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SPECIAL ISSUE: 20 YEARS OF THE STRATEGIC MANAGEMENT CONFERENCE – 3Es FROM ANPAD

TECHNOLOGICAL INNOVATIONS IN AGRICULTURE: MAPPING AND FUTURE TRENDS IN SCIENTIFIC LITERATURE

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Abstract

Objective: Agtechs are startups focused on developing technological solutions for agribusiness. Due to its relevance in the literature, this work aims to map scientific production and point out the trends of future studies on Agtechs, seeking to identify the panorama of contribution to the production of sustainable technologies.

Methodology/approach: This study employed a systematic review of the literature, using bibliometric methods and content analysis methods to analyze the state of Agtech research.

Originality/relevance: This study provides important information for researchers, practitioners, and policymakers. The analysis identified that the subject is in full ascension. In addition, it made it possible to map the existing publications in the area and the evolution of the scientific field, as well as to identify emerging themes and present the main trends for future studies in this field of research.

Main results: The results indicate the importance of the topic and its growing popularity in scientific research. In addition, the analysis identified new research streams that deserve further exploration by the scientific community: Agricultural technological radar; Sustainability; Consequences of agriculture 4.0; Rural Development and Organizational arrangement of Agtechs.

Theoretical/methodological contributions: The study of Agtechs has significant implications for theoretical perspectives related to technological innovation. Consequently, a better understanding of the growing interest in the topic among scholars is needed to leverage its implications and possibilities.

Social/managerial contributions: The analysis indicates that Agtechs are key to guiding the agricultural revolution towards global sustainable growth, being considered essential to optimize all food production in a sustainable way.

Keywords: Agtech. Sustainable development. Innovation. Technology. Sustainability. Agricultural practices.

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INOVAÇÕES TECNOLÓGICAS NO CAMPO: MAPEAMENTO E TENDÊNCIAS FUTURAS DA LITERATURA CIENTÍFICA

Resumo

Objetivo: As Agtechs são startups focadas em desenvolver soluções tecnológicas para o agronegócio. Devido à sua relevância na literatura, este trabalho tem como objetivo mapear a produção científica e apontar as tendências de estudos futuros sobre as Agtechs, buscando identificar o panorama de contribuição na produção de tecnologias sustentáveis.
Metodologia/abordagem: Este estudo empregou uma revisão sistemática da literatura, utilizando métodos bibliométricos e de análise de conteúdo para analisar o estado da pesquisa sobre Agtechs.
Originalidade/Relevância: Este estudo fornece importantes informações para pesquisadores, profissionais e formuladores de políticas públicas. A análise identificou que a temática está em plena ascensão. Além disso, permitiu mapear as publicações existentes na área e a evolução do campo científico, bem como identificar temas emergentes e apresentar as principais tendências de estudos futuros deste campo de pesquisa.
Principais resultados: Os resultados indicam a importância do tema e sua crescente popularidade na pesquisa científica. Além disso, a análise identificou novos fluxos de pesquisa que merecem maior exploração pela comunidade científica: Radar tecnológico agrícola; Sustentabilidade; Consequências da agricultura 4.0; Desenvolvimento rural e, Arranjo organizacional das Agtechs.
Contribuições teóricas/metodológicas: O estudo das Agtechs tem implicações significativas para perspectivas teóricas relacionadas com a inovação tecnológica. Consequentemente, uma melhor compreensão do crescente interesse na temática entre os estudiosos é necessária para alavancar suas implicações e possibilidades.
Contribuições sociais/gerenciais: A análise indica que as Agtechs são fundamentais para nortear a revolução agrícola em direção ao crescimento sustentável global, sendo consideradas essenciais para otimizar toda a produção de alimentos de forma sustentável.

Palavras-chave: Agtech. Desenvolvimento sustentável. Inovação. Tecnologia. Sustentabilidade. Práticas Agrícola.

INNOVACIONES TECNOLÓGICAS EN EL CAMPO: MAPEO Y TENDENCIAS FUTURAS EN LA LITERATURA CIENTÍFICA

Resumen

Objetivo: Las Agtechs son startups enfocadas en el desarrollo de soluciones tecnológicas para la agroindustria. Debido a su relevancia en la literatura, este trabajo tiene como objetivo mapear la producción científica y señalar las tendencias de futuros estudios sobre Agtechs, buscando identificar el panorama de contribución a la producción de tecnologías sostenibles.
Metodología/enfoque: Este estudio empleó una revisión sistemática de la literatura, utilizando métodos bibliométricos y de análisis de contenido para analizar el estado de la investigación Agtech.
Resultados principales: Los resultados indican la importancia del tema y su creciente popularidad en la investigación científica. Además, el análisis identificó nuevas líneas de investigación que merecen ser exploradas por la comunidad científica: el radar tecnológico agrícola; Sostenibilidad; Consecuencias de la agricultura 4.0; Desarrollo Rural y Ordenamiento Organizacional de Agtechs.
Aportes teóricos/metodológicos: El estudio de las Agtechs tiene implicaciones significativas para las perspectivas teóricas relacionadas con la innovación tecnológica. En consecuencia, se necesita una mejor comprensión del creciente interés en el tema entre los académicos para aprovechar sus implicaciones y posibilidades.
Aportes sociales/gerenciales: El análisis indica que las Agtech son clave para guiar la revolución agrícola hacia un crecimiento sostenible global, siendo consideradas esenciales para optimizar toda la producción de alimentos de manera sostenible.

Palabras clave: Agtech. Desarrollo sostenible. Innovación. Tecnología. Sostenibilidad. Prácticas Agrícolas.

1 Introduction

Agriculture plays a crucial role in Brazil and globally, being essential for food security, economy, and job creation. In Brazil, it is a pillar of the economy, significantly contributing to the GDP and generating large-scale employment, especially in rural areas. The country stands out as one of the main global producers and exporters of agricultural commodities. Globally, agriculture is vital for food security, the world economy, and the livelihood of millions of people (Vieira Filho & Fishlow, 2017; Quintam & de Assunção, 2023).

To maintain a substantial contribution and exert significant influence on its economic outcomes, the agribusiness sector must continue with constant modernization, actively incorporating the numerous technological advances that have emerged in recent decades. Among the most recent technologies that have significantly impacted this sector are Industry 4.0 (Dayioglu & Turker, 2021), the Internet of Things (Mahmud, Ramamohanarao & Buyya, 2020; Farooq, Riaz, Abid, Umer, & Zikri, 2020), nanotechnologies (Xu, Phillips, Alarcon, & Kumar, 2021), and automation and artificial intelligence (Kakani et al., 2020). Considering this scenario, various initiatives have emerged to drive and integrate technological innovations into the agribusiness, including the rise of startups in recent years.

A startup is a technology-based, repeatable, and scalable venture, whose growth is difficult to measure (Ries, 2012). These organizations, whether nascent or in recent operation, stand out for their innovation in business models, products, or services. In the startup landscape, Agritechs (or Agtechs) emerge with disruptive proposals to boost technological evolution in the agricultural sector. As Dutia (2014) explains, Agritechs are startups dedicated to developing sustainable agricultural technologies, promoting increased productivity, efficiency, and mitigation of environmental impacts. Thus, Agtechs play a vital role in driving the agricultural revolution necessary for global sustainable growth.

Future research spans five crucial areas: Agricultural Technological Radar (Atik, 2022), Sustainability (Frare & Beuren, 2021), Consequences of Agriculture 4.0 (Barrett & Rose, 2022), Rural Development (Espig et al., 2022), and Organizational Arrangement of Agtechs (Bertucci Ramos & Pedroso, 2022). These domains encompass the assessment of technologies, the implementation of sustainable practices, the analysis of the impacts of Agriculture 4.0, the sociological exploration of rural development, and the investigation of the organizational relations of Agtechs. By addressing these categories, the aim is to gain a holistic understanding of the dynamics of agribusiness in the face of technological and sustainable innovations, aligning with the objectives of the 2030 Agenda for Sustainable Development.

Therefore, this study is justified by the following factors: (I) Economic: Globally, agribusiness has a significant impact on the GDP of countries such as China, the United States, Brazil, and India (Sesso Filho, Borges, Pompermayer Sesso, Brene & Esteves, 2021). (II) Social: Agribusiness is responsible for the global food supply. To ensure sustainable food production and guarantee food security, it is estimated that we will need to produce more food in the next forty years than in the entire course of human history (Dutia, 2014). For this to be possible, Agritechs are essential in optimizing the entire food production process sustainably. (III) Environmental: Sustainable development is crucial for a planet that currently has over eight billion people. We need to reduce negative environmental impacts. Innovations from Agritechs are essential for this issue because they increase agricultural system productivity while also reducing environmental costs.

Consequently, it is evident that agribusiness plays a fundamental role in the development of various nations, exerting a significant impact on their economic indicators. To maintain this positive influence, it is important that the agriculture sector seeks continuous modernization, taking advantage of the technological advances that have emerged in recent decades (Vieira Filho & Fishlow, 2017; Quintam & de Assunção, 2023). Thus, the research objective is to map scientific production and point out future study trends on Agtechs, seeking to identify the panorama of Agritech's contribution to the production of sustainable technologies. For this reason, the study seeks to answer the following question: What is the panorama of the scientific contribution of Agtechs in the production of technologies for sustainability?"

2 Theoretical Structure

2.1 Sustainable Development in Agriculture

Agriculture is considered the pillar of food security, playing an increasingly significant role in the continuation of life and in the socioeconomic development of a country (Dayioglu & Turker, 2021). For this reason, in recent years, there has been a significant increase in the demand for food, both in terms of quality and quantity, thereby generating an urgent need for intensification in agricultural practices (Farooq et al., 2020). This scenario reflects the growing pressure to meet the food demands of the constantly growing global population, highlighting the importance of innovations and advancements in the agricultural sector to ensure food security and long-term sustainability (Farooq et al., 2020). Therefore, agricultural production systems are designed to promote ecosystem sustainability while meeting human needs (Dayioglu & Turker, 2021).

These systems not only seek to improve production efficiency and promote employment, but also aim to value food systems, preserve, and optimize natural resources, raise living standards, and drive economic growth. In this context, the approach adopted, as highlighted by Dayioglu & Turker (2021), not only reinforces the resilience of individuals, communities, and ecosystems, but also aligns with sustainable balance. To ensure sustainability, mechanisms that encourage the provision of sustainable services are necessary. Agricultural, environmental, and economic policies decisively influence the activity of rural producers, affecting strategies in the field (Costa & Costa, 2022).

Field strategies directed at analyzing environmental services are fundamental, as they enable the understanding of procedures, laws, and financial and opportunity advantages directed at farmers. It becomes important to constantly evaluate the actual viability of agricultural production aligned with the principles of sustainable development. In this context, it is crucial to ensure a comprehensive understanding and ensure that practical implementation favors sustainability in agriculture (Costa & Costa, 2022). In the agricultural field, adherence to principles is essential to elevate both productivity and sustainability (Dayioglu & Turker, 2021).

These principles encompass guidelines aimed at improving productive efficiency, promoting responsible practices in the use of natural resources, minimizing environmental impacts, and adopting effective production methods. Furthermore, they foster the implementation of practices beneficial both to the agricultural community and the ecosystem (Dayioglu & Turker, 2021). Thus, it is understood that sustainable development requires attention to the needs of the present without compromising the ability of future generations to meet their own demands. A sustainable community is conceived to ensure that its lifestyles, commercial activities, economy, fiscal structures, and technologies do not harm nature's capacity to sustain life (Costa & Costa, 2022).

2.2 Technologies in the Field

The field of agriculture is constantly evolving and seeking new technologies in the agricultural area (Spanaki et al., 2022). For this reason, with the potential to enable sustainable food production, the agricultural field relies on the aid of technologies and nanotechnology (Xu et al., 2021). Nanotechnology, due to nanoparticles (NPs), plays a significant role in agricultural practices. NPs prove to be efficient agents in the seed preparation phase, as carriers of agrochemicals, direct fertilizers, fungicides, and pesticides. NPs (nanoparticles) play a crucial role in the health conditions of soil and plants. However, despite their importance, they are not widely adopted in current large-scale food production processes. The efficacy of NPs still raises concerns, especially regarding biosafety and environmental impacts (Xu et al., 2021).

In contrast, the continuous advancement in technology and hardware is promoting the expansion of cyber-physical systems (CPSs) to smart environments, including indoor locators and assisted robots within the fields (Mahmud et al., 2020). These technologies represent a significant opportunity to improve agricultural processes and increase efficiency in the agricultural sector (Babenko et al., 2022). Mahmud et al. (2020) aim to study cyber-physical systems enabled for the Internet of Things, which is associated with Agtech. The Internet of Things (IoT) deals with a large volume of data and requires processing services from different applications in real-time (Mahmud et al., 2020). Thus, IoT is being adopted for the creation of smart environments in various domains. It is considered a promising technology that offers innovative solutions to modernize the agricultural sector. Therefore, the main benefit of this innovation is the ability to produce and consume services in real-time (Mahmud et al., 2020).

The implementation of IoT in agriculture is considered the ideal solution, as this area requires continuous monitoring and control. The Internet of Things (IoT) provides benefits through its innovative technologies and offers a way to enhance user perception and capability, modifying the work environment (Farooq et al., 2020). Agriculture also seeks startups that use information technology to address the balance of economic, environmental, and social efficiency to increase productivity in the field (Babenko et al., 2022). Thus, the term AgriTech emerges, signifying a solution-oriented perspective. The context of agricultural technology (AgriTech) is related to applications of artificial intelligence and to a range of data-based analytical techniques (Babenko et al., 2022).

2.3 AgriTech / Agtechs

Artificial intelligence driven AgriTech is considered relevant for agricultural operations towards smart, efficient, and sustainable farming. By incorporating technologies into agriculture, sensors, mobile devices, communication networks, drones, robotics, and artificial intelligence are used to enhance field management. These technologies represent a significant opportunity to boost business processes in agriculture and increase efficiency (Babenko et al., 2022). However, it didn’t start this way, according to Dayioglu & Turker, (2021), the field of agriculture underwent a gradual evolution, transitioning from a primitive level to an advanced level in a gradual manner. Thus, Agriculture 1.0 is considered conventional agriculture practiced in ancient times, when producers used domestic manual tools for labor and animal force-based cultivation (Dayioglu & Turker, 2021).

Agriculture 2.0 refers to the period of increased food production and reduced manual labor, where agricultural machinery was used to prepare the soil, sow, weed, irrigate, and harvest. As a result, the efficiency and productivity of the field significantly increased. Agriculture 3.0 emerged due to advancements in computing and electronics. In this era, developments provided energy savings in machinery use, water savings in irrigation, and reductions in the use of chemicals in the field (Dayioglu & Turker, 2021). In Agriculture 4.0, there is a digital transformation in the agricultural sector, where the impact of technologies is significant (Dayioglu & Turker, 2021). In this era, it is evident that agriculture can reap substantial benefits from technology, mainly through software solutions (Babenko et al., 2022).

The innovations adopted in agriculture, including sensors, mobile devices, communication networks, drones, robotics, and artificial intelligence, promote a significant shift in agricultural practices, enhancing efficiency, precision, and sustainability (Babenko et al., 2022). In this technological context, the field of Agricultural Technology (AgriTech/Agtechs) has been an object of increasing interest and research among practitioners and scholars. The increasingly deep integration of technology into agricultural practices and the rapid evolution of AgriTech are driving in-depth studies in this domain (Spanaki et al., 2022). Given this scenario, it is acknowledged that agriculture requires management strategies that integrate, process, and analyze temporal, spatial, and individual data. These strategies, when combined with other information, guide specific management decisions, aiming to enhance resource efficiency, productivity, quality, profitability, and the sustainability of agricultural production (Dayioglu & Turker, 2021).

3 Methodology

For conducting the analyses, this study employed a systematic literature review, combining bibliometric and content analysis to map and analyze the state of research on Agtechs. According to Donthu (2021), bibliometric analysis is a method that aims to rigorously investigate vast volumes of scientific data, simultaneously enabling the mapping of a certain field or scientific theme and a direction about the main emerging topics. Prado et al. (2016) explain that in this type of research, limitations can occur, such as the delimitation of terms, data collection errors, and a general overview of the field. Thus, to reduce bias, the authors developed a research framework, which we used as a model for systematic method (Table 1). Furthermore, as advocated by Iddy and Alon (2019), we used software for the analysis of bibliometric data, which is considered crucial to mitigate biases during the selection, analysis, and evaluation of articles.

In this way, the combination of bibliometric analysis with content analysis allows the analysis and identification of emerging trends and research gaps in the field of study (Gomes et al., 2018), enabling the researcher to highlight the information obtained, propose inferences and interpretations, considering the theoretical framework, or even identify new leads as a result of the theoretical dimensions that may emerge from reading the material (Minayo, 2000).

First, a preliminary analysis on the topic was conducted, which revealed a growing interest by academia and the market, as well as research gaps and the need for advancements. Table 1 describes the systematic method used, consisting of six macro stages (steps), as well as the procedures carried out in each of these stages, which are described below.

Table 1

Research framework proposed for the review articles

	Stage	Procedure	Description
1	**Operationalization of research**	**1.1**	Delimit the research objectives
		1.2	Choice of scientific bases or journals
		1.3	Delimitation of terms representing the field
2	**Search procedures (filters)**	**2.1**	Define search terms to find references
		2.2	Define the boolean operators for an advanced search
		2.3	Set other search filters for refinement
3	**Selection procedures (database)**	**3.1**	Download references for EndNote software
		3.2	Download references in spreadsheet format
		3.3	Download references for: *CiteSpace, Bibliometrix e VOSviewer* Softwares
		3.4	Organization of references in EndNote
		3.5	Organization of analysis matrices in electronic spreadsheet
		3.6	Importing data into analysis software (CiteSpace, Bibliometrix and VOSviewer)
4	**Analysis of the research front**	**4.1**	Analysis of the volume of publications and temporal trends
		4.2	Analysis of the most cited articles
		4.3	Analysis of the countries where researchers published the most
		4.4	Analysis of the journals that published the most
		4.5	Keyword analysis and Citation Bursts
		4.6	Analysis of the emerging terms
5	**Analysis of the intellectual base**	**5.1**	Analysis of the cocitation network of the most cited articles and Citation Bursts
		5.2	Analysis of the network of cocitations of the most cited authors
6	**Future studies agenda**	**6.1**	Reading the intellectual base year 2022 articles
		6.2	Summary of the main suggestions for future studies
		6.3	Presentation and discussion of the main topics for future studies

Source: Adapted from (Prado et al., 2016).

Initially, for the operationalization of the research (stage 1), we defined as the objective of the work (procedure 1.1) the mapping of the state of research on Agtechs, as well as their evolution and future trends. Data were collected from the Scopus scientific database via Elsevier (procedure 1.2), which is considered one of the main sources of academic work citation data and widely used in bibliometric studies. According to Pranckute (2021), even with the increase of other databases, Scopus is considered one of the primary sources of publication metadata and impact indicators. Furthermore, Scopus provides the largest bibliometric database and contains metadata that can be extracted and exported for bibliometric analysis (Filser et al., 2017).

To conduct a comprehensive literature review, the terms representing the field (procedure 1.3) were defined as Agtech, sustainable development, and innovation. Subsequently, the search procedures (stage 2) were defined. The research protocol with the terms (procedure 2.1) and Boolean operators (procedure 2.2) used in the search procedure is described in Table 2, and the scope was delimited to locate references in the title, abstract, and keywords. Searches in the databases were filtered only by peer-reviewed document type: articles and reviews (procedure 2.3). As observed by (Filser et al., 2017), peer-reviewed documents are primary sources for new research findings; due to their blind review process, they ensure the usefulness and reliability of literature reviews.

The search was conducted on November 4, 2022, without restriction for the period, knowledge area, and language, as the goal of the research was to present an overview of the topic and identify the research trajectory in this field of study. Thus, after refining the data, 637 documents were selected for data processing.

Table 2

Search string used for the bibliometric analysis

Database	Search Terms/Filters	Results
Scopus	TITLE-ABS-KEY (agritech) or (agri-tech) or (agtech) or (agricultural_startup) or (ag-focused_startup) AND TITLE-ABS-KEY (cleaner_production) or (sustainability-oriented) or (sustainab*) or (ecology) AND (EXCLUDE (DOCTYPE,"ch") OR EXCLUDE (DOCTYPE,"cp") OR EXCLUDE (DOCTYPE,"bk") OR EXCLUDE (DOCTYPE,"cr") OR EXCLUDE (DOCTYPE,"no"))	637

Source: Prepared by the authors

After conducting the searches, the metadata of the documents were selected and imported (stage 3). First, the metadata was downloaded to the EndNote reference manager (procedure 3.1), in electronic spreadsheet format (procedure 3.2), and for bibliometric software (procedure 3.3). Subsequently, references were organized in EndNote (procedure 3.4) and matrices for analyses in electronic spreadsheets were organized and tabulated (procedure 3.5). Finally, data were imported into bibliometric analysis software: CiteSpace (Chen, 2004, 2006), Bibliometrix (Aria & Cuccurullo, 2017), and VOSviewer (EcK & Waltman, 2014) (procedure 3.6).

For conducting the analysis of the research front (stage 4) and the intellectual base (stage 5), data were managed and developed using EndNote, Microsoft Excel, CiteSpace (Chen, 2004, 2006), Bibliometrix (Aria & Cuccurullo, 2017), and VOSviewer (EcK & Waltman, 2014). In addition to the analysis using software, tables and graphs were generated to demonstrate the study's results.

The Analysis of the Research Front (stage 4) aimed to analyze the existing literature on the topic in terms of its contributions to the field of research. This analysis allows identifying the state of the art, as well as detecting and analyzing trends and changes related to a research front over time (Chen, 2006). To identify the Intellectual Base (stage 5), analyses of the co-citation networks of the sample were carried out. Chen (2006) defines that the intellectual base of a research front corresponds to its citation paths in the scientific literature. Thus, what is cited by the research front composes its intellectual base.

Finally, the Agenda for Future Studies was presented (stage 6). To identify trends for future research, sample articles published in 2022 were analyzed, and the study gaps pointed out by the authors were synthesized. We chose to limit the analysis to articles published in 2022, as most proposals for future studies may not have been developed at the time of analysis. The final sample for content analysis consisted of 38 articles, which supported the construction of a table with the categories resulting from the main indications of future study trends.

Results of the Bibliometric Analysis and Discussion

This section intends to describe the results obtained from the analyses of the Research Front (stage 4) and the intellectual base (stage 5).

4 Analysis of the Research Front

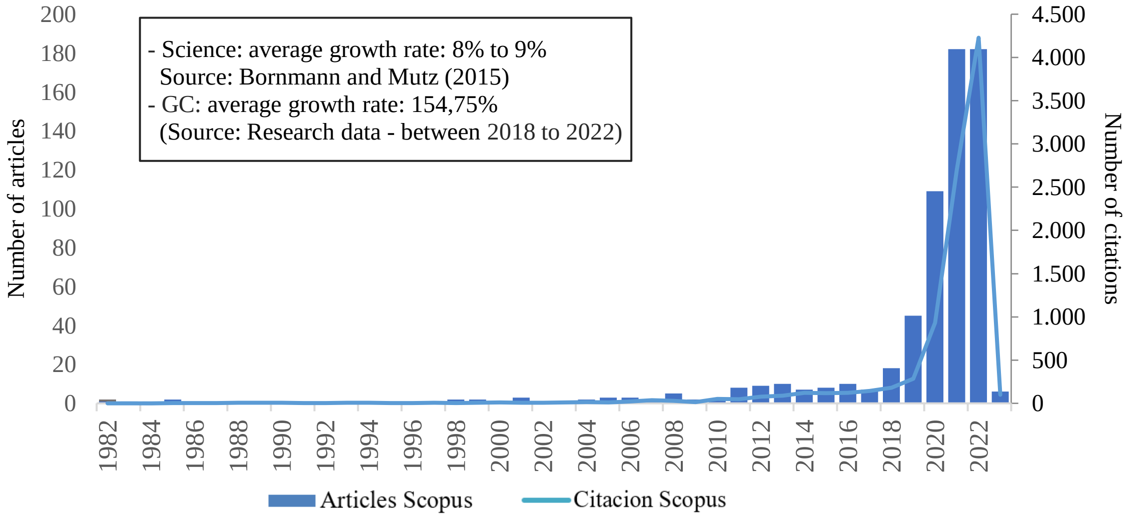
4.1 Analysis of the volume of publications and temporal trends

Figure 1 shows the distribution of the 637 sample publications on Agtechs over the years, as well as the number of citations received in the Scopus database. The analysis period was not delimited, considering the proposal of the article, which is to map the panorama of scientific contribution and identify trends for future studies in the research field.

The initial discussions of the theme, considering the data sample, started in 1982, with a very reduced volume of publications. It is observed that in the period between 1982 and 2010, both publications and citations did not show growth, remaining constant. During this period, 37 articles were published, representing 5.85% of the sample. The period between 2011 and 2017 concentrated 9.34% of the sample, with a total of 59 publications. However, between 2018 and 2022, 536 works were published, representing 84.81% of the sample. Thus, as evidenced in Figure 1, from 2018 there was a significant increase in the number of publications and in the volume of citations of the articles in the sample, demonstrating the increased relevance of this research area in the last five years and the growth trend for the coming years. Although 2023 shows an apparent decrease, it is emphasized that the search was conducted in November 2022, and therefore does not represent the total of works published in 2023.

Figure 1

Number of Articles and Citations per Year (Scopus)



Source: Prepared by the authors

Citations in the Scopus database also showed similar growth. Between 1982 and 2010, the articles received 280 citations, representing 3.00% of the total citations. Between 2011 and 2017, the number of citations accounted for 7.71% of the total, with 719 citations. Similarly, to the number of published articles, citations received by articles between 2018 and 2022 grew exponentially and represented 89.29% of the sample, with 8,327 citations. In this scenario, the data presented in Figure 1 indicate a growing interest in the theme.

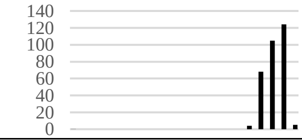
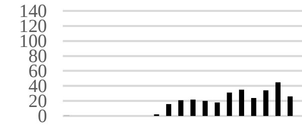
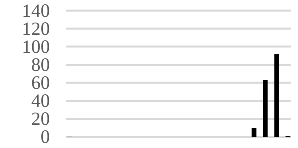
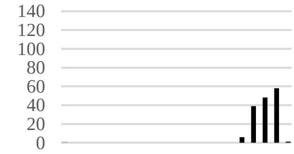
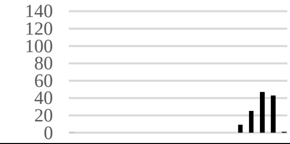
It is highlighted that the average annual growth rate between 2018 and 2022 was 154.75%, as shown in Figure 1. According to studies conducted by Bornann and Mutz (2015), the average rate of scientific growth is approximately 8 to 9% per year. It can be inferred that the behavior of the growth in publications follows the discussions and global concerns regarding sustainable development, which have intensified in recent years, as well as the evolution of information technologies. The development of AgTechs aligns significantly with the United Nations' 2030 Agenda. This agenda presents 17 Sustainable Development Goals (SDGs) aimed at addressing some of the world's most pressing issues, including hunger and environmental sustainability (United Nations, 2015). SDG 2 targets to eradicate hunger, achieve food security, improve nutrition, and promote sustainable agriculture. Also notable is SDG 12, which focuses on ensuring sustainable production and consumption patterns. AgTechs contribute directly to these goals by creating technologies that increase the efficiency and sustainability of agricultural production.

4.2 Analysis of the most cited articles

Table 1 presents the 10 most cited articles from the sample, the total number of citations, and the average number of citations per year in the Scopus database. The data analysis shows that the 10 works with the highest volume of citations represent 1.57% of the sample and accumulate 1,944 citations. The total number of citations from the 638 articles in the sample amounts to 9,424 citations. Thus, 1.57% of the sample accounts for 20.63% of the total citations in Scopus.

Table 1

Most cited articles in the Scopus database

Article title	Authors	Journals (ISSN)	Total Citation	Average per year	Sparkline - Total citations
			Scopus		2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk	Ayaz *et al.* (2019)	IEEE Access (21693536)	310	7,75	
Opportunities and challenges for nanotechnology in the agri-tech revolution	Lowry *et al.* (2019)	Nature Nanotechnology (17483387)	306	7,65	
The genus Phomopsis: Biology, applications, species concepts and names of common phytopathogens	Udayanga *et al.* (2011)	Fungal Diversity (15602745)	294	7,35	
Agriculture 4.0: Broadening Responsible Innovation in an Era of Smart Farming	Rose; Chilvers (2018)	Frontiers in Sustainable Food Systems (2571581X)	196	4,9	
Nano-Biotechnology in Agriculture: Use of Nanomaterials to Promote Plant Growth and Stress Tolerance	Zhao *et al.* (2020)	Journal of Agricultural and Food Chemistry (218561)	166	4,15	
Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?	Klerkx; Rose (2020)	Global Food Security (22119124)	156	3,9	
Nanoparticle Size and Coating Chemistry Control Foliar Uptake Pathways, Translocation, and Leaf-to-Rhizosphere Transport in Wheat	Avellan *et al.* (2019)	ACS Nano (19360851)	152	3,8	
Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities	Rotz *et al.* (2019)	Journal of Rural Studies (7430167)	125	3,125	
A review of microwave synthesis of zinc oxide nanomaterials: Reactants, process parameters and morphoslogies	Wojnarowicz *et al.* (2020)	Nanomaterials (20794991)	121	3,025	
Opportunities and Challenges for Big Data in Agricultural and Environmental Analysis	Weersink *et al.* (2018)	Annual Review of Resource Economics (19411340)	118	2,95	

Source: Prepared by the authors

The most cited article in the sample was "Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk" by Ayaz et al. (2019). The article discusses trends in research in agriculture based on the Internet of Things (IoT) and how to integrate this technology with traditional agricultural techniques. The second most cited article was "Opportunities and challenges for nanotechnology in the agri-tech Revolution" by Lowry, Avellan, and Gilbertson (2019), which addresses the use of nanotechnology and nanomaterials to improve the efficiency of input use, reduce environmental impacts, and boost the agro-technological revolution.

Following this, the article by Udayanga et al. (2011), titled "The genus Phomopsis: biology, applications, species concepts and names of common phytopathogens," is highlighted. The article provides an overview of Phomopsis taxonomy, for the redefinition of the species, which the authors consider fundamental to understanding the epidemiology of diseases and enabling the development of more effective control measures for plant diseases.

Rose and Chilvers (2018) published the fourth most cited article "Agriculture 4.0: Broadening Responsible Innovation in an Era of Smart Farming." The authors advocate the development of a broader framework for responsible innovation in sustainable agriculture, arguing that, while smart farming may offer great benefits for sustainable agriculture, the fourth agrotechnological revolution also presents environmental, ethical, and social risks. Zhao et al. (2020) conducted a study on the application of Nano-Biotechnology in sustainable agriculture and how its use can improve plant performance and stress tolerance.

Klerkx and Rose (2020) reflect on the inclusion and exclusion of Agriculture 4.0 technologies and how they relate to the transition to more responsible agricultural and food systems. Avellan et al. (2019) conducted a study on the properties of nanoparticles and their influence on interactions with plant leaves. Rotz et al. (2019) used the lens of social justice to outline trends observed in agricultural production, technology, and labor, in the Canadian context and the development of more equitable and inclusive Agtech.

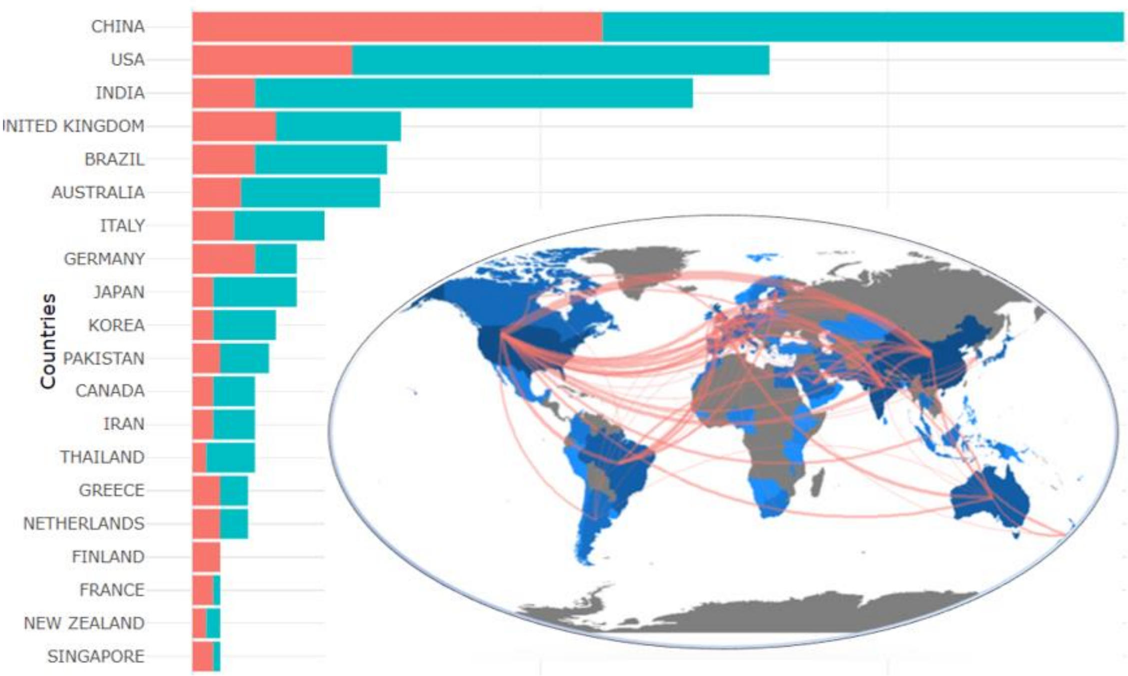
Wojnarowicz et al. (2020) conducted a study to discuss the state of research in relation to microwave synthesis of Zinc Oxide Nanomaterials, both adopted and not adopted. The tenth most cited article in the sample was "Opportunities and Challenges for Big Data in Agricultural and Environmental Analysis" by Weersink et al. (2018), which examines the state of the art regarding the challenges and opportunities arising from the development of Big Data and the political issues involved.

4.3 Analysis of the countries where researchers have published the most

Figure 2 compiles two main elements of information: (I) The bar chart shows the articles produced in coauthorship with other countries (Multiple Country Publications - MCP, represented in orange) and the articles produced exclusively by authors from their own country (Single Country Publications - SCP, represented in green).

Figure 2

Analysis of the influence and relevance of countries



Source: Prepared by the authors using the Bibliometrix software and the Scopus database

In Table 3, below, this information is detailed in relation to the five countries with the highest volume of publications.

China stands out with the highest volume of published articles (134 publications), of which 75 articles were produced within the country, representing 55.97% of the total, and 59 articles were produced in co-authorship with other countries, representing 44.03% of the total. Brazil ranked fifth among the others, producing a total of 28 articles, of which 32.14% were produced cooperatively with other countries (9 articles) and 67.86% were produced solely by Brazilian authors (19 articles).

Table 3

Countries with the highest number of publications

Countries	Articles	Frequency	SCP	MCP	MCP_Ration
China	134	0.23592	75	59	0.440
Estados Unidos	83	0.14613	60	23	0.277
Índia	72	0.12676	63	9	0.125
Reino Unido	30	0.05282	18	12	0.400
Brasil	28	0.04930	19	9	0.321

Source: Prepared by the authors using the Bibliometrix software and the Scopus database

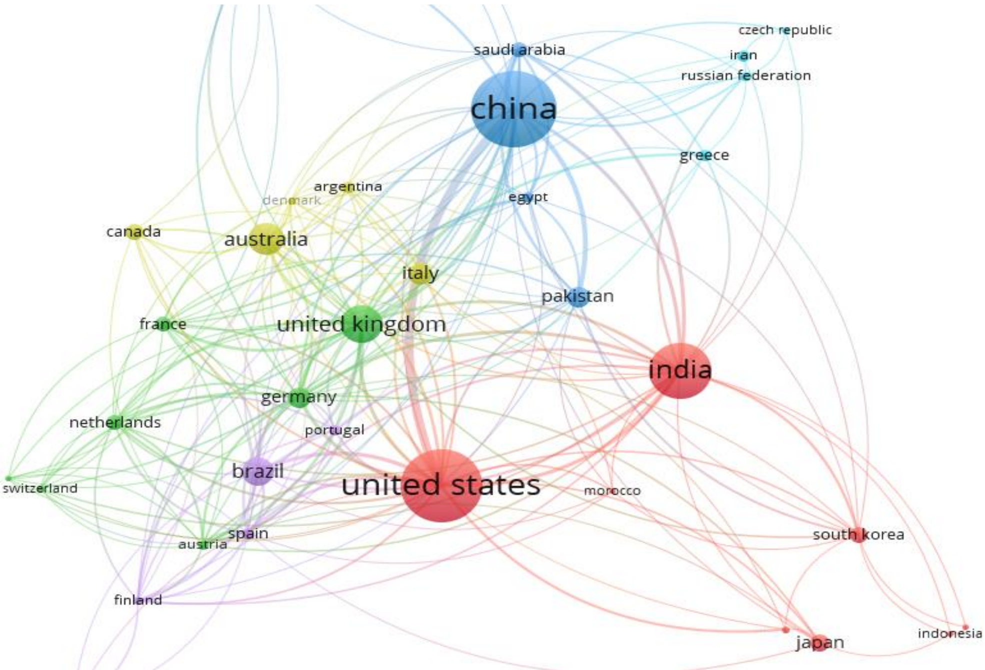
Moreover, Table 3 sheds light on the issue of international integration of countries, that is, the representation of the expansion of international cooperation and the dissemination of scientific production. Among the five countries, China, the United Kingdom, and Brazil show good international integration, considering the percentage of articles in co-authorship with other countries (MCP_Ratio).

The world map demonstrates the flow of collaborative production between countries, as well as their geographical distribution. The figure indicates a concentration of research in China, the United States, India, the United Kingdom, and Brazil. China has the largest volume of co-production with other countries, among which we can highlight: the United States (39), Pakistan (12), and Saudi Arabia (8). The United States mainly has co-authorship of production with: Brazil (9), Germany (8), and India (8). In the case of India, Germany (6), Saudi Arabia (6), and the United Kingdom (6) stand out. The main countries with which the United Kingdom has co-authorship are: Australia (7), France (6), and Germany (5). Finally, regarding Brazil, co-authorship with the United Kingdom (6), Finland (5), and Spain (4) is evident.

Additionally, Figure 3 presents the network of the most cited countries.

Figure 3

Network of countries with the highest number of citations



Source: Prepared by the authors using the VOSviewer software and the Scopus database

The United States appears in first place, with 2090 citations, China in second place, with 1459 citations, the United Kingdom in third place with 625 citations, India in fourth place with 551, and Brazil in fifth place, with 486 citations.

4.4 Analysis of the journals that have published the most works

Table 2 presents the frequency and percentage of total publications on the topic in the journals from the Scopus database. The analysis shows that of all the collected articles, 10 journals are responsible for 30% of all articles in the sample, among them Environmental Science Nano, with 26 published articles.

Table 2

Journals that publish the most works: Scopus database

Journals	Frequency		ISSN	Impact factor (2021)	Citation
	N	%		SJR	Scopus
Environmental Science Nano	26	6,55 %	20518153	1.591	168
Sustainability Switzerland	16	4,03 %	20711050	0.664	126
Science Of The Total Environment	12	3,02 %	489697	1.806	131
Environmental Science And Technology	11	2,77 %	0013-936X	2.635	182
ACS Nano	10	2,52 %	19360851	4.611	257
Environmental Pollution	9	2,27 %	2697491	1.954	48
Frontiers In Plant Science	8	2,02 %	1664-462X	1.359	64
Journal Of Agricultural And Food Chemistry	8	2,02 %	218561	1.018	261
ACS Agricultural Science And Technology	7	1,76 %	26921952		20
Journal Of Hazardous Materials	7	1,76 %	3043894	1.991	81
Nanoimpact	7	1,76 %	24520748	0.91	63

Source: Prepared by the authors using the Scopus database

4.5 Analysis of keywords and citation bursts

The keyword analysis identifies the most frequently occurring terms in the selected sample. According to the sample data, represented in Figure 4, 'Agriculture' and 'Nanoparticle' were the most frequent terms (98 times). Following this, we highlight the following words and their respective frequencies: 'Article' (89), 'Nonhuman' (88), 'Nanotechnology' (52), 'Soil' (51), 'Controlled study' (51), 'Agricultural Robot' (48), 'Crop' (43), 'Nanomaterial' (43), and 'Metabolism' (41).

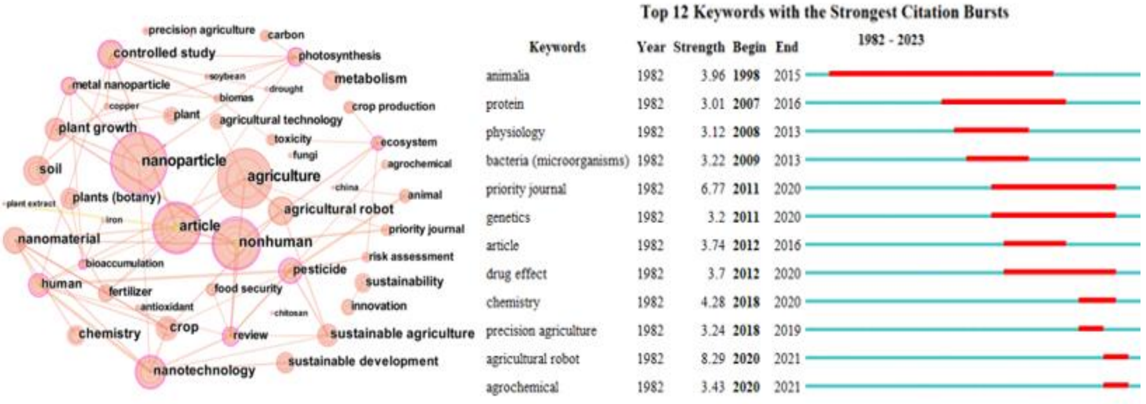
Figure 4 also highlights the explosion of the 10 references with the highest burst of citations. Citation Burst demonstrates the degree of attention given by the scientific community to these terms, indicating an active area of research. The most discussed terms in 2021 were: 'Agricultural Robot' and 'Agrochemical'. In 2020, the topics addressed were: 'Drug effect' and 'Chemistry'. 'Agricultural Robot' showed the strongest citation impact (8.29) in the period between 2020 and 2021.

The high occurrence of the term 'Agriculture' reinforces the understanding of various authors who have used this term as a theoretical basis in studies on Agtechs. The terms 'Nanoparticle', 'Nanotechnology', and 'Nanomaterial' play a significant role in agricultural practices. According to Xu et al., (2021); Lowry, Avellan, and Gilbertson (2019); and Kakani et al. (2020), automation and artificial intelligence allow initiatives to leverage and incorporate technological innovations into agribusiness. Nanotechnologies are also efficient in the seed preparation phase, in carriers of agrochemicals, direct fertilizers, fungicides, and pesticides. Thus, these technologies are important for the health conditions of soil and plants.

The keywords 'Nonhuman' and 'Agricultural Robot' refer to the most recent technologies impacting the agriculture 4.0 sector. The digital transformation in the field relates agriculture to the benefits of technology through software solutions. Technologies used in agriculture can include sensors, mobile devices, communication networks, drones, robotics, and artificial intelligence (Babenko, 2022; Dayioglu & Turker, 2021).

Figure 4

Network of keywords



Source: Prepared by the authors using the CiteSpace software and the Scopus database

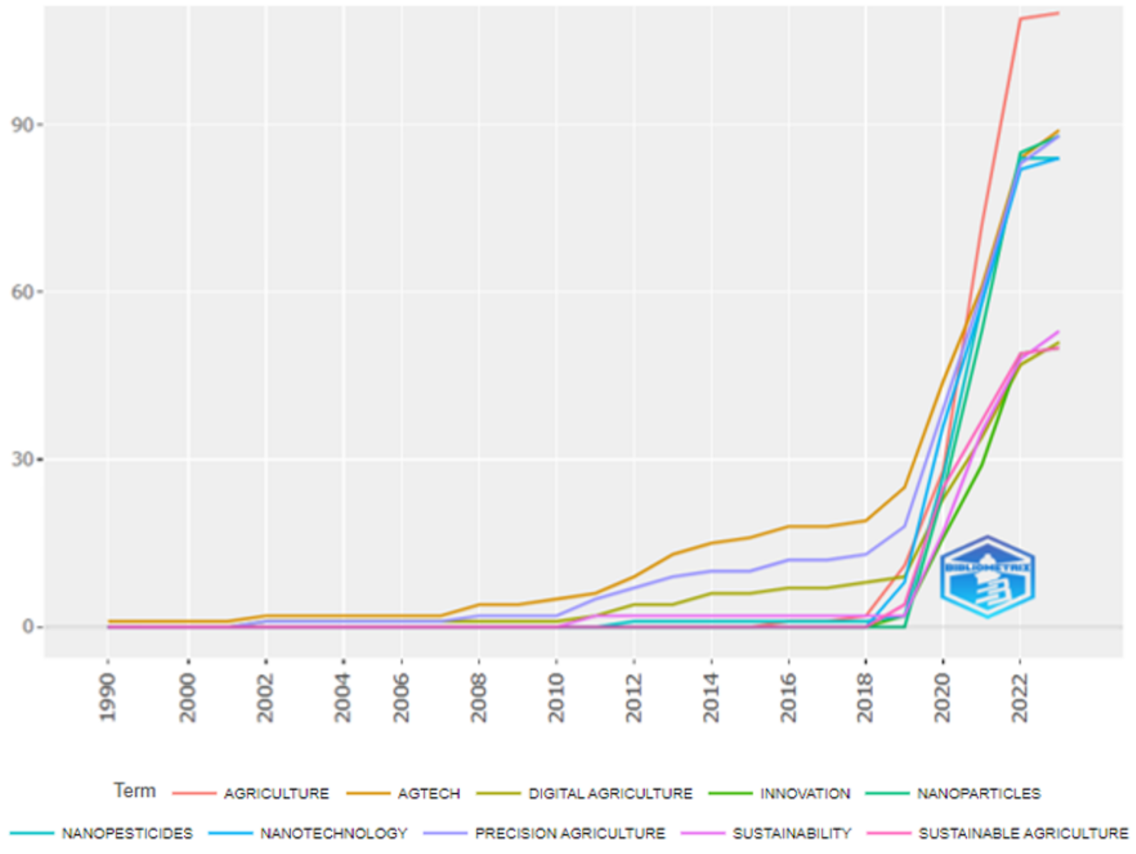
4.6 Emerging terms

Figure 5 shows the behavior of the 10 most used terms over time. Generally, in the period between 1982 and 2012, the use of these terms in publications is constant and shows no growth from 1982 to 2012. The terms start to show growth from 2012, with a significant increase from 2019 onwards.

The terms that showed the most growth were 'agriculture', 'sustainability', and 'nanotechnology'. The term 'Agtech' began to be used more frequently from 2018, showing a high rate of growth in publications from 2020. It is noticeable that the graphical behavior of the appearance of these terms is resembles the behavior of the number of publications graph, presented in Figure 1.

Figure 5

Trends of key terms over time



Source: Prepared by the authors using the Bibliometrix software and the Scopus database

5 Analysis of the Intellectual Base

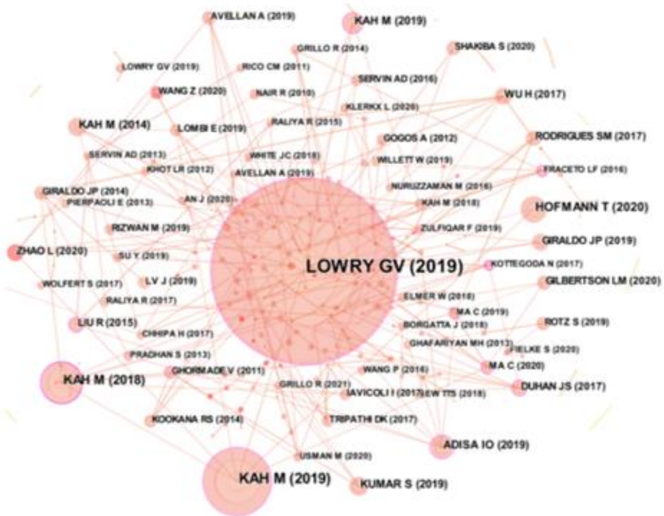
5.1 Analysis of the cocitation network of the most cited articles and citation bursts

Cocitation analysis creates a network of cited documents, which allows identifying highly referenced articles, as it is based on the count of articles that jointly cite two documents (Suominen, Seppänen & Dedehayir, 2019). A reference network with more than 9 citations is demonstrated in Figure 6.

Figure 6 presents the reference network of the most cited authors in the field. The work of Lowry, Avellan, and Gilbertson (2019) appears in first place, being the most cited work in the sample, demonstrating its influence in the field (175 citations). In second place in the ranking is the work of Kah, Tufenkji, and White (2019), with 65 citations. The work of Kah et al. (2018) appears in third position with 39 citations. The next work in the ranking is by Hofmann et al. (2020) with 24 citations.

Figure 6

Analysis of cocitation network of the most cited articles and citation bursts



Top 12 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	1982 - 2023
Kah M, 2019	2019	3.84	**2020**	2021	
Lowry GV, 2019	2019	2.68	**2020**	2021	
Servin AD, 2016	2016	2.38	**2020**	2021	
Kah M, 2018	2018	2.38	**2020**	2021	
Ma C, 2019	2019	1.78	**2020**	2021	
Kottegoda N, 2017	2017	1.78	**2020**	2021	
Hofmann T, 2020	2020	4.09	**2021**	2023	
Kumar S, 2019	2019	2.88	**2021**	2023	
Gilbertson LM, 2020	2020	2.03	**2021**	2023	
Shakiba S, 2020	2020	1.86	**2021**	2023	
Zulfiqar F, 2019	2019	1.69	**2021**	2023	
Ma C, 2020	2020	1.69	**2021**	2023	

Source: Prepared by the authors using the CiteSpace software and the Scopus database

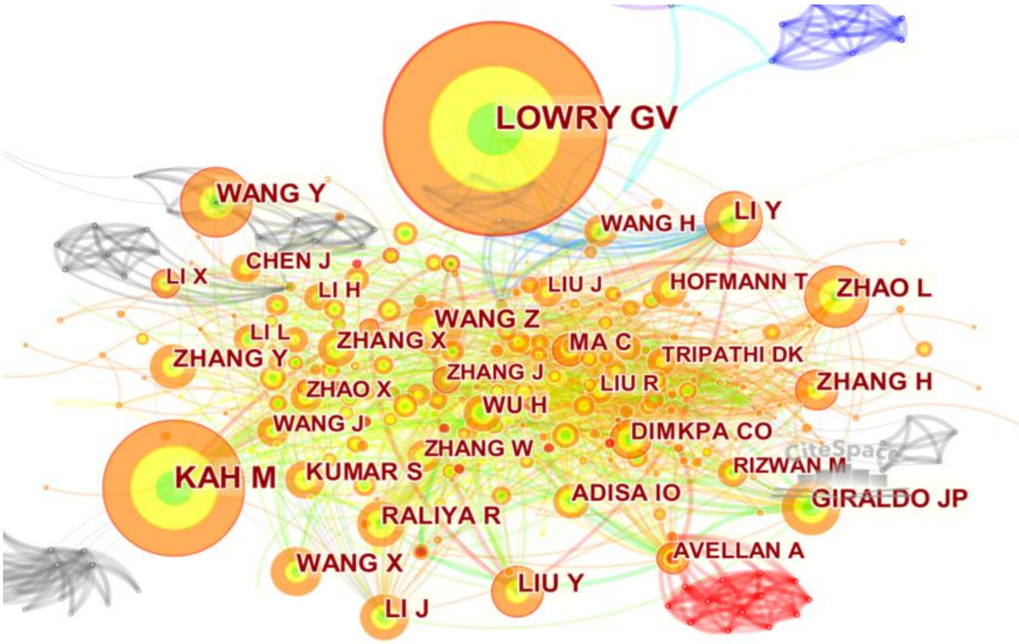
Figure 6 also presents the 10 references with the largest citation bursts and their respective periods. The article by Hofmann et al. (2020), titled "Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture," shows the highest citation strength (4.09), thus exerting a significant influence on the theme. Following this, we can highlight the following works: Kah, Tufenkji, and White (2019) "Nano-enabled strategies to enhance crop nutrition and protection," with a citation strength of 3.84; Kumar et al. (2019) "Nano-based smart pesticide formulations: Emerging opportunities for agriculture," with a citation strength of 2.88, among others.

5.2 Analysis of the cocitation network of the most cited authors

Figure 7 illustrates the cocitation network of the most cited authors with a frequency exceeding 30 citations. The most cited authors included: Lowry, G. V. (229), Kah, M. (147), Wang, Y. (80), Zhao, L. (67), Li, Y. (63), Wang, Z. (62), Giraldo, J. P. (61), Liu, Y. (61), and Wang, X. (59). Lowry's articles address the use of nanotechnology and nanomaterials to enhance the efficiency of input utilization, reduce environmental impacts, and drive the agrotechnological revolution. Melaine Kah's work discusses current technologies and processes in the field.

Figure 7

Cocitation network of the most cited authors

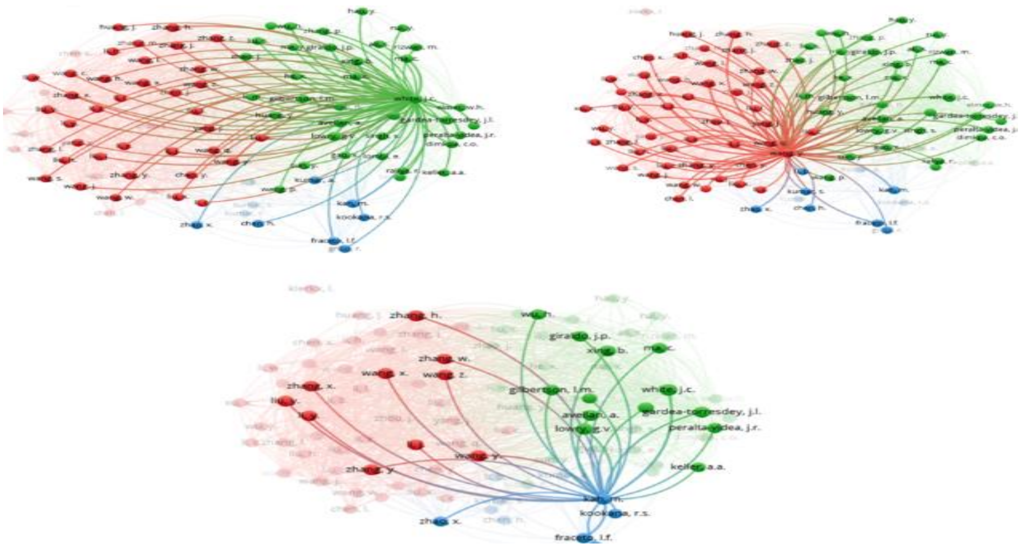


Source: Prepared by the authors using the CiteSpace software and the Scopus database

The figure 8 divides the network into three clusters. In the green cluster, the author with the highest linkage strength (49497) is White, J. C. The author with the highest linkage strength (48746) in the red cluster is Wang, Y. In the blue cluster, Kah, M. is the author with the highest linkage strength (20538).

Figure 8

Cocitation network of the most cited authors divided by cluster



Source: Prepared by the authors using the VOSviewer software and the Scopus database

6 Analysis of future studies

To evaluate the future research trends, the articles published in the Scopus database in 2022 were analyzed in relation to the gaps in the scientific literature identified by the respective authors. We limited this analysis to articles published in 2022, as research in this field is continually evolving and may not yet be fully reflected in the current literature. By delimiting the analysis to this period, we aimed to capture the state of the art in research and identify emerging trends requiring further investigation. Initially, 188 articles published in the Scopus database in 2022 were examined for alignment with the research scope. In addition to identifying suggestions for future research, each article was assessed based on its thematic relevance to the research objectives and its methodological rigor. We chose to use the manual content analysis method due to the sample size, which allowed for greater flexibility and interaction with the data, providing rich and detailed insights into emerging trends and gaps in the scientific literature.

Following a preliminary review, aimed at screening articles aligned with the research proposal, 66 works were selected for a more in-depth analysis. Of these, 10 articles could not be located, and 18 did not offer suggestions for future studies, resulting in a final sample of 38 articles that underwent a more rigorous analysis.

Thus, based on the analysis of the articles that comprised the final sample, we mapped, categorized, and grouped all suggestions into five categories that guide the main trends identified for future studies, as outlined in Table 3: (I) Agricultural Technological Radar, (II) Sustainability, (III) Consequences of Agriculture 4.0, (IV) Rural Development, and (V) Organizational Arrangement of Agtechs.

In relation to the agricultural technology radar, it is proposed that future studies evaluate the creation, development, or optimization of technologies in order to identify their economic, environmental, and social impact. Patent and/or intellectual property studies are also interesting, as they can map the flow of new technology deposits, examine how the transfer of technology related to agriculture 4.0 occurs, and investigate which intellectual properties are being created by Agtechs.

In the sustainability category, it is possible to study the creation of indicators or their monitoring, both for Agtechs and agricultural innovation ecosystems. In addition, empirical studies with Agtechs and rural properties can trace how the sustainable value chain is established.

Table 3

Trends of future studies and the authors who have suggested them

Categories	Subcategories	Authors by subcategory
Agricultural Technological Radar	Agricultural data rights and utilization Optimization of existing technologies Mapping Agtech technologies	Atik (2022), Dineva and Atanasova (2022), Farooq et al. (2022a), Farooq et al. (2022b), Fountas et al. (2022), Jacquet et al. (2022), Maximo et al. (2022), Mendes et al. (2022), Mohapatra and Rath (2022), Munir et al. (2022), Muthukrishnan (2022), Schulz et al. (2021), Spanaki et al. (2021), Sun et al. (2022).
Sustainability	Sustainability indicators Green entrepreneurship Sustainable development	Aliabadi et al. (2022), Farooq et al. (2022b), Fischer et al. (2022), Frare and Beuren (2021), Guzmán; Dominguez (2022), Jacquet et al. (2022), Liu et al. (2022), MacPherson et al. (2022), Manning et al. (2022), Maximo et al. (2022), Mendes et al. (2022), Paget et al. (2022), Parkes et al. (2022), Puntel et al. (2022), Silveira et al. (2023), Spanaki et al. (2021).
Consequences of Agriculture 4.0	Human factor vs. digital factor Responsible innovation	Barrett and Rose (2022), Ding et al. (2022), Espig et al. (2022), MacPherson et al. (2022), Mendes et al. (2022), Munir et al. (2022), Puntel et al. (2022), Shukla et al. (2022).
Rural Development	Rural social practice Public policies (rural education, extension projects, local social issues)	Espig et al. (2022), MacPherson et al. (2022), Jacquet et al. (2022), Manning et al. (2022), Puntel et al. (2022), Schulz et al. (2021), Swain et al. (2022), Zanetti et al. (2022).
Organizational Arrangement of Agtechs	Business models Institutional relationships (blockchain, trust, corporate social responsibility) Dynamic capabilities	Bertucci Ramos and Pedroso (2022), Nandi et al. (2022), Fadul-Pacheco et al. (2022), Ghezzi et al. (2020), Lew et al. (2022), Lin et al. (2020), Mendes et al. (2022), Pigola and Rezende (2022), Zanetti et al. (2022).

Source: Prepared by the authors

Regarding the consequences of agriculture 4.0, it is suggested to conduct studies that investigate the impacts of this revolution, especially on the dynamics of rural properties. Questions arise: does the arrival of technology equally affect both owners and employees? Does it affect the local community? These are some of the questions.

In the rural development category, sociological studies related to the public policy agenda in this area are recommended. In addition to studying the role of Agtechs in this context, it is crucial to understand the actions of bureaucrats, social movements, political parties, media, among others. Furthermore, it would be interesting to determine whether such policies are being developed in a bottom-up or top-down model.

Finally, in relation to the organizational and institutional arrangement of Agtechs, organizational studies are suggested to structure the intra and interorganizational relationships of Agtechs and to establish how their relationships occur in networks, conglomerates, and innovation ecosystems.

5 Conclusion

The purpose of this article was to map scientific production and identify future research trends in Agtechs. Through the presented methodological procedures, it was observed that Agtechs are essential in guiding the agricultural revolution toward global sustainable growth.

The bibliometric study revealed that Agtechs and their related topics have been extensively researched recently, especially in the last four years. This demonstrates the relevance and influence of the subject, both from a sustainability perspective and due to the emergence of disruptive new technologies. The most cited article pertains to trends in research in the field of agriculture based on the Internet of Things (IoT), discussing the importance of integrating this technology with traditional agricultural techniques. The countries with the highest research output were China, the United States, India, the United Kingdom, and Brazil.

The research aimed to contribute to the agenda of future studies by suggesting five categories: (I) Agricultural Technological Radar, (II) Sustainability, (III) Consequences of Agriculture 4.0, (IV) Rural Development, and (V) Organizational Arrangement of Agtechs. These categories provide guidance for various research opportunities for scholars in the fields of social sciences, exact sciences and earth sciences, engineering, and agricultural sciences.

A limitation of this study is that our results are restricted to the Scopus database. Therefore, future studies are recommended to expand their search databases, as new sources and additional records may enhance the research.

In conclusion, this article makes a scientific contribution by providing directions for future research to researchers interested in the Agtechs theme. Through bibliometric indicators, our study mapped existing publications in the field, tracked the evolution of the scientific field, identified emerging themes, and presented key trends in future studies based on suggestions from authors of recent works in the analyzed sample.

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