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TOPICAL REVIEW

# Digital Agriculture: Mapping Knowledge Structure and Trends

**RONGJI ZHOU**[1] **AND YUYAN YIN**[2]
[1]College of Economics and Management, Hengyang Normal University, Hengyang 421002, China
[2]College of Foreign Languages, Jinan University, Guangzhou 510632, China

Corresponding author: Yuyan Yin (yuyan_yin@sina.com)

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**ABSTRACT** With the advancement of digital technologies, digital agriculture improves agricultural efficiency and sustainability, reducing resource waste and environmental burden. Hence, DA has emerged as a new catalyst for grain productivity and a driving force behind climate improvement, with broad prospects. However, digital agriculture is still in its early stage in most countries and there are few systematic reviews. In China, for example, there were only 3 non-core reviews out of 817 literatures on DA. Meanwhile, the use of Citespace is revolutionary as it leverages data visualization to uncover hidden patterns and relationships within literatures, aiding researchers in achieving their objectives. This study aims to address this research gap by using Citespace to produce a non-subjective and testable review on DA. In this study, we collected 2264 literatures by retrieving the WoS database in the timespan 1997-2022. The results show that 1) over time, the annual number of publications on DA has gradually increased and the research can be roughly divided into three stages: start-up, steady development, and rapid development stage; 2) research streams of DA can be further divided into six categories: Remote Sensing, Climate-Smart Agriculture, Artificial Intelligence, Internet of Things, Big Data and System Integration; 3) development of research frontiers could be divided into three parts: "exploration of digital agriculture technologies," "operation management of digital agriculture" and "limitations of digital agriculture;" 4) future research should pay more attention to the innovation and scientific evaluation of digital technology and operation management. Also, effective DA policies should be put forward to provide a theoretical basis and decision-making reference.

**INDEX TERMS** Digital agriculture, bibliometrics, citespace, operation management, research hotspot, research stage, research frontier.

## NOMENCLATURE

| | |
|---|---|
| AI | Artificial Intelligence. |
| BD | Big Data. |
| CAS | Chinese Academy of Sciences. |
| CC | Cloud Computing. |
| CNN | Convolutional Neural Networks. |
| CSA | Climate-Smart Agriculture. |
| CSM | Crop Surface Models. |
| DA | Digital Agriculture. |
| DEM | Digital Elevation Model. |
| DL | Deep Learning. |
| DNGP | Digital Northern Great Plains. |
| FAO | Food and Agriculture Organization. |
| GIS | Geographic Information System. |
| GNSS | Global Navigation Satellite System. |
| IAS | Instituto de Agricultura Sostenible. |
| IF | Impact Factor. |
| IIoT | Industrial Internet of Things. |
| IoRT | Internet of Robotic Things. |
| IoT | Internet of Things. |
| KR | Korea. |
| LiDaR | Light Detection and Ranging. |
| ML | Machine Learning. |
| PA | Precision Agriculture. |
| RCISS | Rural Comprehensive Information Service System. |
| RFID | Radio Frequency Identification. |
| RHoMIS | Rural Household Multi-Indicator Survey. |

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| | |
|---|---|
| RNN | Recurrent Neural Networks. |
| RS | Remote Sensing. |
| SDGs | Sustainable Development Goals. |
| SfM | Structure from Motion. |
| SI | System Integration. |
| SR | Solar Radiation. |
| UAS | Unmanned Aerial System. |
| UAV | Unmanned Aerial Vehicle. |
| UGV | Unmanned Ground Vehicle. |
| UN | United Nations. |
| USDA | United States Department of Agriculture. |
| USGS | United States Geological Survey. |
| USDI | United States Department of the Interior. |
| VI | Vegetation Index. |
| WD | Wind Direction. |
| WoS | Web of Science. |
| WTO | World Trade Organization. |
| ZJU | Zhejiang University. |

## I. INTRODUCTION

The growing population has aroused wide concern about the problem of food shortage. According to the data from Food and Agriculture Organization (FAO), the world population will reach 9.7 billion by 2050 and the demand for grain will increase by 70% [1], [2], [3], [4], [5], [6], [7]. Similarly, the global food price index soared to its highest level since its establishment in 1990, reaching an average of 159.3 points in March 2022. However, limited arable land, poor weather conditions and the COVID-19 outbreak continue to threaten food production. For instance, approximately one-third of the world's soil is degraded, resulting in a loss of soil fertility and a decline in the nutrition of grains. In 2022, the Horn of Africa experienced the most severe drought in the last 40 years, leading to a significant reduction of crop yield. It is estimated that 828 million people worldwide suffer from hunger, an increase of 150 million since the epidemic. In response to these challenges, the UN, FAO and other international organizations have taken corresponding measures. On September 25, 2015, the UN formally adopted 17 SDGs. The second point of SDGs is to achieve food security and advocate sustainable agriculture. In 2019, the FAO stated that DA will help alleviate the contradiction between population growth and food shortages [8]. At the 2021 Qingdao Forum on International Standardization, FAO China Representative Wen Kang Nong said that FAO will work to develop international standards to promote the development potential of digital agriculture and make positive efforts to achieve the SDGs. Meanwhile, on March 14, 2022, the UN announced the creation of a Global Crisis Response Group on Food, Energy and Finance to address the broad impact of the Russia-Ukraine conflict. In total, the World Bank will commit $30 billion to support agricultural production, promote trade and invest in sustainable food by August 2023. In terms of the overall impact of the response, the FAO Global Food Price Index in December 2022 was 17 percent below its level for the same period in 2021. However, food prices are still much higher than pre-epidemic levels, and global food security still faces serious challenges. At present, there are numerous literatures on DA around the world, but there are few literature reviews about it. For example, if we do a simple search in CNKI in the same period chosen for this study, we'll find that there are around 817 articles, of which only 3 are regular reviews. At the same time, all the 3 literature reviews do not belong to the core journals of Peking University, which indicates that these reviews still have a large room for improvement. As a result, visualization analysis of DA literatures based on Citespace is of far-reaching significance to the further development of this field.

Digital agriculture refers to collecting a large amount of data through digital technologies, for example, AI, UAV, satellites and sensors, so as to increase grain output [9], [10], [11], [12], [13], [14], [15], [16]. In addition, these data often need to be combined with people's in-field experience. In the application process of DA, many new terms related to digital agriculture have emerged, such as Precision Agriculture, Smart Agriculture and Agriculture 4.0. Digital agriculture emphasizes the introduction of information technology in agriculture, quantifying agricultural production processes, while precision agriculture is the specific application of information technology in agriculture. For example, the quantitative irrigation of crops and precise fertilization. Compared with traditional agriculture, smart agriculture is an advanced stage of agricultural production, which is the result of the application of information technology in the agricultural field. Agriculture 4.0 refers to an emerging model that uses modern information technologies to promote the sustainable development of agriculture. However, there is essentially no difference between these terms, just different names at different time periods. In the 1990s, researchers called it "precision agriculture" [17]. At the beginning of the 20th century, researchers called it "smart agriculture" or "digital agriculture." In recent years, researchers tend to call it Agriculture 4.0 [10], [18], [19], [20], [21], [22], [23]. DA can not only improve productivity but also protect the environment and reduce farming costs, which has been the focus of researchers and agricultural enterprises in recent years [24].

At present, only a few scholars have incomplete descriptions and analyses of the existing literature on DA. For instance, the authors of [25] are limited to reviewing the policies and laws of Germany and other European countries, emphasizing the influence of the DA system and laws on SDGs. However, these results are fragmented. Also, the authors of [26] focus on the mismatch between digital agricultural technology and end users (farmers and technicians, etc.) in Australia. At the same time, corresponding measures are put forward from the perspectives of government, technology developers and networks to narrow the gap between end users and digital technologies. Similarly, the authors of [17] and [27] systematically reviewed the literature on

CSA, aiming at keeping the mode of sustainable agricultural production and enough grain production even in all types of weather.

Other literatures also focused on more concrete themes: in [28], [29], [30], and [31] researchers mainly focus on Artificial Intelligence (AI). AI refers to the correct understanding of external data with the help of computer programs to complete specific tasks [32], [33], [34], [35], [36]. In fact, AI has only been introduced into DA in recent years. Therefore, compared with other research topics, AI is still underdeveloped. In this field, there are many different branches, for example, machine learning (ML); in [37], [38], [39], [40], and [41] researchers mainly focus on the IoT. The IoT has two meanings in total. First of all, it is based on the Internet. Secondly, the terminals of IoT can not only be mankind but also objects, which can realize the communication and exchange of information between mankind and objects or between objects [42], [43], [44], [45]. In the field of agriculture, it means connecting the growth condition of crops with the Internet through sensing devices, such as RFID, so as to realize the intelligent management of crops. For example, in [46] researchers designed a set of IoT systems. They equipped three experimental fields with humidity and temperature sensors, so that they can obtain real-time data through intelligent pipes, and adjusted them in time to improve yield. With the continuous development of the IoT, many countries have begun to pay great attention to it [47], [48], and [49]. Japan, Korea (KR), the United States, and Europe have issued IoT strategies, taking it as a key area. For example, "U-Japan," "U-Korea," "the Smart Grid" in the United States, and "Internet of Things —An action plan" in Europe; in [50], [51], [52], [53], [54], and [55] researchers mainly focus on Remote Sensing (RS). Broadly speaking, it refers to all non-contact long-distance detection. In a narrow sense, it refers to a comprehensive detection technology that records and analyzes the electromagnetic wave of an object from a distance, thus revealing the features and changes of the object [56], [57], [58], [59], [60]. RS in the field of agriculture refers to the non-contact measurement of energy radiated by crops, soil and sunlight. For example, in [61] researchers focus on the DNGP, a web-based RS system, which not only helps to reduce planting costs, operating costs and environmental costs, but also increases the yield to some extent; in [62], [63], [64], [65], and [66] researchers mainly focus on Site-specific Management (SSM). SSM originated from PA in the 1980s, which means that soils or crops with the same characteristics will be treated similarly [67], [68], [69], [70], [71]. SSM technologies include Yield Mapping (YM), the GIS, and the GNSS. SSM is superior to the traditional practice since it has the merits of finer mapping. For example, in [72], given the fact that satellite imaging technology is often affected by the correction of atmospheric interference, researchers began to pay attention to UAS. Compared with satellites, UAS has higher applicability, because it can achieve higher temporal and spatial resolution while maintaining lower operating costs.

In a word, although a lot of research results have been achieved in DA, there are still the following deficiencies. First of all, only a few literatures have partially reviewed the research results of this field. At the same time, in these documents, the research scope is generally narrow in that most of them are limited to a certain region or a certain country and the time span is relatively short. The second is the limitation of research tools, which means the existing literature rarely uses bibliometric software for quantitative analysis of literature in this field. This is also the main reason why we chose Citespace to conduct a literature review in the field of DA. Given this, the marginal contributions of this study are as follows. First, from the perspective of the research scope, this study comprehensively reviews 2,264 core literatures in the WoS database in the timespan 1997-2022. The research scope is more extensive than before, which makes up for the previous DA literature review to a certain extent. Second, from the perspective of research tools, this study first introduced bibliometric software Citespace into DA for literature review, making up for the limitations of such research. Third, from the perspective of research content, the marginal contribution of this research is mainly reflected in two aspects: research topics and frontiers. Based on the existing research [13], [73], [74], [75], [76], [77], [78], [79], this paper redivides the research topics of DA into 6 categories: RS, CSA, AI, IoT, BD and SI. At the same time, by reading a lot of literatures on DA, the research frontier of this field is also redivided into three parts: "exploration of digital agriculture technologies," "operation management of digital agriculture" and "limitations of digital agriculture." Finally, given the limitations of this field, the corresponding solutions are put forward from three perspectives of policymakers, researchers and practitioners.

Citespace is a practical review analysis software, which is mainly used for quantitative and qualitative analysis of research authors, institutions, journals and keywords, so as to efficiently build a knowledge map of a certain field [80], [81], [82], [83], [84]. In addition, this tool can also show the research hotspots and frontiers of a field clearly, which is helpful in presenting the overall research status of the field [85], [86], [87], [88], [89], [90]. However, the purpose of this study is to review the literature on DA in order to answer four academic questions (1) What is the research status of DA? (2) What are the key authors, institutions, journals and keywords of DA? (3) What are the primary research streams in DA? (4) What are the emerging topics of DA? Therefore, this is why the use of the Citespace approach is a revolutionary step forward for DA and how it helps achieve our research objectives, that is, the answer to the above four academic questions.

## II. MATERIALS AND METHODS

### A. MATERIALS

Given that WoS provides high-quality, organized content from reputable journals and publications and offers in-depth citation analysis, enabling researchers to track the impact of articles, authors, institutions, journals and keywords, some disciplines may be better represented in this database. Therefore, this paper retrieved the data from the WoS core database with the following conditions:

1) Software: Citespace 6.2 (Latest Version)
2) Topic: Digital Agriculture
3) Timespan: 1997-2022
4) (Refined by) Languages: English
5) Indexes: SCI-Expanded, SSCI, A&HCI
6) Time slicing: one year.

In this way, we collected 2264 documents on May 17, 2023, mainly including authoritative journals of DA, which can be verified by retrieving the same WoS core database. We chose 1997 as the starting year because the term "digital agriculture" first appeared in 1997. First of all, we stored literatures in plain text format as the original data. Secondly, in order to avoid duplicate literatures in the original data, we import the original data into Citespace to remove duplicates. Finally, the processed data is used as the basic data for our study.

### B. METHODS

In Citespace, bibliometric methods such as Clustering, Co-citation, Co-occurrence and Burstness Analysis are helpful in reviewing the development process of DA. (1) Clustering Analysis refers to grouping similar keywords of the same topic into one category [91], [92]. First of all, the smaller the cluster number, the more keyword members it has. Secondly, the clustering map can reflect the structural characteristics of each cluster. Finally, there is a color band above the map and different colors represent different times. Therefore, the color of a cluster indicates the time when the cluster first appeared. (2) The research object of Co-citation Analysis can be literatures, scholars and journals, etc. When the literatures of scholars A, B, C... are cited by scholar D at the same time, it is said that there is a co-citation relationship among several scholars A, B, C... For example, if the co-citation frequency of scholar A and scholar B is higher than the frequency of scholar B and scholar C, it means that the academic correlation between scholar A and scholar B is closer [93]. (3) The research object of Co-occurrence Analysis can be keywords, disciplines, etc. For example, the frequency of two or more keywords appearing in the same article can reflect the Co-occurrence strength between keywords [94], [95], [96]. First, the size of a node reflects the frequency of keyword Co-occurrence. The larger the node, the higher the frequency. Secondly, there is a color band above the map, and different colors represent different times. Therefore, the color of the line between nodes represents the time of the first Co-occurrence. (4) The research object of Burstness Analysis can be keywords. This method can visualize the Burstness strength and first Burstness time of keywords, so as to better review the development of cutting-edge trends in DA [97], [98]. Therefore, the Burstness map can help scholars or institutions find suitable academic partners.

The outline of the study is shown below. In section II, this study presented the data source, research tool and research methods of literature analysis, and introduced the selection of the database and the process of data preparation. In section III, the overview of DA was first presented from a macro perspective. In addition, this study also analyzed high-impact scholars, institutions, journals and keywords of this field from a micro perspective. In particular, Co-occurrence analysis, Clustering analysis and Burstness analysis of keywords in DA were conducted, which is helpful in classifying the research streams of DA. Meanwhile, this study has made necessary explanations and enumerated representative papers for each research stream. In section IV, the cutting-edge trends of this field were summarized and divided into three parts, which can provide some references for countries around the world to formulate agricultural policies and promote agricultural modernization. Finally, based on the above research results, this paper provided coping strategies from three aspects of policymakers, researchers and practitioners.

## III. DATA ANALYSIS AND INTERPRETATION

### A. PRELIMINARY ANALYSIS

Based on the research results, 2264 papers related to the DA were published from January 1997 to December 2022, with an average publication of 87 papers each year. These papers are presented in the following figure, which clearly shows the number of publications each year.

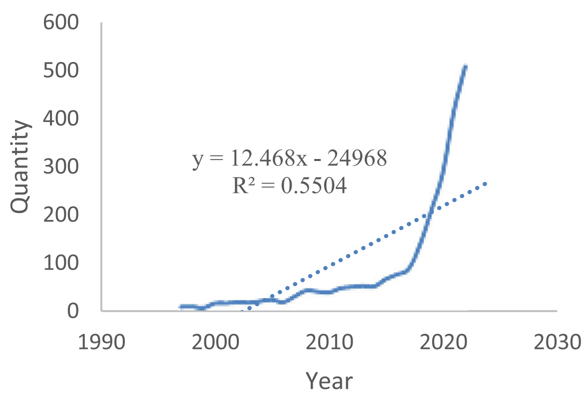



**FIGURE 1.** The annual number of DA papers in 1997–2022.

Based on the changing track of Figure 1, three stages could be divided, the start-up stage (1997–2006), the steady development stage (2007–2017), and the rapid development stage (2018–2022). In the first stage (1997–2006), the start-up stage, research on digital agriculture was just getting started. Besides, during this stage, the number of DA papers is relatively small, averaging around 14. From a macro perspective, the number of DA papers is generally on the rise, which is in line with the trend of agriculture modernization [99], [100], [101]. In the second stage (2007–2017), the steady development stage, research on digital agriculture was gradually maturing with the research results increasing. During this stage, the average annual published literature is 52, which

**TABLE 1.** Top 14 prolific authors on digital agriculture.

| Ranking | Count | Year [a] | Author | Proportion | Strength |
|---|---|---|---|---|---|
| 1 | 11 | 2019 | Klerkx, Laurens | 0.49% | 3.34 |
| 2 | 7 | 2019 | Costa, Corrado | 0.3% | 2.98 |
| 3 | 7 | 2016 | Antonucci, Francesca | 0.3% | 2.28 |
| 4 | 6 | 2019 | Figorilli, Simone | 0.26% | 2.55 |
| 5 | 5 | 2018 | Dematte, Jose A M | 0.22% | \ |
| 6 | 5 | 2020 | Charatsari, Chrysanthi | 0.22% | 2.56 |
| 7 | 5 | 2020 | Bishop, Thomas F A | 0.22% | 2.56 |
| 8 | 4 | 2021 | Mccampbell, Mariette | 0.18% | \ |
| 9 | 4 | 2019 | Duncan, Emily | 0.18% | 1.7 |
| 10 | 4 | 2021 | Brunori, Gianluca | 0.18% | \ |
| 11 | 4 | 2014 | Adhikari, Kabindra | 0.18% | 0.93 |
| 12 | 4 | 2020 | Carolan, Michael | 0.18% | 1.55 |
| 13 | 4 | 2021 | Biswas, Asim | 0.18% | \ |
| 14 | 4 | 2019 | Fleming, Aysha | 0.18% | 1.7 |

means scholars who study digital agriculture have accumulated results persistently. In the third stage (2018–2022), the rapid development stage, research on digital agriculture developed rapidly. The article number of DA increased by 72 in 2019, and many innovative research results were emerging during the third phase, presenting a significant change. The article number of DA amounted to 509 in 2022. Also, between 2018 and 2022, the average published article reached 355 each year.

### *B. AUTHORS*

#### 1) PROLIFIC AUTHORS

Given that Citespace 6.2 can only handle less than 500 nodes. Therefore, we adjusted the k in the g-index from the standard value of 25 to 14, which reduces the number of au-thor nodes from 777 to 484.

Prolific authors are workhorses of research in a field. The number of their publications can highlight to some extent their academic impact and academic status in a particular field. From the perspective of the number of publications, authors with 5 publications include Klerkx, Laurens, Costa, Corrado, Antonucci, Francesca, Figorilli, Simone, Dematte, Jose A M, Charatsari, Chrysanthi and Bishop, Thomas F A. From the perspective of academic cooperation, first of all, Klerkx, Laurens, Brunori, Gianluca, Mccampbell, Mariette and other scholars have formed relatively mature academic cooperation. Second, scholars such as Costa, Corrado have worked hand in glove with Antonucci, Francesca and Figorilli, Simone. From the perspective of Burstness, the most influential scholars of the early period include De deken, R, Hendrickx, G, and Bradford, JM. However, the most influential scholars of the later period include Klerkx, Laurens, Costa, Corrado, Figorilli, Simone, Antonucci, Francesca, Fleming, Aysha, Duncan, Emily, Bishop, Thomas Fa and Charatsari, Chrysanthi. Based on comparative analysis, authors who like to collaborate, such as Klerkx, Laurens, Costa, Corrado, Antonucci, Francesca and Figorilli, Simone, etc. generally have a greater influence than independent researchers, such as Dematte, Jose A M.

Price Law can be used to evaluate research scholars in various fields, especially core scholars [102]. This law was first published in Price's "Little Science, Big Science" [103], and the formula is:

$$M = 0.749\sqrt{N_{\max}}$$

$N_{\max}$ is the total number of publications by scholars who have published the most articles in a certain number of years, and M refers to the minimum number of publications by core scholars. Between 1997 and 2022, 9,520 scholars were studying DA in total. Among them, the scholar with the most publications is Klerkx, Laurens, with a total of 11 publications. After calculation, $M \approx 2.48$, that is, scholars with 2 or more publications can be recognized as core scholars. Therefore, there is a total of 192 core scholars. These 192 scholars published 464 articles in total, accounting for 20.49% of the total publications. This shows that the group of core scholars is gradually forming in the field of DA.

#### 2) HIGH-CITED AUTHORS

Given that Citespace 6.2 can only handle less than 500 nodes. Therefore, we adjusted the k in the g-index from the standard value of 25 to 23, which reduces the number of au-thor nodes from 1185 to 492.

Centrality (C) is one of the indicators to evaluate the importance of nodes. First of all, nodes with high C-value are key nodes connecting two different topics. Secondly, Citespace stipulates that the nodes whose C-value is greater than 0.1 are important nodes, marked with purple circles. Finally, there are mainly two types of nodes that may have high C-value: one is the node that is closely connected with other nodes; the other is the node that is situated in two or more clusters at the same time.

To a certain extent, the analysis of high-cited scholars can reflect the academic correlation between scholars. First of all, from the perspective of the number of citations, the top 5 scholars are [ANONYMOUS], FAO, KLERKX L, WOLFERT S, and KAMILARIS A. It is worth noting that the most cited scholars are anonymous. This shows that there are

**TABLE 2. Top 20 high-cited authors on digital agriculture.**

| Ranking | Count | Centrality | Year | High-cited Authors |
|---|---|---|---|---|
| 1 | 734 | 0.37 | 1998 | [ANONYMOUS] |
| 2 | 209 | 0.21 | 2000 | FAO |
| 3 | 158 | 0.08 | 2019 | KLERKX L |
| 4 | 155 | 0.09 | 2018 | WOLFERT S |
| 5 | 114 | 0.01 | 2019 | KAMILARIS A |
| 6 | 114 | 0.10 | 2009 | MCBRATNEY AB |
| 7 | 111 | 0.01 | 2019 | ROSE DC |
| 8 | 101 | 0.01 | 2019 | CAROLAN M |
| 9 | 99 | 0.02 | 2019 | BRONSON K |
| 10 | 89 | 0 | 2019 | ROTZ S |
| 11 | 79 | 0.01 | 2019 | EASTWOOD C |
| 12 | 79 | 0.03 | 2014 | MINASNY B |
| 13 | 77 | 0.16 | 2013 | HENGL T |
| 14 | 74 | 0 | 2016 | BREIMAN L |
| 15 | 71 | 0.07 | 2015 | BENDIG J |
| 16 | 68 | 0.09 | 2010 | GITELSON AA |
| 17 | 59 | 0.01 | 2019 | JAKKU E |
| 18 | 57 | 0.04 | 2015 | ZHANG CH |
| 19 | 57 | 0.03 | 2015 | ROSSEL RAV |
| 20 | 50 | 0.09 | 2016 | EUROPEAN COMMISSION |

many promising scholars in the field of DA. Similarly, FAO is not a scholar and its full name is "The Food and Agriculture Organization." Secondly, from the perspective of Centrality, the C-value of FAO, MCBRATNEY AB and HENGL T reach 0.1. This shows that there is a wide range of research topics in DA, and there is no frequent academic communication between scholars. Finally, from the perspective of representative articles of high-cited scholars, scholar KLERKX L published a total of five high-cited articles. Among them, the most cited literature is "A review of social science on digital agriculture, smart farming and Agriculture 4.0: New contributions and a future research agenda (328 times)" [104]. Also, scholar KAMILARIS A published a total of two high-cited papers. Both papers were high-cited, that is, "A review on the practice of big data analysis in agriculture (334 times)" [105] and "The rise of blockchain technology in agriculture and food supply chains (326 times)" [106]. In addition, scholar WOLFERT S has also published one high-cited article titled "Digital Twins in smart farming (83 times)" [107].

### C. INSTITUTIONS

Given that Citespace 6.2 can only handle less than 500 nodes. Therefore, we adjusted the k in the g-index from the standard value of 25 to 23, which reduces the number of institution nodes from 527 to 492.

We collect and analyze high-impact institutions, their number of publications, centrality and corresponding countries, as shown in Table 3. First of all, in terms of centrality, among the top 16 institutions, there are four research institutions whose C-value has reached 0.1, namely USDA, RLUK-Research Libraries UK, Chinese Academy of Sciences and CGIAR. This indicates that research institutions with high publication output do not necessarily form mature academic cooperation relationships. Similarly, the scientific research strength of each institution is closely related to its scientific research capability. Secondly, in terms of the number of publications, the top 3 institutions include USDA, RLUK- Research Libraries UK and Wageningen University & Research. Third, in terms of Burstness, high-impact institutions of the early period include USDA, USDI, USGS, and CSIC - Instituto de Agricultura Sostenible (IAS), etc. However, high-impact institutions of the medium period include CAS and ZJU. In recent years, high-impact institutions include Wageningen University & Research, the University of Bonn and the Swiss Federal Institutes of Technology Domain. Finally, in terms of countries, among the 16 high-impact institutions, 7 institutions belong to the United States, accounting for 43.75%. This shows that the United States has a great influence in the field of DA.

### D. JOURNALS

#### 1) PROLIFIC JOURNALS

The 2264 articles are scattered in 757 journals. In 1948, Bradford came up with the "Law of Bradford," which means if journals are sorted in descending order based on the number of articles published by each journal, they can be roughly divided into core zone, related zone, and non-related zone. At the same time, the number of articles in each zone is equal. After calculation, there are in total of 22 journals in the core zone of DA, which are shown in Table 4.

#### 2) HIGH-CITED JOURNALS

Given that Citespace 6.2 can only handle less than 500 nodes. Therefore, we adjusted the k in the g-index from the standard value of 25 to 9, which reduces the number of journal nodes from 1093 to 478.

High-cited journals can reflect the academic correlation between journals to a certain extent. Table 5 clearly shows the high-cited journals in the field of DA, which helps to clarify the foundational journals in this field. Firstly, from

**TABLE 3.** Top 16 institutions on digital agriculture.

| Ranking | Count | Centrality | Institutions | Country |
|---|---|---|---|---|
| 1 | 83 | 0.15 | United States Department of Agriculture (USDA) | USA |
| 2 | 81 | 0.17 | RLUK- Research Libraries UK | UK |
| 3 | 66 | 0.06 | Wageningen University & Research | Netherlands |
| 4 | 58 | 0.13 | Chinese Academy of Sciences | China |
| 5 | 50 | 0.03 | Commonwealth Scientific & Industrial Research Organisation | Australia |
| 6 | 45 | 0.07 | INRAE | France |
| 7 | 39 | 0.11 | CGIAR | USA |
| 8 | 28 | 0.06 | Consejo Superior de Investigaciones Cientificas (CSIC) | Spain |
| 9 | 28 | 0.03 | State University System of Florida | USA |
| 10 | 27 | 0.02 | Universidade de Sao Paulo | Brazil |
| 11 | 27 | 0.03 | Egyptian Knowledge Bank (EKB) | Egypt |
| 12 | 26 | 0.01 | University of Guelph | Canada |
| 13 | 26 | 0 | Purdue University | USA |
| 14 | 26 | 0 | Purdue University West Lafayette Campus | USA |
| 15 | 26 | 0 | Purdue University System | USA |
| 16 | 26 | 0.05 | Texas A&M University System | USA |

**TABLE 4.** Top 22 prolific journals in the core zone.

| Ranking | Journal Name | Count | Impact Factor |
|---|---|---|---|
| 1 | COMPUTERS AND ELECTRONICS IN AGRICULTURE | 97 | 6.757 |
| 2 | REMOTE SENSING | 97 | 5.349 |
| 3 | SUSTAINABILITY | 74 | 3.889 |
| 4 | SENSORS | 49 | 3.847 |
| 5 | AGRONOMY BASEL | 44 | 3.949 |
| 6 | AGRICULTURE BASEL | 40 | 3.408 |
| 7 | GEODERMA | 40 | 7.422 |
| 8 | PRECISION AGRICULTURE | 37 | 5.767 |
| 9 | AGRICULTURAL SYSTEMS | 26 | 6.765 |
| 10 | APPLIED SCIENCES BASEL | 26 | 2.838 |
| 11 | SCIENCE OF THE TOTAL ENVIRONMENT | 24 | 10.753 |
| 12 | FRONTIERS IN PLANT SCIENCE | 23 | 6.627 |
| 13 | INTERNATIONAL JOURNAL OF REMOTE SENSING | 23 | 3.531 |
| 14 | IEEE ACCESS | 21 | 3.476 |
| 15 | JOURNAL OF RURAL STUDIES | 19 | 3.544 |
| 16 | WATER | 18 | 3.354 |
| 17 | BIOSYSTEMS ENGINEERING | 17 | 5.002 |
| 18 | LAND | 17 | 3.395 |
| 19 | REMOTE SENSING OF ENVIRONMENT | 17 | 13.850 |
| 20 | FRONTIERS IN SUSTAINABLE FOOD SYSTEMS | 16 | 5.005 |
| 21 | NJAS WAGENINGEN JOURNAL OF LIFE SCIENCES | 15 | 8.690 |
| 22 | REVISTA CIENCIA AGRONOMICA | 15 | 0.760 |

the perspective of the number of citations, the top 5 journals are COMPUT ELECTRON AGR, REMOTE SENS ENVIRON, REMOTE SENS-BASEL(REMOTE SENSING), SENSORS-BASEL and PRECIS AGRIC. Secondly, from the perspective of centrality, there are only four high-cited journals with centrality greater than 0.1, namely COMPUT ELECTRON AGR, REMOTE SENS ENVIRON, INT J REMOTE SENS and AGR SYST. Thirdly, from the perspective of representative articles from high-cited journals, a total of five high-cited articles were published in COMPUT ELECTRON AGR. Among them, "A review on the practice of big data analysis in agriculture (334 times)" [105] was cited the most. Also, REMOTE SENS ENVIRON published a total of three high-cited papers. Among them, "Accuracy assessment of NLCD 2006 land cover and impervious surface (279 times)" [108] was cited the most. Besides, the journal REMOTE SENS-BASEL has also published three high-cited papers. Among them, the most cited literature is "Processing and Assessment of Spectrometric, Stereoscopic Imagery Collected Using a Lightweight UAV Spectral Camera for Precision Agriculture (316 times)" [24]. Finally, from the perspective of Impact Factor (IF), the average IF of the top 20 high-cited journals in DA is 12.56. This shows that DA has gradually been paid attention to and recognized by international authoritative journals.

### E. KEYWORDS

#### 1) KEYWORD CO-OCCURRENCE ANALYSIS

Given that Citespace 6.2 can only handle less than 500 nodes. Therefore, we adjusted the k in the g-index from the standard

**TABLE 5. Top 20 high-cited journals on digital agriculture.**

| Ranking | Count | Centrality | Cited Journals | Impact Factor |
|---|---|---|---|---|
| 1 | 806 | 0.12 | COMPUT ELECTRON AGR | 6.757 |
| 2 | 539 | 0.16 | REMOTE SENS ENVIRON | 13.850 |
| 3 | 490 | 0.03 | REMOTE SENS-BASEL | 5.349 |
| 4 | 457 | 0.09 | SENSORS-BASEL | 3.847 |
| 5 | 454 | 0.08 | PRECIS AGRIC | 5.767 |
| 6 | 447 | 0.04 | PLOS ONE | 3.752 |
| 7 | 411 | 0.11 | INT J REMOTE SENS | 3.531 |
| 8 | 388 | 0.08 | SCIENCE | 63.714 |
| 9 | 379 | 0.19 | AGR SYST | 6.765 |
| 10 | 364 | 0.09 | SUSTAINABILITY-BASEL | 3.889 |
| 11 | 360 | 0.05 | BIOSYST ENG | 5.002 |
| 12 | 328 | 0.09 | GEODERMA | 7.422 |
| 13 | 307 | 0.07 | NATURE | 69.504 |
| 14 | 288 | 0.02 | AGRON J | 2.650 |
| 15 | 287 | 0.02 | ISPRS J PHOTOGRAMM | 11.774 |
| 16 | 286 | 0.05 | SCI TOTAL ENVIRON | 10.753 |
| 17 | 281 | 0.04 | SOIL SCI SOC AM J | 2.932 |
| 18 | 274 | 0.04 | P NATL ACAD SCI USA | 12.779 |
| 19 | 266 | 0.04 | INT J APPL EARTH OBS | 7.672 |
| 20 | 225 | 0.05 | AGR ECOSYST ENVIRON | 3.540 |

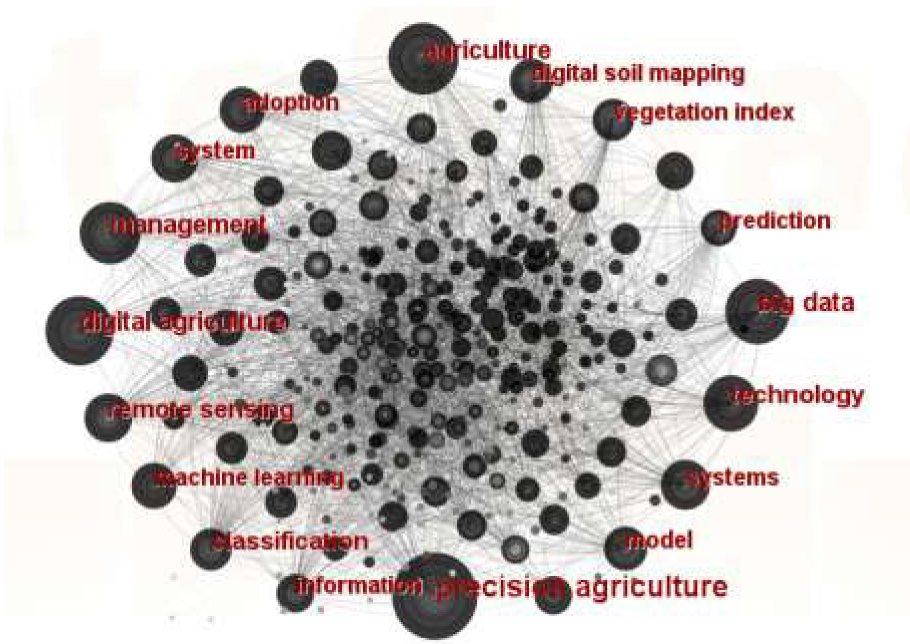



**FIGURE 2. Co-occurrence map of keywords in DA literature.**

value of 25 to 14, which reduces the number of author nodes from 765 to 475. The threshold of keyword co-occurrence is set as 70, and 17 keywords are displayed in total, which is shown in Figure 2.

This map is mainly based on the frequency of keyword citations (Figure 2). The map clearly shows the research focus of DA and helps to review the representative topics in the field. There are 475 nodes and 2733 lines on the map. Each node represents a keyword. The higher the keyword citation frequency, the bigger the node volume. The line between keywords indicates that the two keywords have been cited in the same literature. For example, among the 2264 literatures, the keyword ''precision agriculture'' was cited 51 times with 114 different keywords. Similarly, the keyword ''agriculture'' was cited 3 times along with 12 different keywords.

From the perspective of citation frequency, the top 5 keywords include precision agriculture (345 times), agriculture (198 times), digital agriculture (177 times), management (173 times) and big data (139 times). From the perspective of centrality, there are only two keywords whose C-value exceeds 0.1, namely precision agriculture (0.19) and remote sensing (0.15). This shows that the research topics of DA are

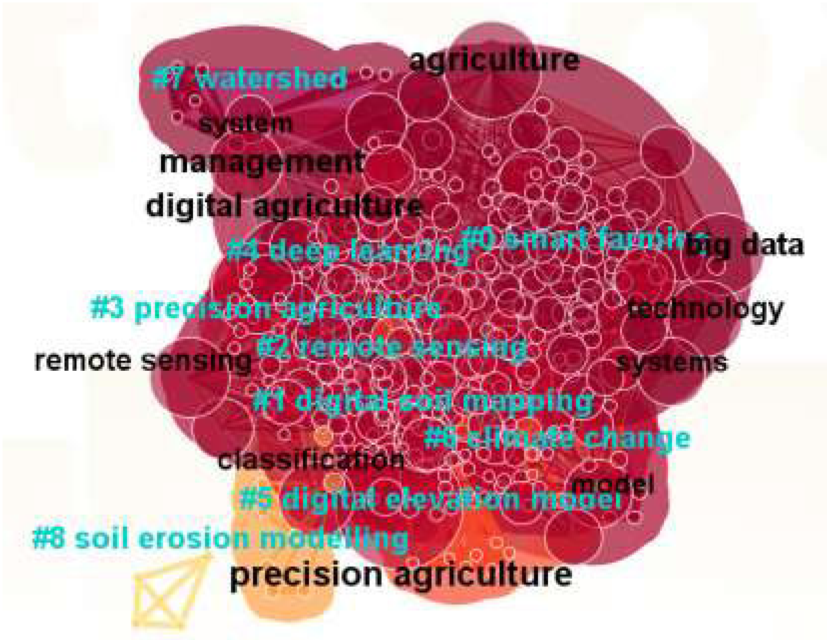



**FIGURE 3.** Clustering map of keywords in DA literature.

various. From the perspective of articles, if precision agriculture is set as the keyword, the most frequently cited article is "A review on the practice of big data analysis in agriculture (334 times)" [105]. Similarly, if management is set as the keyword, the most frequently cited article is "A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda (328 times)" [104].

#### 2) KEYWORD CLUSTERING ANALYSIS

The threshold of keyword co-occurrence is set as 90, and a total of 11 keywords are displayed. The number of clustering labels is set to 9, as shown in Figure 3.

Based on all keywords from 2264 literatures in DA, a total of 9 different clustering labels are obtained. Each cluster label represents a research topic of DA, as shown in Figure 3. Modularity (M) can be used to judge the advantages and disadvantages of the classification result of a field. When M exceeds 0.3, the clustering effect is significant. After calculation, $M \approx 0.7107$. This indicates that the clustering effect of keywords in the field of DA is significant.

The results of keyword clustering, Silhouette and the top terms of each cluster are collected in Table 6. All literatures in a cluster jointly build the knowledge structure of this cluster. Silhouette (S) was first proposed by Chen Yue to judge the reliability of each cluster. When S is less than 0.3, it indicates that the result of clustering is incredible. When S is greater than 0.5, the effect of clustering is reasonable. Therefore, the effect of all the above clusters is reasonable. In general, S-value is positively correlated with the clustering effect.

#### 3) KEYWORD BURSTNESS ANALYSIS

In order to highlight the most cited keywords, the minimum duration was extended from 2 years to 7 years in this study, and the top 20 keywords were selected and ranked in Table 7.

Each keyword represents a research topic in the field of DA. Embedding a keyword into a timeline can clearly present the "active zone" of the keyword in the timeline. All literatures on each research topic together form the knowledge framework for that topic. Paralleling the timeline of each keyword in the chronological order of its first appearance can also highlight the evolution history of research topics in DA, as shown in Table 7.

### *F. PRIMARY RESEARCH STREAMS*

Based on Figure 3 and Table 7, the primary research streams of DA can be roughly divided into 6 categories: Remote Sensing (RS), Climate-Smart Agriculture (CSA), Artificial Intelligence (AI), Internet of Things (IoT), Big Data (BD) and System Integration (SI).

#### 1) REMOTE SENSING

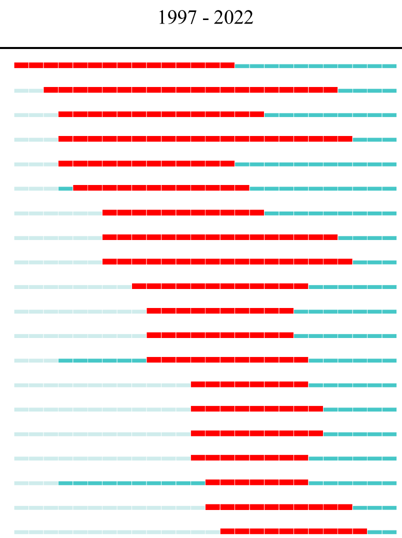
Remote sensing is a highly comprehensive technology, which can be used in the agricultural field for the investigation of agricultural resources, analysis of land use status, monitoring of agricultural diseases and pests, crop yield estimation and crop monitoring. RS can obtain agricultural information quickly and accurately because it might be more objective and is free from human interference. Similarly, it is beneficial to the decision-making of DA and makes precision agriculture possible.

**TABLE 6. Top terms, size and silhouette of each cluster.**

| Clusters | Size | Silhouette | Top Terms |
|---|---|---|---|
| #0 Smart farming | 101 | 0.709 | digital agriculture; socio-digital platform; fmis; digital methods; sustainable farming practice |
| #1 Digital soil mapping | 99 | 0.645 | digital soil mapping; rodent management; digital soil assessment; land suitability assessment; sensitivity analysis |
| #2 Remote sensing | 68 | 0.662 | precision agriculture; unmanned aerial vehicles; precision viticulture; canopy height model; digital terrain model |
| #3 Precision agriculture | 51 | 0.597 | unmanned aerial vehicles; precision agriculture; image processing; weed detection; precision viticulture |
| #4 Deep learning | 43 | 0.78 | deep learning; digital agriculture; machine learning; weed detection; weed classification |
| #5 Digital elevation model | 16 | 0.966 | digital elevation model; dryland agriculture; hydrologic prediction; spatial uncertainty; sequential gaussian simulation |
| #6 Climate change | 12 | 0.9 | climate change; air quality; volatile organic compounds; open hardware; smart cities |
| #7 Watershed | 11 | 0.997 | precision agriculture; food industry; smart food factory; vegetarian diets; value creation |
| #8 Soil erosion modeling | 8 | 0.982 | soil erosion; digital elevation model; laser measurement; mine rehabilitation; rill erosion |

**TABLE 7. Top 20 keywords with the strongest citation bursts.**

| Keywords | Year | Strength | Begin | End |
|---|---|---|---|---|
| corn | 1997 | 4.22 | 1997 | 2011 |
| digital elevation model | 1999 | 7.08 | 1999 | 2018 |
| remote sensing | 2000 | 15.67 | 2000 | 2013 |
| vegetation | 2000 | 8.98 | 2000 | 2019 |
| patterns | 2000 | 4.24 | 2000 | 2011 |
| precision agriculture | 2000 | 5.45 | 2001 | 2012 |
| image processing | 2003 | 5.03 | 2003 | 2013 |
| conservation | 2003 | 4.46 | 2003 | 2018 |
| machine vision | 2003 | 4.29 | 2003 | 2019 |
| erosion | 2005 | 6.43 | 2005 | 2016 |
| accuracy | 2006 | 9.71 | 2006 | 2015 |
| gis | 2006 | 7.37 | 2006 | 2015 |
| classification | 2000 | 5.38 | 2006 | 2016 |
| scale | 2009 | 7.14 | 2009 | 2016 |
| color | 2009 | 6.25 | 2009 | 2017 |
| resolution | 2009 | 5.32 | 2009 | 2017 |
| forest | 2009 | 3.44 | 2009 | 2016 |
| prediction | 2000 | 8.02 | 2010 | 2016 |
| landscape | 2010 | 5.67 | 2010 | 2019 |
| reflectance | 2011 | 4.66 | 2011 | 2020 |




In [53], the authors took developing countries in Asia as research objects, focusing on the application of GIS and RS in flood prevention and control. Unlike previous optical technologies, RS can provide data all day long, thus creating a more accurate flood map. It is found that the depth of the flood makes a difference in the drawing process of flood maps, and DEM is considered to be the most useful method to forecast the depth based on RS data. In [109], the authors first looked at the current situation of RS from a critical perspective, including digital models, UAV data and orthophotos. Then, they took UAV data as an example and believed that it could be continuously improved in the following three aspects, and proposed corresponding solutions. First, the ability to merge data from multiple sensors simultaneously. The availability of coherent spectral and geometry data; Third, ultra-high resolution. Finally, the authors share their opinions on future research directions and draw some conclusions based on the previous discussion.

### 2) CLIMATE-SMART AGRICULTURE

In 2010, the FAO formally introduced CSA. It is a comprehensive method using smart technologies to solve the triple challenges of climate change, greenhouse gas emissions and food security. It is the integration, innovation and transcendence of ecological agriculture, sustainable agriculture and green agriculture. The goal of CSA is to achieve national food security by continuously increasing productivity and strengthening resilience while minimizing greenhouse gas emissions.

In [110], RHoMIS is a household survey device designed to quickly describe many standardized indicators. With the help of RHoMIS, the authors took two very different agroecological systems, the Lushoto district and the Trifinio border region. The research results are as follows. In terms of small farms, the strategy of making production intensive is more conducive to achieving the objectives of CSA. In terms of larger farms, however, increased market orientation was more useful and accessible. At the same time, in terms of different farms, the smartness of climate is largely determined by each farm's characteristics and farm strategies. In [27], taking Cyprus as an example, the authors systematically reviewed CSA literatures from three aspects: RS, IoT and robotics, so as to explain the decisive role of CSA in dealing with the contradiction between climate change and food security. In addition, after analyzing all aspects of Cyprus's CSA, the authors explained its shortcomings and predicted new trends in future research.

### 3) INTERNET OF THINGS

The concept of the IoT was first put forward in 1999. It means connecting everything to the Internet through various sensing devices [111]. Then, practitioners collect and analyze the data, and finally realize the intelligent monitoring and precise management of all objects. Sensing equipment mainly includes RFID, electromagnetic induction sensors, GNSS sensors and infrared sensors, etc. Its application in agriculture is embodied in animal husbandry, food production, environmental monitoring and resource monitoring, etc.

In [40] and [112], the authors first reviewed various Deep Learning (DL) techniques and their respective uses, for example, autoencoders, RNN and CNN, etc. Secondly, the authors list various applications of DL in IoT, such as smart agriculture, smart metering, and smart manufacturing. Finally, this paper also puts forward the challenges encountered in the application of DL-IIoT at the present stage, and predicts the future research direction. In [113], the authors combine IoT and robotic agents, creating a new concept of the IoRT. This is causing a lot of concern in many fields, such as agriculture, manufacturing and health. Then, this study gives a necessary description of the current situation of IoRT in order to emphasize its influence in various fields. Finally, the authors focus on the various challenges and dilemmas encountered in the integration of IoT and robotic agents, leading to further research on remote and automated applications.

### 4) ARTIFICIAL INTELLIGENCE

AI can be informally defined as a system that can observe its surroundings and respond correctly [114]. The application in agriculture is mainly reflected in three aspects, namely large-scale agricultural production, improving the accuracy of weather forecasts and recognizing intelligent images. For example, large-scale agricultural production focuses on staple crops such as rice, wheat, corn and cotton, etc. It specifically refers to the precise regulation in every procedure, such as arable land, seeding, water and fertilizer irrigation and harvest. In addition, studies show that 90% of crop losses are due to bad weather. Therefore, using AI to collect the latest information on weather, such as rainfall, temperature, humidity, SR and WD, can help agricultural workers make more accurate decisions.

In [22] and [39], the authors first conducted a comprehensive literature review on AI, BD and IoT. They then highlighted the important role of these technologies in ensuring food security. Finally, the paper still focuses on the application status of AI and translation research. In [115], the authors first discussed the value of AI in the agricultural field. They found that more accurate and timely agricultural data could help people make more sensible agricultural decisions, thereby increasing food production. However, the emergence of AI has not only brought positive influence, but also certain negative effects. For example, the social and moral issues of AI, the transformation of the identity of traditional farmers, and the subversion of traditional technologies they have mastered. Therefore, at the end of this literature, the authors argued that in-depth research and understanding of AI as a "double-edged sword" can better help us adapt to new trends.

### 5) BIG DATA

Big data (BD) refers to data sets that exceed the capabilities of traditional databases in terms of acquisition, storage and analysis. It has the characteristics of diverse data types, fast data flow, massive data scale and low-value density. BD in the field of agriculture refers to using the ideas, technologies and methods of BD to guide agricultural production and management, including the following four aspects. The first is the monitoring of agricultural conditions. For example, natural disaster monitoring, crop yield estimation and the monitoring of crop growth. The second is the monitoring and early warning of agricultural products. BD provides the technical basis for the comprehensive collection of agricultural product information, enabling the quality of agricultural products to be compared and evaluated in an all-around way and then increasing the accuracy of agricultural product quality monitoring. The third is agricultural decision-making. BD technology can integrate agricultural information from all aspects and provide agricultural practitioners with more efficient agricultural decisions. The fourth is the construction of RCISS. The application research of BD plays an important role in the construction of RCISS.

In [116], the authors first put forward some problems existing in the traditional supply chain of agricultural products. For example, the inadequacy of the management, the lack of industrialization, and information inaccuracy. Given that, the paper introduces a data-driven supply chain and reviews its related literature from 2000 to 2017 and the authors put forward an implementable framework for the workers involved in the supply chain. Finally, this paper also explains the limitations of their research and predicts future research trends. In [117], the authors reviewed relevant literature on

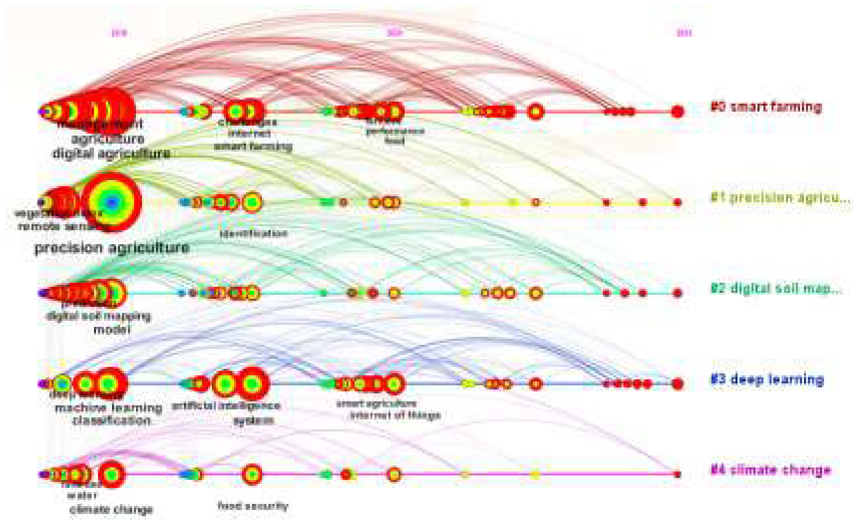



**FIGURE 4.** Time map of keywords in DA literature.

BD and the promise and dilemma of BD in the process of DA reform. Among them, the promise includes producing more food from less arable land, with fewer input costs and less environmental pollution. The dilemma, however, involves two points. One is the inability to analyze the collected data effectively and therefore make more efficient decisions with the help of BD. The second is that many farmers do not know how to use the new tool of BD.

#### 6) SYSTEM INTEGRATION

The essence of system integration is the optimal comprehensive design. Before integration, each part is an independent system. After integration, each part can coordinate with each other to achieve the purpose of optimal performance. In the field of agriculture, it refers to the integration of a variety of agricultural technology and equipment, which is used to improve agricultural efficiency. It includes sensors, AI, IoT, CC and other technologies. Practitioners can realize intelligent control and optimization of the whole process of agricultural production through comprehensive monitoring and precise management of farmland.

In [113], the authors combined the concepts of IoT and robotic agents to form a new concept, the Internet of Robotic Things (IoRT). This brings more possibilities in areas such as health, agriculture and manufacturing. This paper focuses on describing the status of IoRT and its emerging influence and challenges in different fields. Also, this paper highlights the impact of IoRT technology in our daily lives, thus triggering further research on remote and automated applications. In [118], the authors first took India's fresh fruit and vegetable supply chain as an example and pointed out the existing problems in this supply chain, such as unstable supply and demand conditions, asymmetric information and an uncertain market. Secondly, the authors also analyzed a large number of relevant literatures to put forward a scalable, sustainable and inclusive primary supply chain model. This model can efficiently connect farmers and consumers directly, thus minimizing post-harvest losses. Finally, the authors also emphasize that the digital integration model can improve the inclusion of smallholder farmers and the market efficiency of the fresh fruit and vegetable supply chain.

## IV. RESEARCH FRONTIERS

In order to analyze the frontiers of DA research, the time map of keywords in the last five years (2018-2022) was designed, which is shown in Figure 4.

The essence of a time map is to add a time dimension on the basis of a clustering map. Moreover, the time map can show the evolution of keywords in each cluster. Therefore, the time map is helpful to explore the evolutionary path and frontiers of research topics. Based on Figure 4, the frontier research of DA can be roughly divided into three parts: "exploration of digital agriculture technologies," "operation management of digital agriculture" and "limitations of digital agriculture."

Exploration of Digital Agriculture Technologies. The keywords of this stage mainly include quantification, GIS, Vegetation Index (VI), Photogrammetry, Crop Surface Models (CSM) and Artificial Intelligence, etc. At this stage, researchers paid close attention to quantitative analysis or quantification, such as predicting the cutting-edge trends of DA with the help of various digital technologies [119], [120], [121]. Among them, the GIS showed to be the most common technology widely used for SSM [122]. Other technologies of SSM also include the GNSS and YM. The VI can quantify vegetation biomass and plant vigor for each pixel in an RS image. The use of VI pays new attention to the SSM. Before discussing Photogrammetry and CSM, it is important to understand that the sensing technologies in information monitoring can be roughly divided into two types: imaging spectroscopy and spatial configuration measurement [123], [124], [125]. Depending on the measurement method and technology differences, spatial configuration measurement technology can be further divided into Light Detection and Ranging (LiDaR) based on laser direct measurement and Structure from Motion (SfM) based on visible Photogrammetry. In addition, future trends regarding AI in agriculture are expected to be used in conjunction with other methods [126], [127]. At the same time, the integration of multiple data sources is predictable, either from stationary platforms (weather stations) or from mobile platforms (tractors, satellites, UAVs).

Operation Management of Digital Agriculture. The research topics at this stage mainly include challenges, strategies and demonstration projects. At different stages of the development of DA, different challenges will be encountered [128]. First of all, in the basic development stage, it is necessary to focus on the construction of IoT infrastructure and digital standards systems. Secondly, in the practical application stage, it is necessary to focus on the cultivation of digital agricultural business entities and the design of data-driven models and algorithms. Finally, in the mature development stage, it is necessary to focus on the enhancement of DA governance ability and the innovation of its business model from a macro perspective [111]. In order to solve the difficulties in the operation management of DA, scholars put forward the corresponding strategies based on the reference of other relevant disciplines and combined with the practical experience of DA. The first is the industry integration of digital agriculture [129]. It is based on the theoretical basis that after the development of the market economy to a certain extent, the internal differences in various industries are gradually reduced. In addition, the main driving force of industrial integration comes from technology and the market. Among them, technology mainly refers to technological innovation, while market mainly refers to slack market regulation. The second is the process optimization of digital agriculture. It refers to the use of advanced ideas and technologies, such as mathematical models or computer technologies, to completely redesign existing business processes to find the best coping strategies. The third is the scientific management of digital agriculture. It can be further divided into two parts: quality management and knowledge management. Quality management refers to the introduction of an "evidence chain," "information chain" and "trust chain" in traditional agricultural management to provide effective tracking methods for agricultural product quality. Similarly, knowledge management refers to the establishment of an agricultural knowledge management system with the help of IoT to provide effective technical support for the preservation and innovation of agricultural knowledge. Fourth, fostering an enabling and creative environment for cooperation is necessary. Due to the personalized and dynamic characteristics of DA operation management, the business model of "fight alone" can no longer adapt well to market changes, and the business model of "win-win cooperation" is attracting wide attention from the industry. In addition, the third research topic of DA operation management is demonstration projects. In [130], the authors take "Jing-dong Farm," which was founded in 2018, as a demonstration project and propose a DA service plan. Specifically, it includes the formulation of DA development plans with local characteristics, the construction of big data platforms, the construction of high-quality agricultural products demonstration bases, the construction of local high-quality agricultural products management standards, the construction of intelligent logistics systems and the construction of new agricultural personnel training system.

Limitations of Digital Agriculture. The subject terms in this stage mainly include technology upgrading, standards, impacts, inequalities, farmers, policies and effects, etc. First, the ability of technological innovation and the consciousness of adapting to local conditions are relatively weak. For example, with the rapid development of virtualization and AI technology, people are gradually starting to upgrade traditional digital twins (DT) and localize them to adapt to the local environment in China [131]. This is important for advancing low-cost, high-precision smart agriculture to meet the growing demand for high-yield products from farmers around the world. Second, there are no scientific evaluation criteria for DA technologies. Although it is not easy to comprehensively evaluate the impact of digital technology, it is necessary to study different evaluation index systems. For example, in [132], the authors used a GIS-based modeling approach along with criteria to identify potential areas where supplemental irrigation (SI) technology could be expanded at scale. The evaluation standard includes a data layer consisting of climate sur-faces, land-use classification maps and digital elevation models. On this ground, they also developed a spatial algorithm for water allocation. Third, the research on DA policy formulation needs to be further improved. For example, in [133], using Canada as an example, the authors outline barriers to the implementation of DA technologies.

Based on the limitations of DA mentioned above, the advantages of digitalization can be realized sustainably and efficiently only when policymakers, researchers, and farmers all play their roles [134]. First, in terms of researchers, DA technology needs to be further upgraded and localized. Digitization is already an irresistible trend. However, it is still unclear which digital technologies are appropriate for which region or industry. Therefore, [135] focuses on 2225 companies in Brazil to explore the application status of digital technologies in different industries and what digital technologies should be used to improve the performance of agribusiness. In addition, while developed countries are leading the way in the innovation and application of DA technologies, the potential impact of DA on developing countries is also significant. Combining local conditions in the MENA region, [136] reviews the potential and current contributions of digital technologies to the agri-food sector. Second, in terms of farmers or practitioners, a comprehensive, effective and sustainable evaluation standard of DA technology should be established and the standard should be mastered by the majority of farmers. While a large body of literature shows that the introduction of digital technologies into agriculture can help address the food crisis, the actual impact of these digital technologies needs to be evaluated and monitored if DA is to be made more efficient and equitable than before [137]. For example, increased agricultural productivity is an important driving force for poverty reduction and rural economic development. However, many smallholder farmers often have limited access to agricultural information, and one potential mechanism for reducing information constraints is digital extension services (DES). Using raw data from India, researchers have analyzed the relationship between digital extension services and agricultural performance. First, farmers' willingness to pay for DES was estimated, and then propensity score matching (PSM) was used to solve the problem of selection bias. The results show that the use of personalized DES is significantly positively correlated with agricultural performance (farming costs, crop diversity, crop income, crop productivity, etc.) [138]. Third, in terms of policymakers, policies on DA should be further studied in depth. Policies should not only encourage the adoption of digital technologies, but also ensure data protection, equity of access, labor protections, and transparency of use. Policymakers should not only focus on production but also contribute to environmental, economic, and social sustainability. In addition, numerous studies show that many industries often use a single digital technology. Therefore, policies can also be developed to encourage the spread and integration of digital technologies in various industries [135]. Finally, the limitations of DA can be effectively addressed, it can mitigate the issue of climate change and food insecurity to a great extent [139], [140], [141], [142], [143], [144].

## V. CONCLUSION

With the frequent occurrence of extreme weather events and the increase in food demand, DA has gained widespread attention around the world. For the past 26 years, a multitude of research findings have been produced. Especially, the number of literatures on DA has increased rapidly since 2018, as shown in Figure 1. Indeed, a total of 1555 core literatures have been published from 2018 to 2022, which means the number of literatures published from 1997 to 2017 is less than half the number published in the past five years. Similarly, the annual average number of papers has demonstrated a substantial ascent, surging from 7 before the 20th century to 403 in the last three years. This indicates that DA is an emerging field and still needs further research and development. On this ground, the research stages of DA can be split into three stages, namely, the start-up stage (1997-2006), the steady development stage (2007-2017), and the rapid development stage (2018-2022).

This study comprehensively analyzed the research status of DA from four aspects: authors, institutions, journals and keywords. Therefore, the research results of DA can also be elaborated from four aspects respectively. From the perspective of the authors, the frequency of academic exchange among scholars is not quite high, but the group of core scholars is gradually forming. From the perspective of institutions, institutions with numerous publications may not necessarily form mature academic cooperative relationships. Consequently, the research strength of each institution is closely related to its own scientific research ability. From the perspective of journals, the average IF of the top 20 high-cited journals in DA is 12.56, which means that DA has been gradually recognized and paid attention to by mainstream journals. From the perspective of keywords, this study successfully reviewed the high-impact keywords of DA by analyzing the keyword Co-occurrence map. In addition, based on Keyword Clustering and Burstness maps, the research topics of DA could be roughly divided into six categories: remote sensing, climate-smart agriculture, artificial intelligence, Internet of things, big data and system integration, filling the literature gap in this field. Each research topic develops as time goes by and has different characteristics at different stages. In order to explain each research topic more clearly, this paper not only presents necessary definitions and explanations but also enumerates corresponding representative literatures so that their interrelations can be better presented.

The alterations of keywords reveal the development of research frontiers. The change of keywords, from "remote sensing" and "geographic information system" before 2016 to "management" and "Internet of things" after 2018, has revealed the focus of DA was changing from the exploration of digital technology to the operation management of DA. The change of keywords, from "demonstration projects," "integration" and "system" to "impacts" "technology upgrading" and "policies," has revealed the focus of DA was changing from the exploration of DA management to the upgrading and limitations of digital technologies. The change of keywords, from "inequalities" and "challenges" to "strategies" and "policy-makers," has revealed the focus of DA was changing from the challenges or dilemmas encountered to the corresponding solutions. Similarly, by designing the time map of keywords over the last five years, we also found that the research frontiers of DA can be further divided into three parts. The first part focuses on the exploration of DA technologies, such as RS, AI, GNSS, IoT and YM. The second part focuses on the operation management of DA, which includes three research topics of challenges, strategies and demonstration projects. The third part focuses on the limitations of DA, for example, the lack of capacity for technological innovation, the lack of scientific evaluation criteria for technologies and the lack of appropriate policies, etc. In order to better play the role of DA in combating climate change and food security, this study proposes corresponding strategies from three aspects of researchers, practitioners and policymakers.

In reality, there are still literature gaps in digital agriculture because only a few documents provided partial literature review in this field. This review presents the current research status of digital agriculture, what research topics does digital agriculture include and where it is heading. This is where this paper contributes to the DA. More attention should be paid to developing more advanced digital technologies, improving the ability of DA operation management and proposing appropriate policies to prove that digital agriculture does have the ability to meet the basic requirements of agricultural sustainable development. Finally, in the future, the limitations of digital agriculture need to be further analyzed and investigated in order to minimize their potential impacts.

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**RONGJI ZHOU** received the Ph.D. degree in agricultural economics and management from Hunan Agriculture University, in 2011. He is currently the first "Xiangjiang Scholar," which means a Distinguished Professor, with Hengyang Normal University. He is also the Director of the Hunan Provincial Key Research Base for Rural Industry Revitalization Research. He has coauthored more than 30 articles published in various journals. In addition, he has also authored three books in the field of agriculture, which have received significant acclaim. These books have been recognized and awarded at the provincial level or even higher. His research interests include digital agriculture, ecological agriculture, and multifunctional agriculture.

**YUYAN YIN** is currently pursuing the master's degree in applied linguistics with Jinan University. In particular, she was a member of innovation and sustainability of digital agriculture with the Hunan Provincial Key Research Base of Philosophy and Social Sciences in Colleges and Universities or Rural Industry Revitalization Research Center. On these topics, she is the coauthor of several academic publications and popular articles. Her research interests include agricultural economics and applied linguistics.