INFERENCES BETWEEN SMART FARMING AND SUSTAINABLE DEVELOPMENT OF AGRICULTURE

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ABSTRACT

Agriculture faces significant challenges related to global population growth, climate change and pressure on natural resources. In this paper, the positive impact of integrating digitalization into farming practices to promote sustainability and efficiency in the agricultural sector is explored. The research aims to highlight the importance of smart farming in the sustainable development of agriculture. This analysis will be carried out at the level of scientific studies conducted according to the Scopus database. The main results show that the interest in exploring IoT and digitalization in agriculture has increased in the last ten years, mostly because adopting sustainable practices and regenerative technologies minimizes the environmental impact and promotes biodiversity. The findings add knowledge to the literature and contribute to a better understanding of the benefits of implementing digitalization in agriculture; as such, farmers make more informed decisions about fertilization, irrigation, and crop protection, while reducing resource use and environmental impact.

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Introduction

Sustainable development has been a ubiquitous topic since the Brundtland Report promoted the concept in 1987. Each country has adapted to the 2030 Agenda, the strategy approved by the United Nations since 2015 (UN, 2015). This sets goals for 2020 and targets for 2030, all encompassed in the 17 Sustainable Development Goals (Jeronen, 2020; Andrei et al, 2023). Among them, agriculture is also targeted.

Agriculture can become a significant source of pollution if appropriate practices and technologies are not adopted to manage environmental impacts (Conway and Pretty, 2013). The main ways in which agriculture can contribute to pollution include water pollution, soil erosion, green-house gas emissions, agricultural waste, and biodiversity loss (Evans et al., 2019; Adegbeye et al., 2020; Singh et al., 2021). To reduce the negative environmental impact of agriculture and promote its sustainable development, durable agricultural practices such as organic farming, efficient water management and promotion of crop diversity must be adopted. Investment in research and innovative agriculture can also contribute to the development of more efficient and environmentally friendly solutions (Streimikis and Baležentis, 2020).

Agriculture and sustainable development are two interlinked concepts that are key to ensuring future global stability and prosperity. Agricultural sustainability involves practices and policies designed to meet the needs of the present without compromising the ability of future generations to meet their own needs (Nhemachena et al., 2018; Avakumović & Avakumović, 2025). Given the level of development that agriculture has reached in countries with a tradition in this sector, a final proposal on managing and minimizing the use of resources to achieve sustainable development refers to technological innovation, i.e. the use of modern technologies in agriculture, such as precision farming, the insertion of IoT in this sector and automation (Molina-Maturano et al., 2020).

Therefore, these considerations led to achieving the purpose of the present research, namely, to conduct both a literature review on smart agriculture, IoT, linking agriculture to sustainable development and a bibliometric analysis. The objective of this study is to highlight trends in international research on these topics and the significant impact of technology on agriculture. Finally, the results of the literature review and the bibliometric analysis are compared, and the overlaps are explored.

The hypothesis of the research starts from the assumption that technologies, such as precision farming, the use of drones and sensors, play a significant role in the sustainable development of agriculture, and this will result from both the literature review and the bibliometric analysis. The research hypothesis is based on previous studies showing that the use of modern technology and agricultural innovations can increase efficiency while reducing the environmental impact (Adenle et al., 2020).

The paper is structured as follows: after the introduction, the literature is reviewed, showing the progress in research on the topics of IoT, digitalization and smart farming.

The third part presents the methodology, and the fourth one presents the results using different criteria for analyzing the progress in literature: co-occurrence, link strength, country, year, type of paper, and language of origin of the manuscript. Then, the results of the inference between IoT, digitalization in agriculture, and smart farming are discussed in relations to their impact on sustainable agriculture, considering the three pillars of sustainability – economic, social and environmental. Finally, conclusions are drawn.

Literature Review

By adopting certain principles and promoting a balance between economic, social and environmental needs, agriculture can become a driver of sustainable development, while helping to protect the environment and ensure a sustainable future for generations to come (Bastan et al., 2017). This statement is sustained by several drivers and principles, explored in the following.

According to the literature, a first principle is considered the conservation of natural resources. Sustainable agriculture focuses on protecting soil, water and biodiversity. The use of farming practices such as conservation agriculture, crop rotation and organic farming helps maintain soil fertility, water quality and natural habitats (Kilcher, 2007; Rusu et al., 2015).

Attention should also be drawn to resource efficiency. Sustainable development involves the efficient use of available resources, such as water and energy, to maximize agricultural yields without having a negative impact on the environment (Kumar et al., 2020).

The literature also refers to climate change recovery. Agricultural practices such as regenerative agriculture, efficient management of agricultural waste and the use of renewable energy contribute to reducing greenhouse gas emissions and storing carbon in the soil (Shahzad et al., 2021).

Other key aspects of the relationship between agriculture and sustainable development include the promotion of food security, i.e. the involvement of small producers and local agriculture to ensure equitable access to food; and community engagement and education, which refers to educating farmers and consumers with the help of local communities about sustainable agricultural practices (Viana et al., 2022; Getman, 2025; Francis et al., 2017).

Moreover, new innovative technologies can also support food safety, i.e. the development of blockchain technology in supply chains. It can be used to ensure traceability and transparency in agricultural supply chains, tracking the origin and production process of food from farm to fork. This helps prevent food fraud and promotes sustainable farming practices (Chandan et al, 2023).

However, in the current context of technological development in agriculture and the need to go beyond the current level of sustainable development indicators, by far the most important key element in the relationship outlined above is that of technological innovation. According to the literature, there are several ways to implement innovative

technologies in agriculture to improve challenges related to productivity (either labor or yield), efficiency and sustainability. The most common form is precision agriculture. This involves the use of technologies such as GPS navigation systems, drones, and sensors to collect and analyze precise data on soil, crop and weather conditions. This information allows farmers to make more informed decisions about fertilization, irrigation, and crop protection, while reducing resource use and environmental impact (Odara et al., 2015).

Agricultural biotechnology is more present at the global level, given that it is subject to limits and restrictions at the European level. Agricultural biotechnology includes techniques such as genetic modification and genome editing to improve plant quality and increase resistance to pests, diseases, and adverse climatic conditions. These innovations can increase crop yields and reduce reliance on pesticides and fertilizers (Moshelion and Altman, 2015).

The implications of smart irrigation systems are also included in the research. Their use refers to the application of sensors and automated control technologies to optimize the utilization of water in agriculture. At the same time, these systems monitor soil moisture and weather conditions to deliver precise amounts of water at the right time, leading to a reduction in water wastage (Obaideen et al., 2022).

Regarding the restrictions on the limitation of cultivated areas, in conjunction with global population growth, the concept of vertical agriculture and urban horticulture is also found in the literature. Modern technology allows plants to be grown in vertical systems and in confined urban spaces using artificial lighting, automatic irrigation systems and climate control. These systems can make food production more efficient and sustainable, while reducing transport distances and associated emissions (Chatterjee et al., 2020).

Another pervasive theme in research is robotics and automation. This topic is increasingly being addressed, given the situation facing rural areas today (at least in Europe), regarding depopulation of these areas and a shrinking workforce. The use of robots and automation in agriculture can reduce the reliance on human labor and improve the efficiency of agricultural operations. For example, robots can be used for crop harvesting, precision weeding or plant health monitoring (Yuan et al, 2023).

Thus, the main directions of research exploring the complex relationships between smart farming and sustainable agriculture are: conservation of natural resources, resource efficiency, climate change, food security and safety, vertical and urban agriculture, technological innovation, agriculture biotechnology, smart irrigation systems, robotics and automation.

Materials and methods

To confirm the directions of research present in the literature, exploring the relationships between smart farming and sustainable development of agriculture, a detailed bibliometric analysis is carried out. Bibliometric analysis is an essential tool in

scientific research, used to assess the impact and evolution of a particular field of study (Donthu et al., 2021).

Research objectives and rationale

Having in mind that one of the main objectives of the research is to identify the positive impact of the emerging technologies on sustainability and efficiency in agriculture, the use of modern technologies, such as IoT, smart farming and digitization, which provide innovative solutions for real-time monitoring and management of crops, thereby reducing resource consumption and minimizing negative environmental impacts, is explored.

Another objective of the research is to highlight the importance of modernization in agriculture, arguing that modern technologies enable farmers to make informed decisions based on accurate data. This not only improves yields but also reduces the risks associated with traditional farming practices.

Finally, the research highlights the growing trends and interest in IoT, smart farming and digitization in agriculture, considering the adoption of these technologies as a necessity imposed by the current challenges of global agriculture. Emerging technologies are enabling a more sustainable and resilient agriculture, able to respond to current and future challenges.

These arguments explain the selection of the search phrase "IoT in agriculture" OR "Smart farming" OR "Digitalization in agriculture" AND "Sustainable Agriculture" for this particular inquiry.

The rationale behind this piece of research starts with database selection, SCOPUS, continues with the selection of search criteria, title, keywords and abstract. Then, the search phrase and criteria have been selected. After data extraction, the results have been analyzed, mapped and discussed.

Finally, the research highlights the growing trends and interest in IoT, smart farming and digitization in agriculture, considering the adoption of these technologies as a necessity imposed by the current challenges of global agriculture.

Data Collection Process

This analysis was carried out at the level of scientific studies written, according to the SCOPUS bibliometric database. The SCOPUS database has been selected for this research based on its broad coverage and disciplinary diversity, providing access to a wide range of relevant studies in areas such as agriculture, environmental sciences and technology. SCOPUS is recognized for its quality and rigor, with strict article selection criteria ensuring the credibility of sources. In addition, it provides advanced bibliometric analysis tools essential for assessing existing literature and identifying influential papers.

After choosing the database, the research continued by querying the bibliometric database, searching according to the criteria "Title, Keywords, Abstract", and the search phrase mentioned before. Therefore, all scientific papers that contained either the term IoT in agriculture, Smart farming or Digitalization in agriculture, in conjunction with Sustainable agriculture, have been identified. These particular terms have been selected because they cover the main application areas of IoT and digitization in agriculture in the context of sustainability. The inquiry has been limited to the title, keywords and abstract because they provide a full and comprehensive picture of the focus and purpose of the papers and are essential for identifying their relevance in the context of the topics studied.

In order not to be limited from a time framing perspective, no restrictions have been made in terms of time period; the results identify scientific research from 1998 to the present for this theme. The timeframe has been chosen as a variable to capture the evolution and trends in IoT and digitization in agriculture over an extended period covering both the beginnings of these technologies and recent developments. The choice of a broad time span allows to observe progress and changes in the scientific approaches and technologies applied in this field.

Table 1. Centralization of bibliometric database query results

Database	**Search Terms**	**Results**	**Data format**
SCOPUS	"IoT in agriculture" OR "Smart farming" OR "Digitalization in agriculture" AND "Sustainable Agriculture"	Articles, books, book chapters, conference papers, reviews	Bibliography - Research Information Systems (.RIS)
Total Results	3113	Not in the English Language	50
		Eliminate Duplicates and Irrelevant	119
Final dataset	**2944**		

Source: authors' contribution

A total of 2,944 valid scientific documents have been identified according to this inquiry phrase, all published from 1998 to the present. These data have been then analyzed in time and as occurrence, using VOSviewer software to identify the correlations between keywords, as well as the correlations between authors and countries of publication of these scientific materials.

The bibliometric analysis aimed to analyze collaborative networks and geographical influence on the development of research, as well as to examine the themes and topics of interest that have been addressed over time. Providing a comprehensive overview of the literature and its evolution, as well as helping researchers to identify gaps and opportunities for future research, are elements that contribute to the usefulness of bibliometric analysis. Through this methodology, the paper provides a detailed and grounded understanding of the interconnections between IoT, smart farming and digitization in the context of sustainable agriculture, highlighting major contributions and trends in this field.

Results

The results are presented in two separate sections. The first one presents general information about the papers selected, and the second one shows the keywords' co-occurrence and link strength.

Number, language and type of papers

The number of scientific papers published is increasing from year to year, from 1998 to 2025. However, this topic has shown little interest for researchers and academics for 17 years, since the first research was carried out, with 31 research papers being written until 2015. With the global acceptance of the concept of sustainable development through the 2030 Agenda (in 2015), the topic has grown exponentially, with more than 2,960 scientific papers produced in the last 9 years. Analyzing the average annual growth rate over the whole period, it can be estimated that each year the publications on this topic have increased by 29.6%, but when analyzing the period 2015-2024, since the topic has grown significantly, the average annual growth rate is approximately 43%.

Continuing the analysis of the results obtained from the database query, a structural analysis of the 2,994 scientific documents, regardless of language, was carried out according to their type: 1,539 articles (51.40%), 35 books (1.17%), 350 book chapters (11.69%), 543 conference papers (18.14%), 1 conference review (0.03%), 1 data paper (0.03%), 12 editorials (0.40%), 3 letters (0.10%), 14 notes (0.47%), 490 reviews (16.37%) and 6 short surveys (0.20%).

A classification of scientific documents has been made according to the language in which they have been written: 19 Chinese (0.63%), 2,944 English (98.33%), 2 French (0.07%), 19 German (0.63%), 1 Portuguese (0.03%), 1 Russian (0.03%), 8 Spanish (0.27%). As can be seen, out of the total number of scientific documents, more than 98% them have been written in English.

Analysis of keyword co-occurrence and link strength

Using the VOSviewer software, the co-occurrences between keywords for the 2,944 scientific documents have been analyzed and given the multiplicity of keywords in all these documents, the criterion was chosen that these keywords should record a minimum of 20 co-occurrences to make the results as conclusive as possible. A total of 254 keywords were recorded that met this requirement, and the analysis and creation of neural maps were performed with this volume of keywords.

In Table 2, there are extracted the top 25 keywords with the minimum number of co-occurrences are extracted as required by the total link strength. From these results, it can be determined that the searched phrases are in this top 25-word ranking, with phrases such as "IoT" being the second keyword in terms of total link strength, but also in terms of number of co-occurrences. The phrase "smart farming" used in document search ranks 9th with 272 co-occurrences. The phrase "sustainable agriculture" ranks 10th with 248 co-occurrences.

The most frequently encountered word is agriculture, with a total of 637 co-occurrences, and in the third position is the word "crops". It can also be highlighted that phrases such as "precision agriculture", "agricultural robots", "artificial intelligence", and "machine learning", all of which lead to the technological innovation discussed at the beginning of the research, are also shown in the literature as drivers for the sustainable development of agriculture.

Table 2. Top 25 keywords by total link strength

No	Label	Occurrences	Total link strength
1	agriculture	637	4245
2	internet of things	450	3325
3	crops	270	2311
4	precision agriculture	329	2202
5	agricultural robots	247	1948
6	machine learning	234	1811
7	sustainable development	223	1804
8	farms	196	1772
9	smart farming	272	1691
10	sustainable agriculture	248	1676
11	agricultural technology	182	1574
12	artificial intelligence	202	1364
13	food supply	156	1354
14	climate change	203	1339
15	cultivation	150	1249
16	sustainability	214	1224
17	smart agricultures	140	1212
18	Article	108	1159
19	smart agriculture	159	1096
20	Iot	167	1086
21	decision making	139	1085
22	Nonhuman	96	1039
23	remote sensing	149	989
24	machine-learning	95	966
25	antennas	114	962

Source: own processing based on Scopus data using VOSviewer

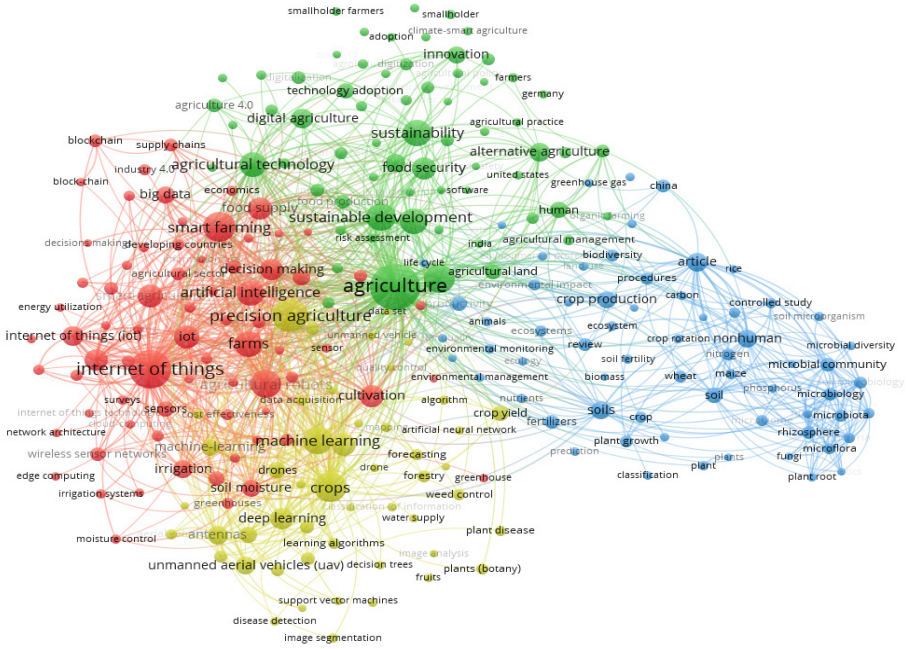
The 254 identified keywords have been classified into 4 clusters according to their relatedness and strength of linkages and co-occurrences. Of the total keywords identified, 29.1% (74 words) are grouped in cluster 1 (red), 26% of the words (66 words) are grouped in cluster 2 (green), 25.6% of the words (65 words) are grouped in cluster 3 (blue), and 19.3% of the words (49 words) are grouped in cluster 4 (yellow). Figure 1 shows the neural map of the 4 clusters according to the 254 keywords and their interconnections.

According to the map of the totality of keywords according to occurrences, it can be seen that the term agriculture is in the center of the map, having also the most occurrences, as mentioned above. Then, the phrase "internet of things" has been identified in cluster 1 and "precision agriculture" in cluster 4, but it can be seen that in cluster 3, there is no item with such a high significance as those presented above.

In cluster 1, keywords such as Internet of Things, smart farming, artificial intelligence, decision making, big data, blockchain, and network architecture have been identified. Thus, it can be appreciated that the publications whose keywords have been classified in this cluster have focused on research in the field of IoT and smart farming, with a vision of decision making based on this data and the creation of a network architecture based on big data and blockchain.

This exposure leads to the hypothesis that the integration of emerging technologies can lead to improved decision-making in agriculture. By integrating these technologies, an advanced network infrastructure can be created to efficiently collect, analyze and use agricultural data to make smarter decisions and optimize agricultural processes, resulting in higher yields and reduced environmental impact.

Figure 1. Map of interconnections between keywords and clusters.



Source: own processing based on Scopus data using VOSviewer

In Cluster 2, interconnections between words such as agriculture, sustainable development, sustainability, food security and safety, alternative agriculture and technologies and digital agriculture can be observed. Therefore, this cluster contains keywords from the research that focused on these concepts whereby alternative

agriculture, respectively digital agriculture, leads to sustainability and sustainable development, and the first objective of this development is to ensure food for the population, thus ensuring food security and safety.

It can be noted that this set of keywords highlights the researchers' focus on the following main issues: developing alternative and digital agriculture to promote sustainability and sustainable development, with a focus on feeding the population and ensuring food security and safety. This demonstrates the growing recognition of the importance of adopting innovative agricultural practices and digital technologies to meet society's food needs in a sustainable and environmentally responsible way.

In cluster 3, there are keywords such as: crop production, productivity, environmental impact, soils, fertilizers, non-human, microbacterial and other words that make this cluster a more technological one in terms of research, i.e. through these researches we have pursued the impact of the questioned theme on the production sector, on productivity, yields, non-human intervention in the soil and the fight against all microbacterial aspects.

Therefore, it can be stated that the research in this cluster aims to explore and understand the impact of technical and agronomic factors on agricultural production, productivity and sustainability in an environmental context. Through these studies, the aim is to evaluate and optimize agricultural practices, to minimize environmental impacts and improve the performance of the agricultural production sector.

Cluster 4 contains keywords such as: precision agriculture, robotics, machine learning, crops, algorithms, and drones. Thus, in this cluster, keywords from research that can support the theme under investigation, namely IoT and smart farming for sustainable agricultural development, have been included. This research creates better links between technical (digital) and technological (agricultural) sides. These keywords reflect interest in areas such as automation, data analysis and the use of artificial intelligence in agriculture to optimize farming processes, make smarter decisions and maximize crop yields.

Therefore, it can be stated that the research in this cluster explores and assesses the potential and benefits of advanced agricultural technologies to support the development and implementation of more efficient and sustainable agricultural practices.

Discussions

The results prove that the interest of researchers in smart and sustainable agriculture has increased in the last ten years. These findings, made on the scale of the research, are also confirmed by statistical forecasts of the market value of smart agriculture worldwide between 2021-2027. In the period 2021-2023, this value has increased from $12.8 billion to $17.6 billion, and the report forecasts that it will reach $33 billion in 2027 and then exceed the $50 billion threshold in 2030 (Statista, 2025).

The inferences between smart farming and sustainable agriculture are confirmed, also in the literature. Barroso-Barroso (et al., 2025) argued that smart agriculture is an engine of sustainability and innovation, because it integrates science and technology to cope the global issues of climate change, food security, and sustainable development. Pentoś (et al., 2025) claimed that the growth of precision agriculture and AI technologies can contribute to the further development of sustainable agriculture. Rađenović (et al., 2025) highlighted the main benefits of digitalization in agriculture and stressed its importance for sustainable development in rural areas.

The main directions of research found in the literature, which overlapped with the results of the bibliometric analysis, confirm the interest of scientists in exploring the links between smart farming and sustainable agriculture.

Coming back to the main directions of research found in literature and listed in the final part of the section literature review, they can be found in different clusters of the bibliometric analysis, as follows: conservation of natural resources, resource efficiency and climate change in cluster 3, food security and safety and vertical and urban agriculture in cluster 2, technological innovation, agriculture biotechnology, smart irrigation systems in cluster 1 and robotics and automation in cluster 4.

Emerging technologies in agriculture and their economic impact

Integrating emerging technologies in agriculture can significantly improve process efficiency and resource use. To sustain this statement, some drivers are explored. Firstly, the integration of innovative technologies has a direct impact on agricultural yields, leading to higher yields by optimizing production processes, as argued by Kumar (et al., 2020). Farmers could thus achieve a higher agricultural output with the same level of resource consumption, or even a lower one, thus directly influencing the profitability of the farmer's activity.

Digital farming and technological innovation can also make farmers more competitive in the market. By adopting digital and innovative technologies, farmers can develop higher quality and sustainable products, as stated by Moshelion and Altman (2015), which could attract more customers and open up new business opportunities. Using these emerging technologies to optimize agricultural production processes can reduce the use of certain resources such as water and energy, while contributing to significant long-term savings for farmers, as demonstrated by Rusu (et al., 2015). Optimizing resources can also lead to lower environmental impacts, so we can also talk about reducing environmental costs.

Thus, the integration of emerging technologies in agriculture can have a significant positive impact on the economy, making the agricultural sector more efficient, competitive and sustainable.

Emerging technologies in agriculture and their social impact

Increasing agricultural yields not only influences producers, but also consumers. This intensive agricultural development with emerging technologies can increase access to quality food for the whole population, especially for less privileged communities, as argued by Chandan (et al, 2023). Subsequently, this could reduce food insecurity and improve the health and well-being of communities. Food security cannot be achieved without considering food safety. The use of emerging technologies in agriculture can help improve production practices and reduce the risks associated with food contamination or other food safety issues. As a result, consumers can feel more confident in the food they eat, contributing to a healthier and happier society.

Last but not least, the integration of emerging technologies in agriculture can help increase access to agricultural education and training, as explored by Francis (et al., 2017). As a result, young people and farm workers can acquire relevant skills and knowledge to take advantage of new technologies and innovative farming practices.

Thus, the integration of emerging technologies in agriculture can have a significant positive social impact, helping to improve access to quality food, increase food security, create jobs, and promote education and training in agriculture.

Emerging technologies in agriculture and their environmental impact

In relation to reducing environmental costs, this results from decreasing the use of resources, mainly water and energy. One impact of the emerging technologies in the environmental pillar vision relates to the reduction of natural resource use. These technologies can contribute to the conservation of water resources as well as to the reduction of water and groundwater pollution, as stated by Adegbeye (et al., 2020).

Continuing with the idea of optimizing production processes, smart and precision farming can reduce the use of chemical pesticides and fertilizers, as demonstrated by Moshelion and Altman (2015). Farmers can identify areas that need special treatment, reducing inefficient use of pesticides and fertilizers. This reduces soil and groundwater contamination and protects biodiversity.

Advanced farming techniques can contribute to reducing carbon emissions through the use of soil management practices such as conservation and organic farming, as shown by Shahzad (et al., 2021). These practices can help store carbon in the soil and reduce greenhouse gas emissions associated with deforestation and the burning of agricultural land. Moreover, the use of sustainable farming practices, supported by technologies such as soil and crop monitoring systems, can help protect soils from erosion and degradation (Li et al., 2014). This helps protect soil fertility and biodiversity, with a positive impact on agriculture and natural ecosystems.

The complexity of the effects of emerging technology on the economy, society and environment, described above, confirms the hypothesis formulated at the beginning of the research that technologies, such as precision farming, the use of drones and sensors, play a significant role in the sustainable development of agriculture.

Conclusions

This paper sought to highlight all research in the areas of "IoT in agriculture", "Smart farming", "Digitalization in agriculture", with influences on "Sustainability in agriculture". A final answer to the research question is that smart farming is strongly related to sustainable agriculture, contributing to its development, as demonstrated by both literature review and the bibliometric analysis.

This conclusion is sustained by the growing interest of scientists in exploring the topics mentioned above and by the links and co-occurrences between the keywords. The number of papers published in the field of smart farming and sustainable agriculture reached a peak in 2015, with the implementation of the Sustainable Development Strategy (Agenda 2030) by the United Nations. While 31 research papers have been written in the period 1998-2015, more than 2,960 papers have been published, after 2015, demonstrating an increasing interest in these topics.

At the same time, this scale of research comes against the backdrop of limited natural resources and the totality of strategies to protect the environment. At present, in developed countries, performance in the agricultural sector has reached a peak, and the only optimal option for sustainable agricultural development is considered to be smart farming, in all its forms.

Whereas the importance of smart farming and its effects on sustainable development has been demonstrated in literature, as proven in this paper, practical actions for digitalization implementation in farms and measures of agricultural policy for supporting it should be investigated in future scientific papers.

The research has its limitations, since only the SCOPUS database has been inquired, leaving out papers from other databases, and, like this, some inferences and co-occurrences may have been missed.

Conflict of interests

The authors declare no conflict of interest.

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