Main drivers and barriers to the adoption of Digital Agriculture technologies

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ABSTRACT

The transition from traditional agriculture to Digital Agriculture involves various elements that make it challenging. Given the different contexts and particularities, this paper aims to identify and analyze the primary factors and barriers to adopting Digital Agriculture, to promote an understanding of this transition. By conducting a bibliometric assessment and analyzing case studies, the results show that the economic condition, availability of technological infrastructure, technical knowledge, age of farmers, type of organization, reliability of technology, and concerns about security and privacy are important elements in adopting Digital Agriculture. The study also reveals a limitation linked to the data sources used in their preparation by analyzing the case studies. This finding reveals the existence of a gap in the literature concerning the scarcity of indicators capable of measuring the adoption of digital agriculture while at the same time providing a perspective devoid of producer bias. Furthermore, by considering the insights provided by the identification and analysis of those factors and barriers, policymakers can tailor policies to address specific challenges and promote the widespread adoption of digital technologies in agriculture.

Introduction

Digital Agriculture - also known as Digital Farming, Agriculture 4.0, Smart Farming, or Smart Agriculture - comprises the use of information and communication technologies in collecting, generating, transmitting, storing, and analyzing data to enhance decision-making at all stages of the agricultural value chain. In other words, it encompasses many aspects from pre-production to post-production, enhancing resilience, productivity, and sustainability in the agricultural sector [1,2].

The integration of these technologies in the farm is emerging as a process that aims to transform the traditional paradigms of the agricultural sector, aiming to improve efficiency, reduce environmental impacts, and increase the sustainability of production and market systems [3]. Among the main features of Digital Agriculture is the provision of connectivity linked to the use of digital technologies (such as Internet of Things (IoT), sensor technologies, Big Data, cloud computing, Artificial Intelligence (AI), remote sensing, and data analytics), which provide farmers with access to valuable data and insights, allowing them to make computerized decisions and optimize their production practices [4,5].

Nevertheless, implementing these innovative technologies is permeated by challenges and obstacles. These include issues related to learning and adaptation by farmers [3], privacy and data security, since these technologies can generate sensitive information about farmers, their farms, and practices [4], the economic and financial issues linked to the adoption and use of these technologies [6], among others.

Identifying these barriers and analyzing the adoption factors of Digital Agriculture is essential for understanding the challenges and opportunities inherent in this technological transition in the agricultural sector. By considering the intersection of these elements, it is possible to develop more effective strategies and policies to overcome existing challenges and optimize the benefits provided by Digital Agriculture.

This paper aims to identify and analyze the factors and barriers to adopting Digital Agriculture, based on bibliometric data and selected case studies. In fact, the aim is to answer the following question: based on the scientific literature, what are the main factors and barriers that impact the Digital Agriculture adoption process?

Although other studies have addressed this issue, additional literature is crucial for determining the main barriers and factors in adopting Digital Agriculture to gain a comprehensive understanding of these

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elements. This gap extends beyond bibliometric studies conducted for specific regions, as illustrated in the article by Stoica et al. [7], and also encompasses research that exclusively adopts the perspective of farmers to depict this panorama, focusing solely on a specific context (as demonstrated by Caffaro & Cavallo [8]; Caffaro et al. [9]; Michels et al. [10]; Kaňovská [11], among others). Therefore, this paper aims to address this gap by shedding light on the primary factors and barriers that influence the adoption of Digital Agriculture.

Methodologically, the study adopts an exploratory approach and utilizes bibliometric review along with the selection and analysis of case studies. Structurally, the paper consists of two main parts, in addition to the introduction and conclusions. The first part outlines the methodological procedures employed in this study. The second part, divided into two sections, presents the results and discussions derived from the bibliometric research and the selected case studies.

Materials and methods

This research utilized a mixed-methods approach combining bibliometric assessment and case study analysis to offer a comprehensive and thorough understanding of the primary barriers and factors affecting the adoption of Digital Agriculture. As advocated by Zupic and Čater [12], bibliometric research provides an overview of a particular area of knowledge and helps understand trends and connect research topics. In addition to bibliometric analysis, case studies serve to substantiate and validate the findings, thereby enhancing the credibility and reliability of our study [13].

The Scopus and Web of Science databases were used to conduct the bibliometric research, and the results were filtered and standardized using the VOSviewer 1.6.19 software.

The data covers the period from 2014 to October 2023, when this search was carried out. To do this, a set of keywords were used: ("smart farming" OR "smart agriculture" OR "digital agriculture" OR "agriculture 4.0″ OR "agriculture 5.0″) AND ("adoption" OR "barrier"), filters were used for the type of publication (only articles, book chapters, and event proceedings) and the language of the publication (only English). After compiling the results ($n = 877$), the publications were screened by reading the titles and abstracts ($n = 814$) to keep the productions that referred only to the adoption of digital technologies by the agricultural sector, considering both those that dealt with barriers and factors of adoption, and those that presented practical adoption experiences.

The data was parameterized to use the VOSviewer software, which has the functionality to build and visualize bibliometric networks. The tool used at this stage refers to the analysis of the co-occurrence of authors' keywords, which generated two visualizations (Network Visualization and Overlay Visualization) representing the frequency of occurrence of keywords. The proximity of the terms indicates their association, belonging to the same cluster, given the frequency of their co-occurrence [14,15].

Subsequently, considering the publications that had been screened, we conducted a new filter to select the case studies. Thus, only publications on the subject of "Digital Agriculture" were considered (publications on the subject of "Smart Climate Agriculture" were excluded since this is a particular case that emphasizes the sustainable dimension) and which necessarily referred to barriers and/or factors in its adoption. As a result, 20 publications were selected as case studies. After reading and analyzing them, we categorized the barriers and adoption factors identified, presenting an overview of the main determinants and obstacles to implementing Digital Agriculture.

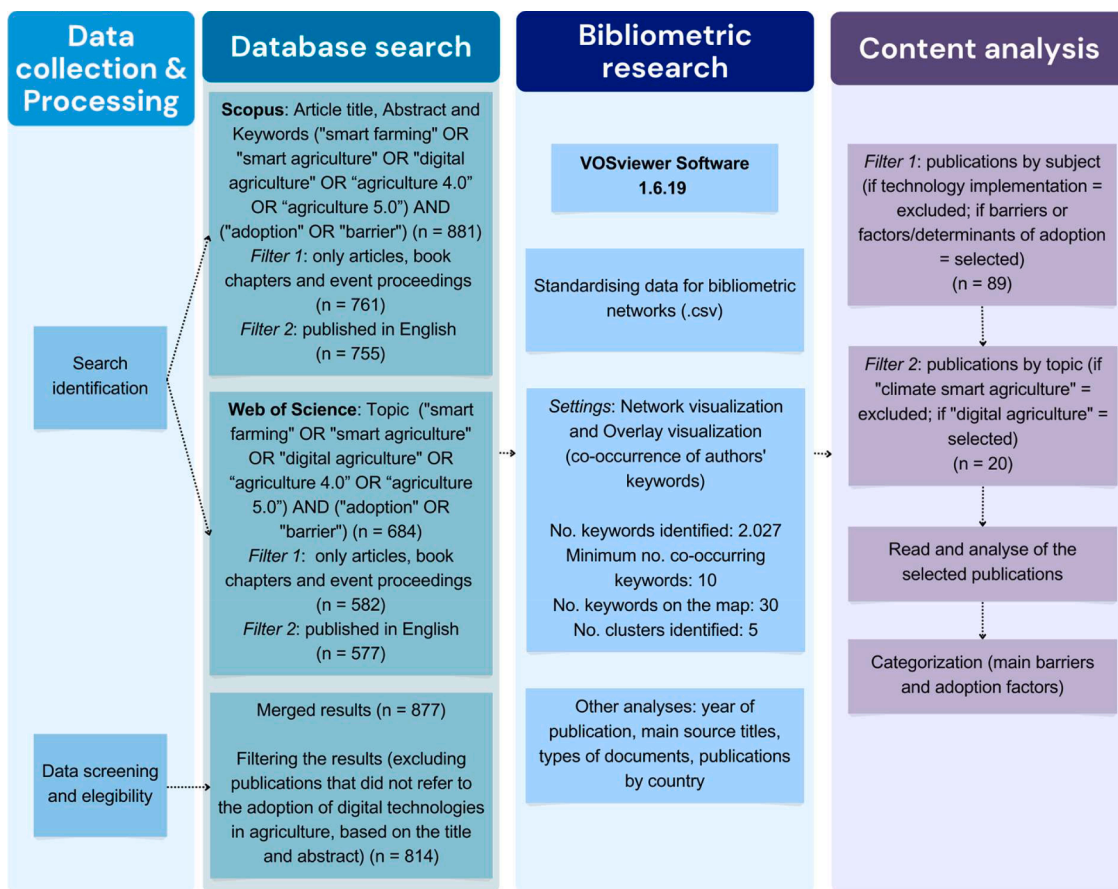A total of seventy barriers were grouped into twenty categories of

Fig. 1. Methodological design of the study, considering the bibliometric research and content analysis process.
Source: Authors' elaboration.

Table 1

Top 15 main source titles.[1]

#	Source title	No. publications
1	Sustainability	33
2	Frontiers in Sustainable Food Systems	18
3	Agricultural Systems	15
4	Agriculture-Basel	13
5	Land use policy	11
6	Sensors	11
7	Computers and Electronics in Agriculture	10
8	Heliyon	10
9	Agronomy-Basel	9
10	Agricultural Systems	8
11	Climate Risk Management	8
12	Journal of Cleaner Production	7
13	Journal of Rural Studies	6
14	Wageningen Journal of Life Sciences	6
15	Land	6

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[1] A total of 432 data sources were identified in the bibliometric research, including journals and scientific events. Among these sources, 290 journals were identified. All of the data can be consulted in the Supplementary Document linked to this paper.

analysis, while another seventy-six adoption factors were grouped into twenty-one categories. Ten categories were classified as barriers and adoption factors both cases covered them. The methodological design of the research (Fig. 1) illustrates the processes conducted to obtain the results.

Results and discussions

The results and discussions in this paper are divided into two sections. The first aims to discuss and present the results obtained through bibliometric analysis. The second aims to present the results of the selected case studies, as well as the categorization of the main barriers and factors influencing the adoption of Digital Agriculture.

Bibliometric analysis

Initially, it is crucial to present the data on the sample analyzed. A total of 814 publications were identified and analyzed based on the proposed theme. These publications were available in various sources and formats, as seen in Tables 1 and 2. Regarding the authors, 3347 were identified by the VOSviewer software, with an average of 6.9 authors per publication.

As for annual scientific production, the number of publications per year can be seen in Graph 1. This graph shows a considerable increase in publications in the area from 2019 onwards, covering the period of analysis (from 2014 to October 2023). These are, therefore, recent productions on the topic under investigation.

The analysis of productivity by country can be seen in Fig. 2, revealing a greater number of publications from countries such as India (244 documents), the United States (128 documents), and Kenya (83 documents). In the case of India, it is assumed that its leadership in terms of knowledge production is aligned with its position as one of the leading players on the international agricultural scene; while the United States stands out due to the availability of an advanced technological infrastructure; and Kenya, due to its sustainable approach to the agricultural production process.

An analysis of the geographical distribution of publications also reveals a significant concentration in specific areas, notably sub-Saharan Africa and Latin America. This concentration may be associated with climatic, socioeconomic, and political factors that directly influence agricultural practices in these regions, and the tropical zone to which they belong. Specifically regarding this tropical region, it is possible to observe in the literature a series of scientific productions that address

Table 2

Type of publications.

Type of publication	No. publications
Article	631
Book chapter	77
Proceedings paper	106
Total	**814**

Source: Authors' elaboration.

the intensification of sustainable agricultural practices and the construction of collaborative platforms to optimize production in these regions. The complexity of the tropical environment demands the development and implementation of coherent and specific strategies to deal with the challenges it faces [16–18].

In Fig. 3, the examination of keyword co-occurrence is presented, focusing on authors discussing both the factors and barriers related to the adoption of Digital Agriculture, as well as those exploring practical experiences in its implementation. The network graph, derived from bibliometric research data, reveals five interconnected clusters, each distinguished by distinct colors.

The red cluster, comprised of eleven keywords, presents the relationship between the concept of "Climate Smart Agriculture" and sustainability, the adoption of these technologies by small producers, the relationship with global climate change, food security, and the gender perspective. Although it is a concept not explored in this paper, this cluster presents a series of studies that can be highlighted, such as those conducted by Andati et al. [19] and Musafiri et al. [20], which explore the determinants of adopting Climate Smart Agriculture technologies in the Kenyan context. In this cluster, the dimension of environmental sustainability is highlighted, given the global climate changes that can also be generated (and, on the other hand, mitigated) by the activities of the agricultural sector. Also noteworthy are the studies conducted by Agarwal et al. [21] and Khoza et al. [22], which address the gender perspective in implementing sustainable digital technologies in the field, demonstrating that gender equity is important to changing perspectives and adopting these technologies.

The green cluster, comprised of eight keywords, deals with the relationship between Digital Agriculture and Precision Agriculture, the innovation process, and its relationship with the digital transformation in the agricultural sector. Among the primary studies, Carrer et al. [23] and Fulton e Port [24], explore the importance of Precision Farming for the digital revolution in agriculture (also called Agriculture 4.0), evaluating the main determinants of its adoption. The innovation process and the farmer's behavior regarding the risks of adopting digital technologies are also analyzed, given the digital transformation and the use of big data technologies in agriculture [9,25,26].

The blue cluster, comprised of five keywords, deals specifically with digital technologies implemented in the agricultural sector, considering Digital Agriculture and Climate Smart Agriculture. In this regard, the use of technologies related to the Internet of Things, artificial intelligence, machine learning, sensors, and cloud computing stand out. According to the study produced by Roussaki et al. [27], more emphasis is given to the use of IoT in agriculture, about aiding decision-making and the possibilities related to harnessing the total value of their data. The use of other Artificial Intelligence technologies and tools has also been addressed by other studies in different contexts, such as the publications produced by Rotz et al. [28], Maindi et al. [29], Monteiro and Barata [30], and Sood et al. [31].

The yellow cluster, comprised of four keywords, highlights the interconnection between the barriers associated with implementing digital technologies in agriculture, adapting to these technologies, and initiatives to mitigate climate change through their use. Publications by Bhardwaj et al. [32] and da Silveira et al. [33] are examples of studies that deal specifically with the barriers to adopting digital technologies in agriculture. As for adapting to these technologies, Bhattacharyya et al.
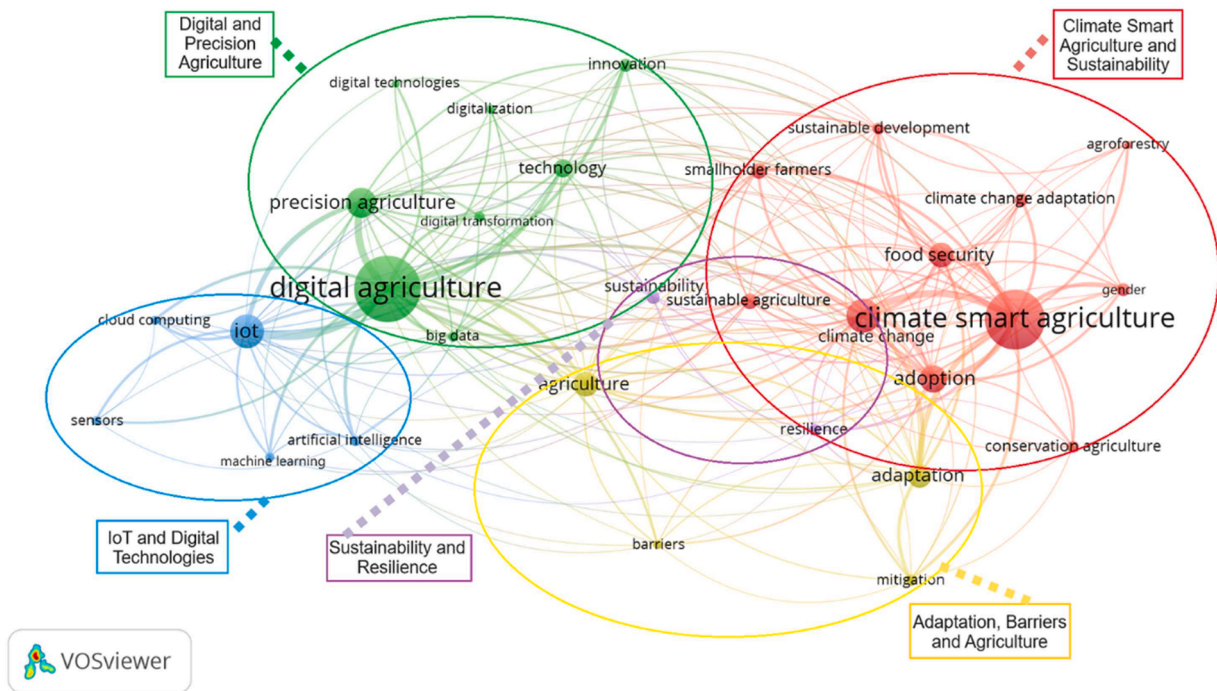
Graph 1. Year of publication of the scientific production.
Source: Authors' elaboration.

Fig. 2. Publications by country.
Source: Authors' elaboration.

[34] and Mashi et al. [35] highlight farmers' perceptions, difficulties related to the level of knowledge, and other factors that impact their use. Particularly regarding issues related to climate change mitigation, the studies produced by Das et al. [36] and Kifle et al. [37], highlight favorable arguments for the potential use of these technologies in the agricultural sector.

Finally, the purple cluster, made up of just two keywords, connects resilience in agriculture to sustainability. As an example of this relationship, we highlight the studies conducted by Jellason et al. [38], Bongole et al. [39], and Mallappa et al. [40], which argue that increasing agricultural resilience can be made possible through the adoption of sustainable digital technologies, being a fundamental tool for guaranteeing productivity and, by extension, a country's food security. In other words, it is a relationship between the context in which agricultural farmers are inert (especially in the case of small producers in a context of vulnerability) and the adoption of technologies that facilitate decision-making while enabling the sustainable management of the entire production process.

The cluster's analysis, although differentiated by color, reveals a direct interconnection between them. This interconnection symbolizes the close relationship between terms that cover both "Digital Agriculture" and those associated with the "Climate Smart Agriculture" concept, which is more closely linked to sustainability. In the specific context addressed in this paper, which focuses on Digital Agriculture, its correlation with adopting various digital technologies becomes evident. The in-depth analysis covers the potential and experiences linked to the use of these technologies while highlighting the barriers that hinder the full implementation of these innovations in the agricultural sector.

Fig. 4 provides a temporal view of the clusters already identified in Fig. 3, introducing a temporal dimension through the average number of mentions of the terms over time. In this case, the color scale - which intensifies towards yellow - indicates the level of trend in the discussions related to each term, as is the case with the keywords "digitalization", "digital technologies", "artificial intelligence" and "barriers". This observation suggests a temporal dynamic in the evolution of discussions, indicating a significant increase in interest and attention to these specific topics in a more recent period. Such an analysis also provides valuable insights into thematic and emerging trends in the field, shedding light on

Fig. 3. Network visualization of bibliometric research, considering the identification of thematic clusters.
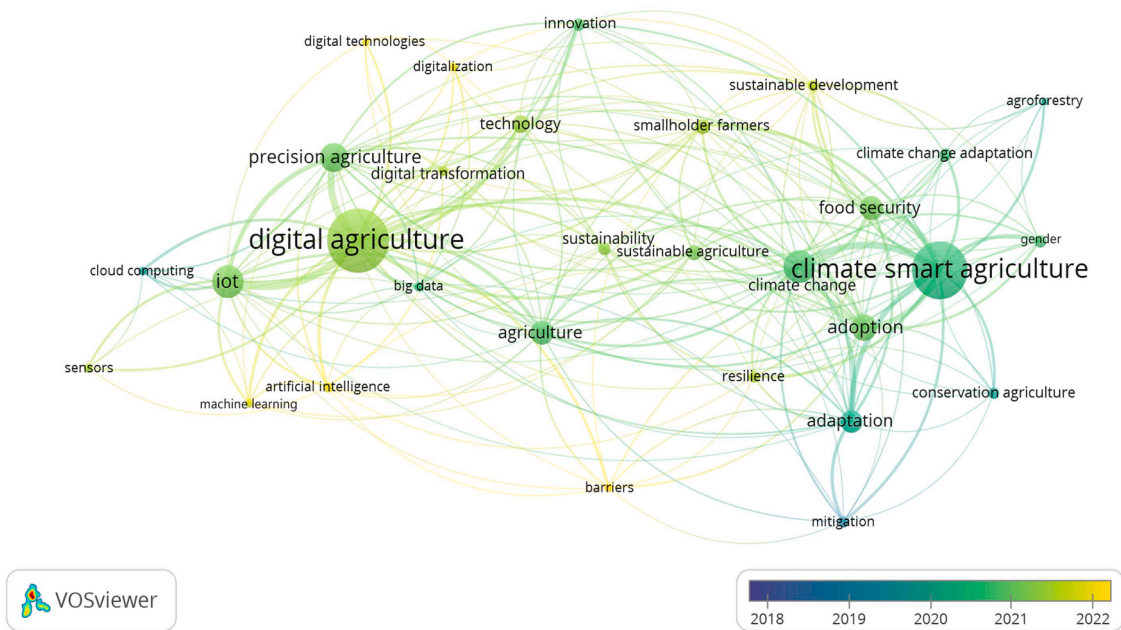Source: Authors' elaboration.

Fig. 4. Overlay visualization of bibliometric research, considering the average mentions of keywords per year.
Source: Authors' elaboration.

priorities for discussion and debate.

Case studies

In order to improve the validation of results from the bibliometric research, twenty case studies were selected and analyzed. The purpose of this selection was to categorize the main barriers and factors related to the adoption of Digital Agriculture. The case studies were chosen to

address these barriers and/or adoption factors, exploring particular and generic contexts, i.e. without specifying an analysis by country or region.

As shown in Table 3, the studies cover a variety of contexts, with eight focused on the European continent, four on Asia, four on America, one on Africa, and three with no specific region/context. However, although these studies present particularities inherent to their contexts, these barriers and adoption factors can be compared due to their

Table 3
Selected case studies.

#	Context / Region	Barriers of adoption	Factors of adoption	Reference
1	Italy / Europe	Education; Farm size; Working alone; Farmers' perceived barriers.	Not applicable.	Caffaro & Cavallo [8]; Caffaro et al. [9]
2	Germany / Europe	Not applicable.	Access to mobile device; Access to mobile internet; Age; Innovativeness; Farm size; Region.	Michels et al. [10]
3	Italy / Europe	Not applicable.	Personal-informal source of information; Personal-formal source of information; Perceived usefulness.	Caffaro et al. [46]
4	Not applicable	Not applicable.	Individual dimension; Technological dimension; Multiple dimensions.	Mohd Ghazali et al. [47]
5	Czech Republic / Europe	Low need for information; Another source of information; Conservative approaches; Ignorance of digital technologies; Financial demands; Low state support; Age.	Not applicable.	Kaňovská [11]
6	Portugal / Europe	Interoperability; Lack of knowledge; Costs; Risks; (Cyber) Security.	Not applicable.	Gaspar et al. [41]
7	Germany / Europe	Not applicable.	Age; Work experience and farm size; Constructs social influence; Facilitating conditions; Hedonic motivation; Trust; Technology readiness, Behavioral intention and use behavior.	Schukat & Heise [48]
8	Japan / Asia	Not applicable.	Corporation forms; Human capital; Profit targets; Main crops; Self-evaluation; Age; Education background.	Mi et al. [49]; Mi et al. [50]
9	China / Asia	Not applicable.	Availability bias belief; Loss aversion bias belief.	Sun et al. [51]
10	Brazil / America	Individuals' adopter categories.	Belief in IoT smart agriculture as a tool that offers an advantage to existing needs; Ease of use; Easily testable to identify its functionalities and benefits.	Strong et al. [44]
11	Italy / Europe	Not applicable.	Deliver higher productivity, cost efficiency and sustainability performances; Easy to use; Supported by social environment; Farms' size.	Giua et al. [52]
12	Kosovo / Europe	Economic/Financial resources; Lack of state support; Knowledge to know how technology invests; Trust/security in adoption.	Not applicable.	Kasemi et al. [42]
13	Not applicable	Not applicable.	Individual characteristics; Environmental factors; Structural factors; Technology factors; Demographic factors.	Sood et al. [31]
14	Brazil / America	Not applicable.	Education level; Age; Experience; Propensity to take risks; Use of tools to plan productivity/crop season; Organization; Participation in agricultural information sharing groups/apps.	Mendes et al. [53]
15	Indonesia / Asia	Not applicable.	Reasons for adoption; Reasons against it.	Harisudin et al. [54]
16	Brazil / America	Lack of infrastructure and solutions accessible to farmers; need to foster R&D and innovative business models; age group risk; lack of efficacy in the data on the rural environment.	Not applicable.	da Silveira et al. [33]
17	India / Asia	Lack of awareness and Knowledge; Regulatory Challenges and Government Policies; Infrastructure; Choice of Technology; Networking Challenges.	Not applicable.	Bhardwaj et al. [32]
18	Not applicable	Lack of training and infrastructure investment; Necessity of tests.	Not applicable.	da Silva et al. [45]
19	Brazil / America	Technological Complexity; Incompatibility between Components; Energy Management Problems; Lack of: Infrastructure, Solutions Accessible to Farmers, Farm-Centered and Farmer-Centered Approaches, Digital Skills and/or Skilled Labor, Efficacy in the Data on the Rural Environment; Concerns about: Reliability Issues, Environmental, Ethical, and Social Costs; High Cost of: Facility Maintenance, Skilled Labor, Operational Components, Sustainable Sources of Energy; Limited: Availability and Accessibility, Techniques for Data Collection on Farms; Need for an Action Plan for Technology Implementation; Political Challenges and/or Lack of Procedures and Agreements regarding the use of Data; Need to foster R&D and Innovative Business Models; Problems in Education; Age Group Risk; Asymmetry of Information; Interruption of Existing Work; Challenges of the Influence of Climate and of System Behaviors; Sustainable Restrictions.	Not applicable.	da Silveira et al. [26]
20	Nigeria, South Africa and Zambia / Africa	Responsibility diffusion; Lack of crop and seed supply; Lack of technological equipment; Collision with farming traditions; Lack of knowledge; Lack of funding; Lack of trust; Risk of diseases.	Food security; Local economy; Community independence; Opportunities for young people; Community well-being; Educational opportunities.	Richter et al. [43]

equivalence and similarity.[2]

In general, the studies highlighted present a series of barriers and factors that influence the adoption of Digital Agriculture, which show similarities. Initially, concerning barriers, issues related to economic

and financial resources stand out, which are linked both to the process of incorporating these technologies (due to high costs) and to maintaining their use and the availability of trained Workers [33,41–43]. The second most frequent barrier refers to the lack of infrastructure, considering the resources associated with the availability of Internet and electronic equipment [44,26,32,45]. The third barrier deals with a lack of knowledge, which is related to the absence of training and knowledge of digital/technological platforms on the part of farmers [41,32,33,43].

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[2] Further information on the case studies can be found in the Supplementary Document of this paper.

This barrier is directly related to issues linked to the farmer's educational background and age, which are also barriers associated with the adoption of Digital Agriculture [8,46,11,26].

Other relevant barriers were identified in the case studies analyzed, namely the farmer's lack of confidence in the usefulness and benefits of the technology [42,43]; challenges arising from government regulations and policies [34]; conflict with agricultural traditions [43]; interoperability issues [41]; deficiency in the effectiveness of rural-related data [26]; lack of state support [42]; need for testing and development of an action plan for implementing the technology [26]; focus on agricultural activities (profit and business objectives) [26]; challenges associated with the network of farmers [32]; risks related to diseases and natural causes [43]; security and privacy concerns [41]; farm size [8,9]; interruption of current activities [33]; low demand for information [11]; and the type of organization (individual or cooperative work) [8,9].

Source: Authors' elaboration.Several variables influence farmers' decisions about the determining factors for adopting Digital Agriculture. Among them, it is worth highlighting the perception of usefulness by farmers, evidenced by the advantages associated with increased productivity, reduced costs, agility in work, and reduced time spent [46,47, 54] In addition, the propensity to take risks and innovate [10,31], conditions related to the ease of use of the technology [48,52], the age of the farmer [10], the experience of the farmer [31] and the influence of personal and informal sources of information (such as family, neighbors and friends) [46] emerge as preponderant factors.

In addition, the educational background [53], the farm size [52], the expectations generated by the farmer [31], the type of organization to which the farmer belongs (membership of a cooperative being associated with a higher likelihood of technology adoption) [49,50], the availability of technological infrastructure (such as mobile devices, Internet, etc.) [47,48], the farmer's confidence in using digital technologies [48,51], the focus of agricultural activity (with profit and business objectives) [49,50], issues related to the community's food security [43], issues related to keeping young people on farms (generating opportunities) [43], the influence of personal and formal sources of information (such as training courses/seminars, consultants, farmers' associations) [46], issues related to security and privacy [31], the financial conditions of the farmer and the local economy [43], the region where the farm is located [10] and the technological knowledge of the farmer [47] are key factors considered in the process of adopting Digital Agriculture.

In both scenarios analyzed, the categories related to the economic and financial condition of the farmer, the availability of technological infrastructure, technological knowledge, educational background, the age of the farmer, the type of organization to which the farmer is linked, reliability in technology, the focus of agricultural activity (with profit and business objectives), security and privacy, and farm size stand out as barriers and determining factors in the process of adopting Digital Agriculture. The factors that received the most mention in the studies analyzed are related to the farmer's economic and financial condition, the availability of technological infrastructure, the farmer's educational background, and age.

These adoption factors are in line with the challenges highlighted by Schroeder et al. [55], which focus on elements linked to the farmer's profile (age, education, gender, willingness to take risks), property characteristics (property size, type of property, level of debt, resource endowment), social relations (local cultures, social environment, attitudes), support institutions, the legal environment (laws and regulations); economic factors (cost of investment, return on investment and profitability), dimensions related to technological infrastructure (ease of use, perceived usefulness, availability of technical support, complexity of the system, compatibility with other technologies), information on technological availability (exhibitions, fairs, seminars, and demonstrations), and decision support systems (ease of data processing, support for decision-making). Therefore, these elements are the main factors in adopting Digital Agriculture.

Other studies that did not appear in this bibliometric analysis can also be highlighted, such as the study conducted by Lassoued et al. [56] on the Canadian context. The paper discusses the transformation of agriculture through emerging technologies, the importance of innovation capacity for companies, the challenges and opportunities in the innovation process and the role of public support and regulation in promoting innovation in the agricultural technology sector. The main barriers to innovation in the sector are: cost of doing R&D, regulations, limited internal financial sources and incomplete information about markets. The main drivers for innovation and the adoption of digital technologies are economic benefit, market size, organizational strategic goal, availability of skilled personnel, competition in the enterprise's market, information about new products/technologies, access to government financial support and intellectual property rights. Research facilities like research parks, incubators, and accelerators are significant drivers of innovation in the agricultural technology sector.

In another study, Olvermann et al. [57] highlights the importance of a successful research and innovation policy for agricultural transition, in response to climate policy objectives and consumer demands. From the perspective of German farmers and an analysis of OECD countries, the authors indicate that the combinations of policy, polity, and politics factors acts as a driver for the agricultural transition. Among the necessary conditions are economic incentives, policy outcomes and transition processes (green parties in government).

Specifically on the Portuguese context, Gaspar et al. [58] discusses the importance and rapid spread of Information and Communication Technologies (ICT) in the context of the Europe 2020 strategy. After a survey analysis, the findings emphasize the significance of ICT in boosting productivity and competitiveness in agriculture and traditional agri-food sectors, also considering the need for capacity building and training to improve the chances of adopting these technologies in the rural areas.

Da Silveira et al. [59] also emphasizes the importance of understanding and addressing challenges and barriers in implementing Digital Agriculture across technological, economic, political, social, and environmental dimensions to ensure global benefits. A total of 25 barriers were identified by the authors: technological complexity; incompatibility between components; energy management problems; lack of infrastructure; concerns about reliability issues; high cost of facility maintenance; high cost of skilled labor; high cost of operational components; lack of solutions accessible to farmers; concerns about environmental, ethical and social costs; problems in increasing availability and accessibility; lack of farm-centered and farmer-centered approaches; need to develop an action plan to implement; political challenges and/or lack of procedures and agreements about the use of data; need to foster R&D and innovative business models; problems in education (training, qualification, training in agricultural data analysis, transfer of data to practical knowledge); age group risk; lack of digital skills and/or skilled labor; asymmetry of information; interruption of existing work; challenges of the influence of climate and of system behaviors; lack of efficacy in the data on the rural environment; sustainable restrictions; limited techniques for data collection on farms; and concerns about sustainable sources of energy.

All those studies confirm the results of our analysis, and in order to summarize them, Fig. 5 shows the main barriers and factors to the adoption of Digital Agriculture, considering the amount of mentions in the case studies analyzed. The elements in bold act both as barriers to adoption and as factors in the adoption of Digital Agriculture.

Although these categories are intrinsically connected, it is possible to outline a multifaceted scenario in which various elements play distinct roles, contributing to the complexity of adopting these technological innovations in the agricultural context. In this context, the significance of factors related to the type of organization to which farmers are affiliated is noteworthy. It is evident that being part of cooperative networks enhances a stronger inclination to embrace digital technologies [8,9,26]. This environment may foster the integration of these

Barriers of adoption

1. **Economical/financial conditions (costs of adoption, facility maintenance, skilled labor)**
2. **Technological infrastructure (mobile internet, mobile device, broadband internet)**
3. **Technological knowledge (digital training)**
4. **Education background**
5. **Age/generation of producer**
6. **Lack of trust in technology**
7. Regulatory challenges and government policies
8. Collision with farming traditions
9. Interoperability
10. Lack of efficacy in the data on the rural environment
11. Lack of state support
12. Necessity of tests and an action plan for technology implementation
13. **Farming business focus (profit targets)**
14. Networking challenges
15. Risk of diseases and natural causes
16. **Data security and privacy**
17. **Farm size**
18. Interruption of existing work
19. Low need for information
20. Organization (working alone)

Factors of adoption

1. Perceived usefulness (increased productivity, cost reduction, work more quickly, workload reduction)
2. Propensity to take risks and innovate
3. Facilitating conditions (easy of use)
4. Farmer experience
5. Personal-informal source of information (relatives, neighbours/friends)
6. **Age/generation of producer**
7. **Education background**
8. Farmer expectation
9. **Farm size**
10. Organization (cooperatives)
11. **Technological infrastructure (mobile internet, mobile device, broadband internet)**
12. **Trust in technology**
13. **Farming business focus (profit targets)**
14. Opportunities for young people (rural youth)
15. Food security
16. Personal-formal source of information (training courses/seminars, consultants, farmers association)
17. **Data security and privacy**
18. **Economical/financial conditions**
19. **Technological knowledge (digital training)**
20. Local economy/market and region

Fig. 5. Main barriers and factors of adoption of Digital Agriculture.
Source: Authors' elaboration.

technologies independently of reliance on state funding and support.

The dynamics of collaboration, the encouragement to share resources, and the exchange of knowledge inherent in these cooperative networks can help mitigate some of the barriers identified earlier, such as the lack of financial resources, and limited technological knowledge, as can be seen in the Brazilian context [26,33,44,53]. Therefore, these types of organizations can emerge as catalysts for the transition to Digital Agriculture.

Even though these results are relevant for formulating public policies aimed at this public and sector, it is essential to recognize the inherent limitations of the case studies analyzed. In all cases, the source of information about barriers and adoption factors was derived exclusively from the perspective of the farmers interviewed in each analyzed case study. However, this view may be subject to farmer bias and does not necessarily accurately reflect the actual scenario of the main barriers and factors of adoption in Digital Agriculture. It is therefore argued that there is a need to use data secondary to the methodologies applied by the studies analyzed, such as the use of official data and, by extension, the development of indicators capable of capturing the adoption of these technologies.

Conclusions

The transition to Digital Agriculture is a complex process, full of challenges and opportunities that require a multifaceted approach. This paper sought to analyze the main barriers and factors in adopting Digital Agriculture to build a scenario capable of shedding light on the nuances involved in this transformation in the agricultural sector.

The analysis of the barriers revealed that challenges related to the availability of economic and financial resources, coupled with the absence of infrastructure and technological expertise, are significant hurdles in the transition to Digital Agriculture. Within the realm of factors influencing technology adoption, the perception of usefulness,

willingness to take risks and innovate, and ease of use of these technologies emerge as crucial determinants. These elements play a pivotal role in farmers' decisions to adopt new technologies, particularly in the context of Digital Agriculture.

In both analyses, various elements play a significant role in shaping the process of adopting Digital Agriculture. These include the economic and financial status of the farmer, the accessibility of technological infrastructure, the level of technological literacy, educational attainment, the age demographic of the farmer, the organizational affiliation of the farmer, the reliability of the technology, the focus of agricultural activities (with an emphasis on profit and business goals), concerns regarding security and privacy, and the scale of the farm, among others.

In summary, these barriers and factors of adoption underscore the complexity and interconnection of various elements that directly impact the possibility of adopting and using digital technologies in the rural areas. While the significance of these findings is undeniable, it is important to acknowledge the limitations inherent in the analyzed case studies. In all cases, the information on barriers and factors of adoption comes exclusively from the perspective of the farmers interviewed in each case study. It is crucial to point out that this view may be subject to farmer bias and does not necessarily accurately reflect the real picture of the main barriers and adoption factors in Digital Agriculture.

Considering this gap in the literature, there is a necessity to complement the methodologies applied in the analyzed studies by incorporating secondary data, such as official data sources. Integrating these additional sources of information can enrich the analysis, fostering a more comprehensive and objective understanding of the dynamics associated with the adoption of digital technologies in agriculture, Including the expansion of bibliometric analysis to encompass the entirety of the year 2023. Furthermore, there is an argument for the development of indicators capable of measuring the adoption of these technologies, which are essential for evaluating trends and identifying patterns accurately.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

Declaration of generative AI and AI-assisted technologies in the writing process

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Thais Dibbern: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Luciana Alvim Santos Romani:** Writing – review & editing, Writing – original draft, Supervision. **Silvia Maria Fonseca Silveira Massruhá:** Writing – review & editing, Writing – original draft, Supervision.

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.

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Supplementary materials

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