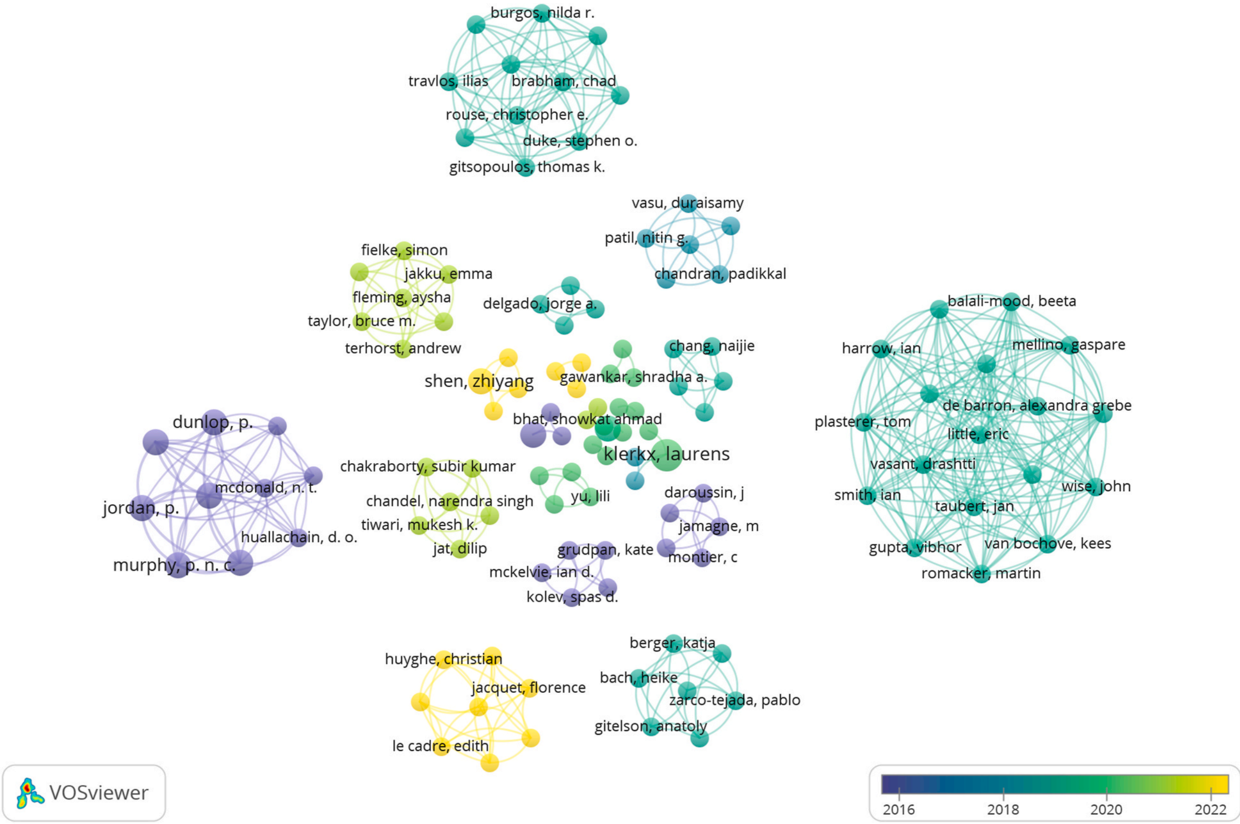

Fig. 6. The overlay visualization of authors co-authorship analysis.

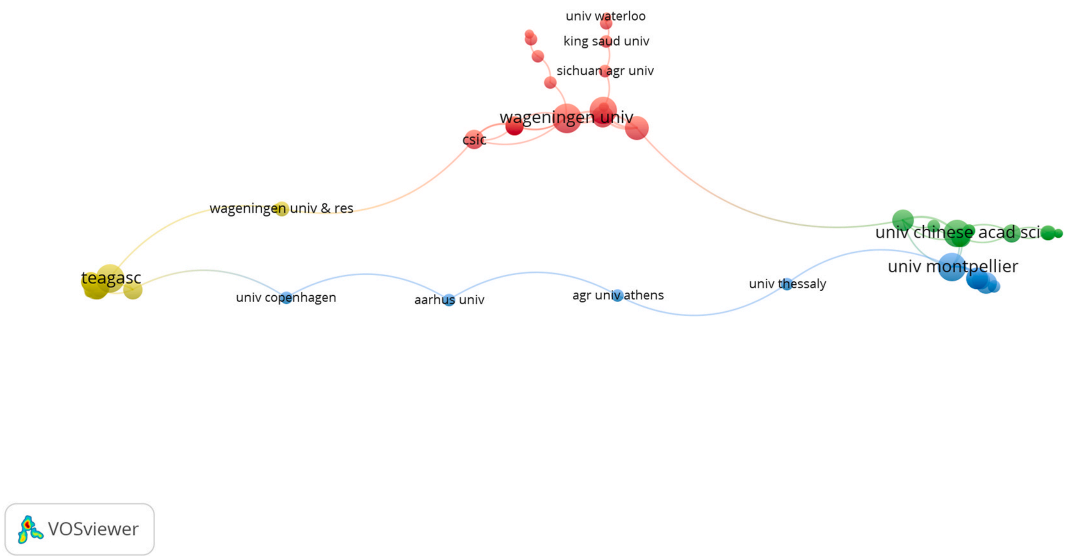

Fig. 7. The network visualization of organizations co-authorship analysis.

Fig. 11 illustrates the co-occurrence of keywords, comprising four separate yet interconnected clusters. Subsequently, Table 12 summarizes the co-word analysis of literature on sustainable agriculture in the digital era, presenting cluster labels, the volume of keywords, and typical keywords.

Table 7
Organizations co-authorship clusters.

Cluster	Number	Organizations
1 (Red)	18	China Agricultural University, China University of Geosciences, Chinese Academy of Agricultural Sciences, Consejo Superior de Investigaciones Científica, Griffith University, Hungarian University of Agriculture and Life Sciences, King Saud University, Ministry of Agriculture, Newcastle University, Northwest A&F University, Sichuan Agricultural University, South China Agricultural University, University of Guelph, University of Melbourne, University of Plymouth, University of Reading, University of Waterloo, Wageningen University
2 (Green)	11	Beijing Engineering Research Center of Intelligent Systems and Technology, Chinese Academy of Sciences, Dalhousie University, Guizhou University, Nanjing Agricultural University, Renmin University of China, Southwest University, University of Chinese Academy of Sciences, Wuhan University, Zhejiang University, Zhengzhou University
3 (Blue)	10	Aarhus University, Agricultural University of Athens, INRAE, Institut Agro, Université de Bourgogne Franche-Comté, Université de Bretagne Occidentale, University of Copenhagen, Université de Montpellier, Université Paris-Saclay, University of Thessaly
4 (Yellow)	10	AgriFood and Biosciences Institute, Environmental Systems Research Institute, International Institute of Tropical Agriculture, Norwegian Institute of Bioeconomy Research, Swedish University of Agricultural Sciences, TEAGASC, University College Dublin, University of Ulster, USDA Agricultural Research Service, Wageningen University & Research

4. Discussion

4.1. Hotspot research

Co-citation analysis identified four clusters of hotspot research themes to unveil past and current evolutionary trends. Each cluster was defined as follows.

Cluster 1 (Red) comprises 19 publications titled "Prosperity and challenges in agricultural sustainability." In the face of escalating global food demand projections and mounting pressure on agricultural ecosystems, the urgency for sustainable farming practices has never been more pronounced [52]. Exploring agricultural sustainability delves into the multifaceted dynamics of transformative potential, ethical considerations, and broader implications for societal well-being. The prospects of sustainable agriculture are closely

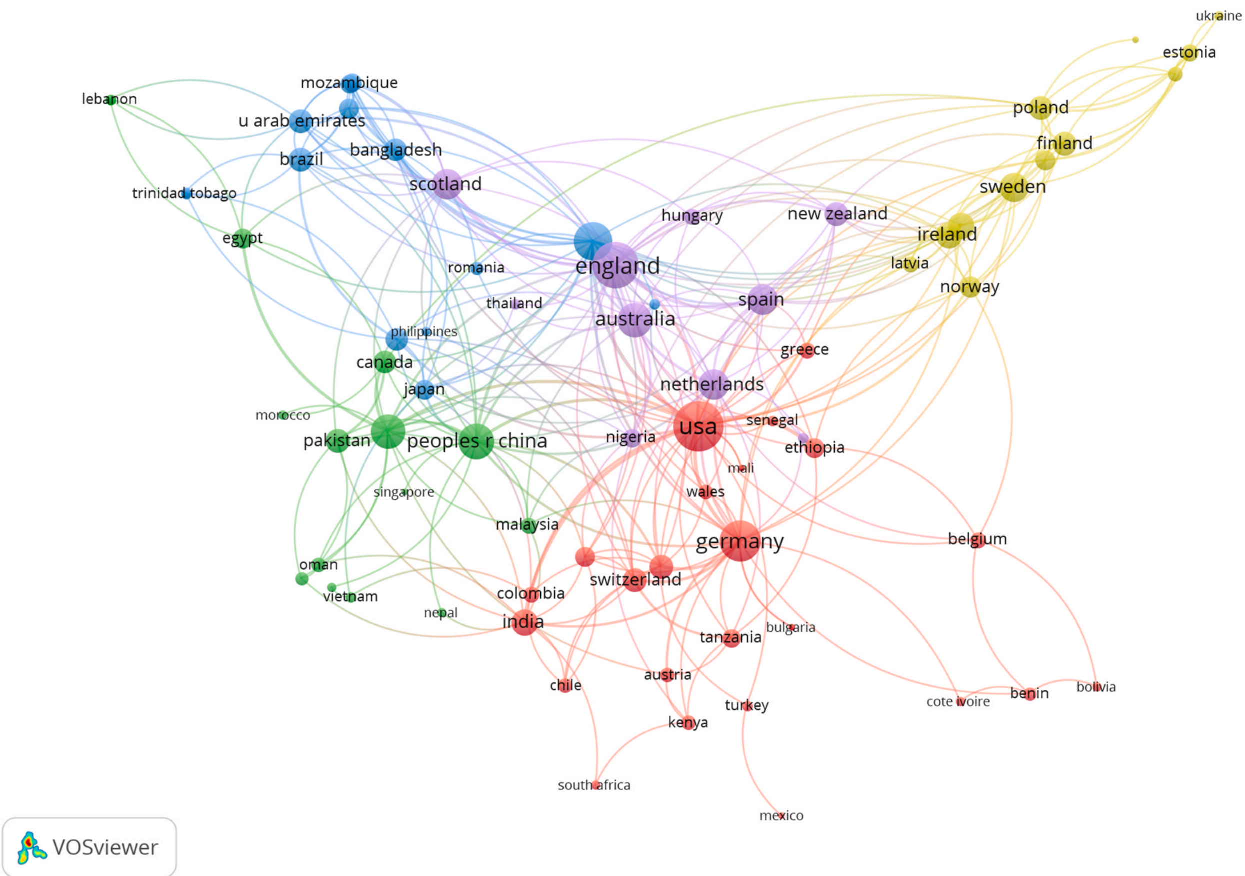

Fig. 8. The network visualization of countries co-authorship analysis.

Table 8
Countries co-authorship clusters.

Cluster	Number	Countries
1 (Red)	26	Austria, Belgium, Benin, Bolivia, Bulgaria, Chile, Colombia, Côte d'Ivoire, Czech Republic, Ethiopia, France, Germany, Greece, India, Kenya, Mali, Mexico, Russia, Senegal, South Africa, South Korea, Switzerland, Tanzania, Turkey, U.S.A., Wales
2 (Green)	15	Canada, Egypt, Jordan, Lebanon, Malaysia, Morocco, Nepal, Oman, Pakistan, People's Republic of China, Saudi Arabia, Singapore, Slovakia, Taiwan, Vietnam
3 (Blue)	14	Bangladesh, Brazil, Indonesia, Iran, Italy, Japan, Mozambique, Philippines, Romania, Sri Lanka, Trinidad and Tobago, Turkey, United Arab Emirates, Zambia
4 (Yellow)	12	Botswana, Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, North Ireland, Norway, Poland, Sweden, Ukraine
5 (Purple)	10	Australia, England, Hungary, Israel, Netherlands, New Zealand, Nigeria, Scotland, Spain, Thailand

intertwined with technological advancements. From precision agriculture technologies enabling efficient resource utilization to decision support systems guiding evidence-based farming practices, technology is pivotal in bolstering agricultural sustainability [66–68].

Moreover, the rise of digital agriculture heralds promising prospects for crafting sustainable agricultural systems. By integrating digital and geospatial technologies, stakeholders can effectively monitor, assess, and manage agricultural resources, thus driving economic, environmental, and social sustainability [53,69]. The convergence of digital agriculture with high-level policy agendas underscores sustainable agriculture's promising future, emphasizing technology's crucial role in shaping its trajectory [72].

Table 9
Top 10 documents ranked by co-citation.

Rank	Documents	Citation	Total link strength
1	Wolfert, S.; Ge, L.; Verdouw, C.; Bogaardt, M.J. Big Data in Smart Farming – A Review. Agric. Syst. 2017, 153, 69–80.	31	147
2	Klerkx, L.; Jakku, E.; Labarthe, P. A Review of Social Science on Digital Agriculture, Smart Farming and Agriculture 4.0: New Contributions and a Future Research Agenda. NJAS Wageningen J. Life Sci. 2019, 90–91.	29	156
3	McBratney, A.B.; Mendonça Santos, M.L.; Minasny, B. On Digital Soil Mapping. Geoderma 2003, 117, 3–52.	21	50
4	Walter, A.; Finger, R.; Huber, R.; Buchmann, N. Smart Farming Is Key to Developing Sustainable Agriculture. Proc. Natl. Acad. Sci. U. S. A. 2017, 114, 6148–6150.	19	79
5	Rotz, S.; Duncan, E.; Small, M.; Botschner, J.; Dara, R.; Mosby, I.; Reed, M.; Fraser, E.D.G. The Politics of Digital Agricultural Technologies: A Preliminary Review. Sociol. Ruralis. 2019, 59, 203–229	14	98
6	Hrustek, L. Sustainability Driven by Agriculture through Digital Transformation. Sustain. 2020, Vol. 12, Page 8596 2020, 12, 8596.	12	35
7	Lajoie-O'Malley, A.; Bronson, K.; van der Burg, S.; Klerkx, L. The Future(s) of Digital Agriculture and Sustainable Food Systems: An Analysis of High-Level Policy Documents. Ecosyst. Serv. 2020, 45, 101183.	12	86
8	Klerkx, L.; Rose, D. Dealing with the Game-Changing Technologies of Agriculture 4.0: How Do We Manage Diversity and Responsibility in Food System Transition Pathways? Glob. Food Sec. 2020, 24, 100347.	11	77
9	Rose, D.C.; Sutherland, W.J.; Parker, C.; Lobley, M.; Winter, M.; Morris, C.; Twining, S.; Ffoulkes, C.; Amano, T.; Dicks, L. V. Decision Support Tools for Agriculture: Towards Effective Design and Delivery. Agric. Syst. 2016, 149, 165–174.	11	46
10	Rose, D.C.; Chilvers, J. Agriculture 4.0: Broadening Responsible Innovation in an Era of Smart Farming. Front. Sustain. Food Syst. 2018, 2, 387545.	11	82

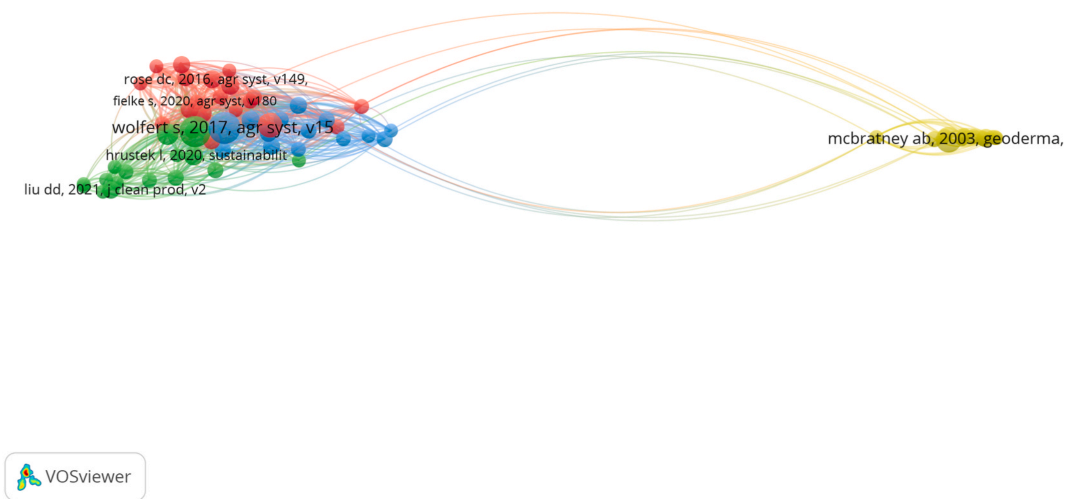

Fig. 9. The network visualization of co-citation analysis and hotspot themes.

Table 10
Co-citation clusters.

Cluster	Label	Number	Representative publications
1 (Red)	Prosperity and challenges in agricultural sustainability	19	[17,52,53,66–72]
2 (Green)	Digital information and agricultural development	17	[13,16,23,64,73–78]
3 (Blue)	Innovations for sustainable agriculture	14	[19,63,79–87]
4 (Yellow)	Geospatial analysis in environmental studies	12	[65,88–94]

Table 11
Top 10 keywords ranked by co-occurrence.

Rank	Keyword	Occurrences	Total link strength	Average publication years	Average citation scores
1	Sustainable agriculture	59	159	2021.32	13.81
2	Agriculture	43	123	2019.88	18.16
3	Precision agriculture	38	126	2020.68	12.05
4	Management	33	121	2021.45	21.61
5	Sustainability	28	57	2021.61	21.25
6	Digital agriculture	24	91	2021.88	17.42
7	Adoption	23	85	2022.04	6.39
8	Big data	23	96	2021.74	38.78
9	Information	22	77	2022.23	12.27
10	Technologies	17	66	2021.65	22.88

Technology-driven agriculture intertwines with labor dynamics, rural communities, and the overarching food system [71]. However, the journey towards agricultural sustainability is fraught with challenges. Ethical dilemmas surrounding big data in agriculture underscore power dynamics between farmers and agribusinesses, necessitating equitable data access [70]. Additionally, the adoption of precision agriculture varies across regions and is influenced by factors like farm size, income, and attitudinal differences [17].

Cluster 2 (Green) comprises 16 publications under the theme “Digital information and agricultural development,” focusing on the profound changes digital information has catalyzed in the agricultural sector. For instance, digital finance platforms, as part of the broader landscape of digital information in agriculture, have empowered smallholder farmers by providing access to credit, thereby facilitating the adoption of sustainable agricultural practices [23]. The integration of digital information is acknowledged as a catalyst for green growth in China, offering productivity enhancements while minimizing environmental impacts [73]. Similarly, blockchain technology revolutionizes supply chains, enhancing transparency and trust surrounding digital information among stakeholders [74]. Furthermore, integrating agricultural robotics with digital information presents promising prospects for optimizing farming processes, increasing productivity, and mitigating labor shortages [77]. On the other hand, it is crucial to bridge the digital divide to ensure equitable access to transformative information and technologies among smallholder farmers, as emphasized in discussions concerning Tanzania [13]. Under this consideration, mobile technology emerges as a powerful tool for disseminating agricultural knowledge,

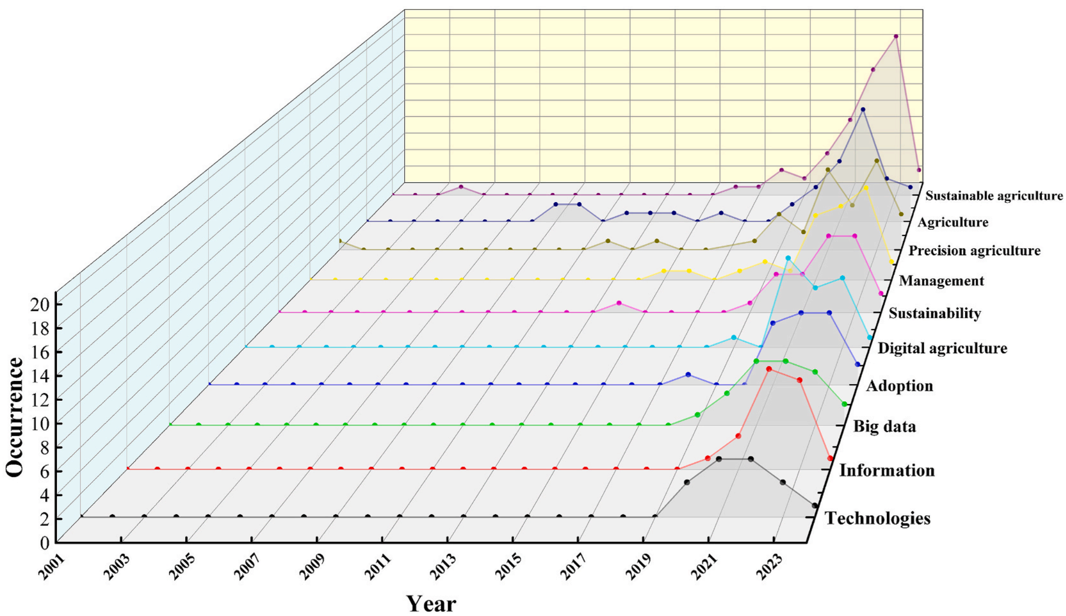

Fig. 10. The temporal trends of the top 10 keywords.

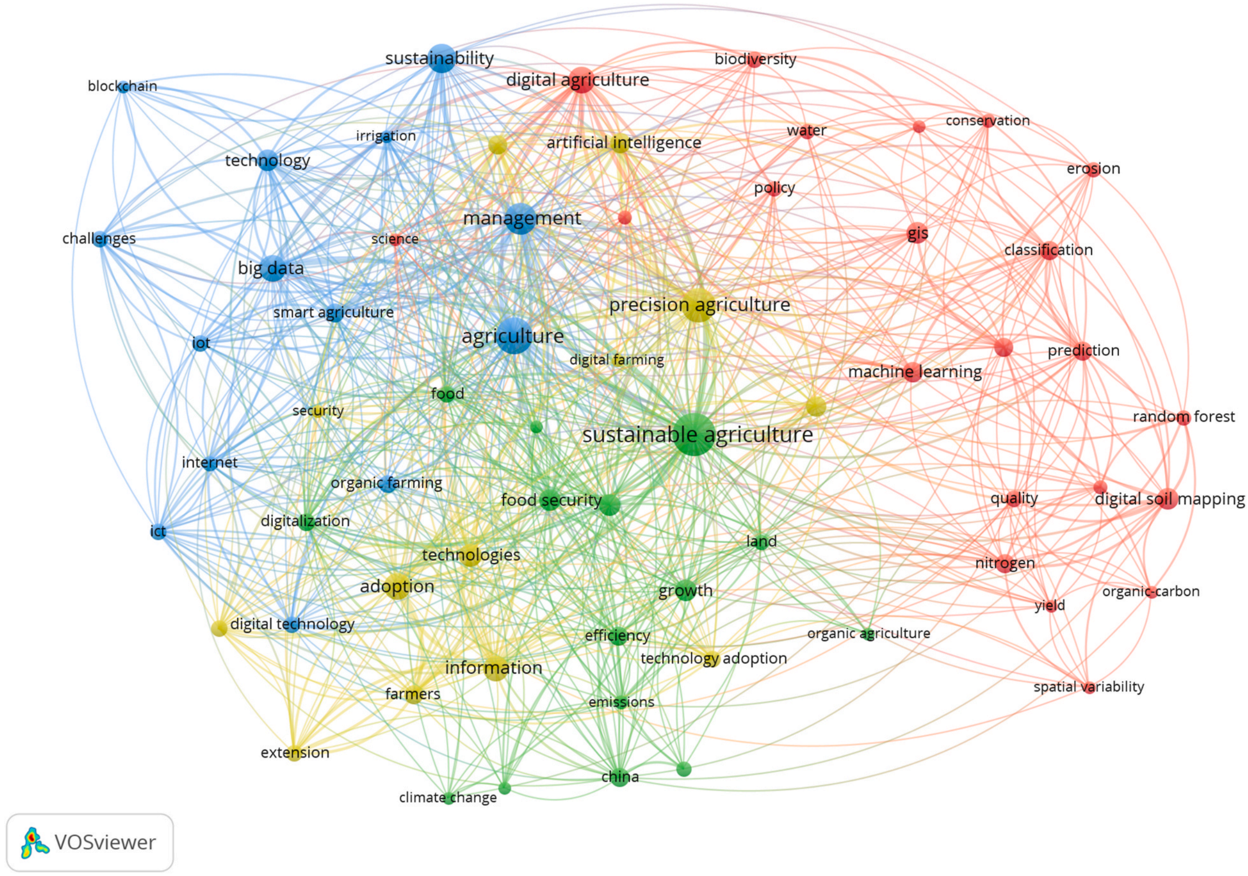

Fig. 11. The network visualization of co-word analysis and emerging trends.

overcoming information barriers, and promoting inclusive growth [76]. In summary, the convergence of digital information with farming brings opportunities for agricultural sustainable development worldwide, shaping a resilient and inclusive agricultural future.

Cluster 3 (Blue) comprises 14 publications named "Innovations for sustainable agriculture," incorporating technical and socio-economic innovations to achieve sustainable agricultural development. Sustainable agricultural innovation represents a comprehensive strategy to tackle the intricate challenges confronting modern agriculture while ensuring the sustainability of agricultural systems and minimizing adverse environmental impacts [79]. Leveraging big data analytics, machine learning and remote sensing, precision farming techniques are enhanced to realize sustainable agriculture, reduce greenhouse gas emissions, optimize input usage, improve farm economics, and bolster food security [86,87]. These innovative technologies are pivotal in optimizing resource utilization, boosting productivity, and mitigating environmental footprints by facilitating real-time monitoring, data-informed decision-making, and targeted interventions across the agricultural value chain [19,63,80,81]. Precision agriculture techniques are thereby employed for broader socio-economic dimensions; agricultural innovations underscore the significance of inclusive governance structures [82], responsible innovation frameworks [83], and equitable access to transformative technologies [80] to ensure the equitable distribution of innovation benefits among stakeholders, including smallholder farmers and marginalized communities.

Table 12
Co-word clusters.

Cluster	Label	Number	Representative Keywords
1 (Red)	Smart agriculture and biodiversity conservation	22	Biodiversity, Classification, Climate-change, Conservation, Digital soil mapping, Dynamics, Ecosystem services, Erosion, GIS, Machine learning, Nitrogen, Organic-carbon, Policy, Prediction, Quality, Random Forest, Remote sensing, Spatial variability, Water, Yield.
2 (Green)	Digitalization and sustainable agriculture	15	China, Climate change, Digital economy, Digitalization, Efficiency, Emissions, Food, Food security, Growth, Innovation, Land, Mitigation, Organic Agriculture, Sustainable Agriculture, Sustainable development.
3 (Blue)	Technologies and agricultural challenge management	14	Big data, Blockchain, Challenges, Digital technology, ICT, Internet, IOT, Irrigation, Management, Organic farming, Sustainability.
4 (Yellow)	Digital intelligence and farmer adoption	13	Adoption, Artificial intelligence, Digital farming, Extension, Farmers, Information, Knowledge, Precision agriculture, Smart farming, Soil, Technology adoption.

Additionally, addressing the challenges posed by increasing population and consumption necessitates the integration of ecological principles and technological innovations [84,85]. By harnessing the potential of innovative technologies and embracing socio-economic sustainability principles, stakeholders can pave the way for more environmentally sustainable agriculture.

Cluster 4 (Yellow) contains 12 publications titled “Geospatial analysis in environmental studies,” emphasizing the pivotal role of geospatial techniques in unraveling complex environmental processes and informing sustainable management practices. This analytical approach spans various fields. In ecological studies, geospatial analysis methods demonstrate applications in understanding ecosystem structure and function. An intricate relationship exists between landscape composition, habitat characteristics, and critical ecological indicators such as pollinators and vegetation distribution. The method unveils environmental factors' impacts on plant and animal communities at different scales, aiding biodiversity conservation efforts and ecosystem health promotion [88,89]. In soil science, geographic information systems, remote sensing data, and machine learning algorithms predict soil properties across diverse landscapes [65,90]. By evaluating and comparing various classification techniques, researchers can identify optimal approaches for delineating soil taxonomic units and informing land-use decisions [91]. Besides, high-resolution satellite data and machine learning models could map soil properties locally, promising to improve soil information in data-scarce regions and guide sustainable agricultural practices [92]. Studies in terrain analysis highlight the significance of terrain features in hydrological processes and land use. Such analysis enhances understanding of surface water flow, erosion processes, and land degradation, providing a scientific basis for land management and disaster risk reduction [93,94]. By integrating knowledge and techniques from diverse fields, geospatial analysis methods help protect the environment, utilize resources sustainably, and achieve sustainable development goals.

4.2. Emerging trend

Co-word analysis explores four influential topics, indicating directions for future trend evolution. All four clusters were examined and discussed in the following manner.

Cluster 1 (Red) contains 22 keywords titled “Smart agriculture and biodiversity conservation,” encapsulating the integration of advanced technologies and ecological principles to promote sustainable farming practices while safeguarding biodiversity. Digital technologies such as digital soil mapping, Geographic Information Systems (GIS), and remote sensing are pivotal in optimizing resource management and enhancing productivity while minimizing adverse effects on biodiversity [95–98]. Geographic information systems help farmers maximize resource utilization and minimize environmental impacts like erosion [99], thus playing a pivotal role in safeguarding biodiversity. By employing machine learning algorithms and predictive modeling, farmers can analyze spatial variability in soil properties and predict crop yields with greater accuracy, thereby reducing the overuse of fertilizers and pesticides that can harm biodiversity [100,101]. Furthermore, intelligent agriculture leverages data-driven approaches to tackle issues associated with climate variability and its effects on agricultural systems [102]. By applying advanced analytics and modeling techniques, farmers can anticipate changes in climatic patterns, mitigate risks associated with extreme weather events, and adapt their farming practices to maintain ecosystem resilience and biodiversity [103]. Conservation efforts within smart agriculture extend beyond on-farm practices. By implementing agroforestry practices and adopting precision conservation techniques, farmers can enhance biodiversity while simultaneously improving soil quality and water retention [9,104]. Policy interventions also play a crucial role in fostering smart agriculture and biodiversity conservation through subsidies and regulations. By aligning agricultural policies with conservation objectives, policymakers can create an enabling environment for farmers to transition towards more ecologically resilient and biodiversity-friendly farming systems [105,106].

Cluster 2 (Green), comprising 15 keywords, is labeled “Digitalization and sustainable agriculture,” focusing on integrating digital information into agricultural practices to promote sustainability across various dimensions such as efficiency, innovation, and mitigation of climate change impacts. Organic agriculture, for instance, reduces reliance on synthetic inputs and minimizes emissions associated with conventional farming methods [107,108]. Integrating digitalization into sustainable agriculture enhances its efficacy by providing real-time data on agricultural yield, biomass potential, and nitrogen, enabling farmers to make informed decisions that optimize yields while minimizing environmental harm [7]. Furthermore, digitalization contributes to broader goals of sustainable development by fostering innovation in agricultural practices, improving access to markets and information for smallholder farmers, and facilitating the adoption of climate-smart technologies [13,109], encompassing economic growth, social interaction and environmental protection [23,110]. Digitalization offers a pathway to enhance agricultural productivity while minimizing negative environmental impacts, especially in the Chinese context, where rapid industrialization and urbanization have put pressure on land resources and exacerbated environmental issues [111]. By leveraging digital technologies such as precision farming and data analytics, farmers could reduce emissions, optimize resource use, promote food security and improve overall efficiency in agriculture [11,112]. In conclusion, by harnessing the power of digital technologies within the agricultural sector, countries can promote environmentally sustainable practices while ensuring food security and fostering economic growth in the long run.

Cluster 3 (Blue), with 14 keywords, is titled “Technologies and agricultural challenge management,” referring to how advancement technologies address difficulties within the agricultural sector from a macro level. A primary challenge confronting modern agriculture is the sustainable management of natural resources [113]. With IoT sensors and intelligent irrigation systems, precise management of soil moisture levels and water distribution can be achieved, ensuring water resources are allocated accurately to where and when they are needed. This proactive management approach conserves water and mitigates the environmental impact of excessive irrigation [114], thus highlighting the pivotal role of technological innovations in agricultural challenge management for sustainable practices. Information and communication technology (ICT) is essential in crop and nutrition management by providing real-time data and analysis tools, ultimately improving agricultural efficiency and productivity [115]. Moreover, blockchain technology revolutionizes agricultural management by creating an immutable and transparent record of every transaction within the supply chain. This allows consumers to verify the authenticity and trace the journey of their food, thereby fostering trust and addressing challenges from food security [116]. Integrating diverse technological solutions lays the foundation for smart agricultural management, presenting a comprehensive approach to effectively tackling sustainability challenges [6]. Effective challenge management strategies, encompassing a range of activities, including resource allocation, decision-making, and organizational structuring, are designed to optimize agricultural processes while minimizing negative environmental impacts [117].

Cluster 4 (Yellow) comprises 13 keywords labeled "Digital intelligence and farmer adoption," emphasizing micro-level farmer behaviors. Across various agricultural domains, farmers demonstrate increasing adoption of digital intelligence. With AI advancements, farmers leverage data analytics to optimize decision-making processes [118]. AI's analysis of vast agricultural data enables tailored practices based on yield, harvesting, irrigation periods, and meteorology [18]. Furthermore, digital intelligence leverages platforms to disseminate knowledge and provide technical support to farmers, empowering farmers with the latest innovations and best practices [119]. The formed digital agricultural community facilitates technology adoption and allows farmers to implement digital solutions on their farms [120]. Besides, farmers can detect crop diseases and weeds early by deploying sensor-based technologies and AI-driven analytics [101,121], improving farm productivity and contributing to resource conservation and environmental sustainability. To encourage the widespread adoption of digital technologies, data security and privacy insurance are essential to build farmers' trust [103]. Moreover, investments in digital infrastructure, including reliable internet connectivity and affordable technology access, are pivotal to bridging the digital divide and stimulating digital intelligence adoption by farmers, particularly in remote areas [122]. In summary, farmers' adoption of digital intelligence drives efficiency and sustainability in agriculture from a grassroots level.

5. Conclusions

This paper offers a thorough bibliometric review of sustainable agriculture in the digital era using a quantitative method to uncover the most influential publications, the interactions between works, historical hotspots, and emerging trends. Related literature surfaced in 1998 and witnessed a significant surge since 2019. Document citation analysis identified the most cited publications. Besides, the International Journal of Production Economics was the most influential, while Laurens Klerkx was the most impactful author in this area, ranked by average citations. Still, based on average citations, the University of Reading and Israel were the most influential institution and country, respectively.

The co-authorship analysis highlights that Gawankar, Gunasekaran, and Kamble are the top authors by average citations, and the largest collaboration clusters were most active in 2019. At the institutional level, Université de Montpellier and Wageningen University & Research lead in collaborations. Additionally, the USA, England, and Italy exhibit the highest levels of co-authorship with numerous countries.

Co-citation analysis generated four clusters for historical and contemporary hotspots: prosperity and challenges in agricultural sustainability, digital information and agricultural development, innovations for sustainable agriculture, and geospatial analysis in environmental studies. These historical themes first introduce the prosperity in promoting agricultural sustainability and consider the corresponding challenges. The topics also depict the effectiveness of digital information in reshaping agricultural production and management. Sustainable agriculture innovations also integrate technological innovation with ecological principles and social-economic dimensions. The last topic emphasizes the application of geographic technologies in environmental research to enhance the understanding and management of environmental issues.

Concurrently, clusters from the co-word analysis are smart agriculture and biodiversity conservation, digitalization and sustainable agriculture, technologies and agricultural challenge management, and digital intelligence and farmer adoption. Thus, future research could explore how integrating innovative agricultural practices contributes to preserving biodiversity while enhancing agricultural productivity in depth. Besides, research will continue to examine the utilization of digital information to achieve sustainable and efficient agricultural production. It is also essential to conduct research from both macro-agricultural management and micro-farmer adoption perspectives, emphasizing the utilization of technologies for tackling agricultural management challenges and exploring how farmers adopt digital intelligence to enhance productivity.

The theoretical implications of this study are manifold. Initially, influential publications, cooperation between authors, historical hotspots, and emerging trends are identified through quantitative bibliometric analysis, and the academic landscape is thoroughly analyzed. This contributes to the theoretical understanding of sustainable agriculture, informing future research directions and theoretical frameworks in the digital era. Furthermore, classifying past and current trends into distinct clusters highlights the interconnectedness of various themes within the digital era' of sustainable agriculture. By elucidating these interrelations, the study contributes to theoretical discussions surrounding the holistic nature of sustainable agricultural practices. In addition, the co-word analysis reveals meaningful thematic clusters, providing a foundation for future theoretical advancements and empirical investigations.

The practical implications of this study are significant for policymakers, researchers, practitioners, and industry stakeholders. Firstly, policymakers can use the insights to inform policy decisions supporting integrating digital technologies in agriculture. By understanding historical trends and emerging clusters, they can prioritize funding for relevant research and development initiatives. Secondly, researchers and practitioners can stay updated on the latest trends and findings by referencing influential publications identified in the study, ensuring alignment with current advancements. Thirdly, agricultural organizations can make informed investment decisions and establish collaborations with leading experts and institutions to advance research and implementation efforts. Finally, the identified thematic clusters offer practical avenues for innovation, guiding agricultural technology companies and startups in developing solutions that address challenges and opportunities in sustainable agriculture and digital technology adoption.

This study has several limitations. Firstly, recent papers may not yet have accumulated a significant number of citations, potentially underestimating their current impact compared to older publications [123]. Secondly, the citation impact analysis primarily focuses on first authors, which may overlook the contributions of co-authors involved in other influential papers [124]. Thirdly, the choice of data source, in this case, Web of Science, may introduce biases, as alternative databases like Scopus or Dimensions could yield different results [125]. Additionally, there may be subjectivity in determining and interpreting clusters, as the process relies on the authors' judgment [126]. To mitigate these limitations, future studies could explore other methods, such as systematic reviews and meta-analyses to address bibliometric constraints, employ multiple databases for comprehensive coverage, and incorporate qualitative inquiries to gain deeper insights into the relationship between blockchain and carbon emissions.

Data availability statement

Data included in article/supp. material/referenced in the article.

CRediT authorship contribution statement

Jiahui Xu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yanzi Li:** Writing – original draft, Validation, Methodology, Funding acquisition, Formal analysis. **Meiping Zhang:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Shuhan Zhang:** Writing – original draft, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e34612.

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