Journal of Agricultural Science and Technology A 15 (2025) 51-71
doi: 10.17265/2161-6256/2025.02.001

Food Safety in the Era of Digital Agriculture: A Bibliometric Study on IoT-Based Innovations

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Abstract: Roughly one-third of the food produced globally is lost or wasted at some stage along the supply chain, according to the United Nations Food and Agriculture Organization. Inefficiencies along the food value chain and in consumption have considerable environmental, economic, and social impacts, thus representing a global challenge. Digitalization in agriculture has great potential to improve efficiency, effectiveness, sustainability, resilience, and competitiveness across this sector through Internet of Things (IoT), Blockchain, sensors, data analytics and AI-based tools, leading to more targeted and precise agricultural operations and improved traceability. The EU Policy Guidelines for 2024-2029 showcase this potential by giving a key and priority role to supporting the entire food supply chain. In this research, particular attention will be given to safeguarding food safety through the use of IoT. A bibliometric analysis will be conducted on the Scopus research items (timeframe: 2012-2024). This analysis will enable us to examine the intellectual structure of this field of study and outline its main applications, as well as identify the key critical issues in its implementation. The future lines of research, as well as their academic and practical implications, will be highlighted.

Key words: IoT, food safety, smart food, food supply chain, digital agriculture, bibliometric analysis.

1. Introduction

The European Union (EU) and its member countries are committed to achieving the United Nations Sustainable Development Goal (SDG) of halving global food waste per capita at the retail and consumer levels by 2030, as well as reducing food losses along production and supply chains.

Inefficiencies along the food supply chain and in consumption have considerable environmental, economic, and social impacts. The main implications of food waste concern [1]: environmental impact, causing 16% of greenhouse gas emissions from the EU food system; economic impact, with around €132 billion lost due to food waste; and social impact, as almost 33 million people in the EU cannot afford a full meal every other day, while tons of food are wasted.

A large body of EU-level rules regulates the entire food production and processing chain within the EU, including imported and exported goods. The EU is committed to ensuring compliance with regulations on food and feed hygiene, animal and plant health, foodborne zoonoses, and the prevention of food contamination. The EU also regulates food and feed labeling. Following the COVID-19 pandemic, food safety objectives have also been expanded to include mitigating crisis-induced food insecurity. The European Commission’s Policy Guidelines for 2024-2029 highlight the agri-food sector’s strategic potential, placing particular emphasis on supporting the entire supply chain through targeted investments and innovation. These interventions involve various players such as farms, cooperatives, agri-food businesses, and small and midsize enterprises (SMEs), promoting the sector’s balanced and sustainable development [2]. The European Commission (EC), in its 2025 vision for agriculture, emphasizes innovation to boost the sector’s competitiveness, sustainability and resilience. It promotes advanced genomic techniques, digitalization, and improved agricultural data management

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to support farmers and ensure EU food security. In this context, the EU Digital Strategy for Agriculture plays a key role, through the creation of the Common European Agricultural Data Space and the adoption of digital and intelligent technologies throughout the agri-food supply chain [3].

Over the years, EC has funded many research and innovation projects (for example, H2020), and dissemination efforts to contribute to shaping the digital evolution of the agricultural sector [2]. In this context, EU efforts to integrate digitalization and digital technologies into European agriculture have proven to be highly effective. In fact, introducing digital technologies in agriculture can improve overall performance, promoting environmental sustainability, increasing productivity, and enhancing resilience. This is possible thanks to the use of solutions such as the IoT (Internet of Things), sensors, data analytics tools—including those based on artificial intelligence (AI)—and decision support systems. These technologies enable more targeted and precise agricultural practices, as well as improve traceability along the entire value chain [2].

In this research, particular attention will be given to safeguarding food safety through the use of IoT. This paper provides a comprehensive bibliometric analysis of the primary literature on how IoT can contribute to food safety, analyzing the intellectual structure of these thematic areas, considering publications up to 2024.

This paper enables us to understand the primary sources and their impact, the prominent and influential authors on this topic, and the key countries involved. This paper also offers temporal trends, mapping the evolution of research interests over time. This paper identifies the top 20 keywords and the main trends in 2023 and 2024. Starting from this, this research enables the identification of motor themes related to this topic. By applying science mapping techniques, this paper identifies the relevant studies in this domain of analysis. To identify a thematic flow, this paper identifies main thematic clusters that represent the key areas of focus in IoT applications for food safety, highlighting their role in advancing sustainable practices.

From a practical standpoint, this paper, positioned within the field of agri-food technologies and digital innovation, provides useful insights for various stakeholders, including scholars, sustainability managers, technology developers, and policymakers. It supports academic research by mapping key themes and gaps, guides sustainable innovation in food safety practices, and informs policy and technological development aligned with emerging trends in IoT applications.

Overall, this paper is structured as follows: Section 2 provides a literature review on IoT and food safety, while Section 3 describes the methodological framework. The results of the bibliometric analysis are discussed in Section 4. Section 5 identifies the relevant application areas and challenges; Section 6 presents the research limits and future research trajectories, and Section 7 concludes this manuscript.

2. Literature Review and Research Questions

IoT is one of the most significant technological innovations of the digital era, characterized by the interconnection of intelligent devices through the Internet, enabling the seamless exchange of data and automation of processes across various sectors [4, 5]. Originally introduced in the 1990s, the IoT concept has experienced exponential growth, especially with the proliferation of advanced wireless communication technologies, the increasing availability of cloud infrastructures, and the integration of Artificial Intelligence (AI), which collectively enhance the capabilities and scalability of connected systems [6].

The IoT architecture is typically organized into multiple foundational layers, each with distinct but interdependent functionalities. The first layer consists of physical devices and sensors responsible for collecting data from the environment. These are followed by the connectivity layer, which ensures reliable data transmission through communication protocols such as MQTT, CoAP, and HTTP, tailored to the specific needs of IoT applications [7, 8]. Network technologies such as Low Power Wide Area Network (LPWAN), Wi-Fi, and the more recent 5G networks enable high-speed and energy-efficient data exchange, which is crucial for the real-time operation of IoT ecosystems [9]. The data processing layer involves edge and cloud computing platforms that aggregate, filter, and analyze the collected data, supporting the application layer where insights are utilized for decision-making and process automation. Scholars emphasize that an IoT system can be effective if it addresses critical aspects such as scalability, to support a growing number of devices, and security, to prevent data breaches and unauthorized access [10].

IoT has emerged as a fundamental element of Industry 4.0, a paradigm that envisions smart manufacturing systems capable of autonomously managing complex industrial operations. Through automation, real-time monitoring, and predictive maintenance, IoT improves operational efficiency, reduces human error, and minimizes production downtime [11]. Smart sensors integrated into industrial machinery are now regularly used to collect real-time performance data. This information can be analyzed to predict equipment failures and schedule maintenance activities in advance, ultimately extending the operational lifespan of machines and reducing overall costs [12]. The integration of IoT with cloud computing and AI has significantly enhanced manufacturing capabilities, enabling the processing of large datasets for more precise forecasting, anomaly detection, and adaptive control [13]. These advancements have allowed smart factories to become more responsive to market fluctuations, capable of large-scale production customization, and more efficient in their use of resources. At the same time, they contribute to reducing waste, thus supporting broader goals related to sustainability and operational efficiency [14].

The influence of IoT, however, extends well beyond industrial applications. In the field of food safety and supply chain management, it is playing a transformative role. The use of smart sensors and IoT-enabled tracking systems allows for continuous monitoring of key parameters (such as temperature, humidity, and contamination risk) during the storage, transport, and distribution of food products [15, 16]. These technologies enhance traceability, ensuring that every stage of the supply chain is accurately recorded and verifiable, which is crucial for maintaining product quality and consumer trust [17]. Furthermore, integrating blockchain and IoT provides a secure, tamper-resistant record of food handling and transactions, which significantly improves transparency and lowers the risk of food fraud or mislabeling [18]. Enhanced traceability also facilitates quicker and more efficient recalls, enabling the rapid identification and removal of compromised products. Additionally, advanced IoT systems can include early-warning mechanisms capable of detecting biological or chemical threats in real time, thereby supporting regulatory compliance and safeguarding public health through timely intervention [19].

In sum, IoT is a critical driver of digital transformation among various industries, promoting smarter operations, data-driven decision-making, and enhancing user experiences. Its applications—from smart manufacturing to food safety—are increasingly reshaping conventional practices through real-time monitoring, data-driven insights, and increased process transparency. However, as the IoT landscape continues to develop, it becomes imperative to address critical challenges such as interoperability, data governance, and cybersecurity to realize its transformative potential on a global scale.

To further explore the development and current status of this research field, the following research questions are proposed to guide this analysis:

RQ1: What is the current state of the art in the field of IoT for food safety?

RQ2: What are the emerging IoT-based technological solutions related to food safety?

Several previous studies have contributed to mapping the intellectual structure in the research field of digital technologies applied to the agri-food sector, primarily through bibliometric analyses. Bouzembrak et al. [15] analyzed publications up to 2018, focusing on emerging technologies in food safety. Sinha et al. [20] expanded the scope by examining various technologies for traceability, not limited to IoT. Liu et al. [21] concentrated on artificial intelligence applications in food safety, also addressing related IoT aspects. Xu et al. [22] highlighted the potential of IoT within for precision agriculture. Zhang and Zuo [23] analyzed the intellectual structure of research on IoT and food safety by examining publications indexed in Web of Science up to 2022. In a similar vein, Zhu et al. [24] focused on quality and food safety management, including IoT-related studies published up to April 2024. Some studies have taken a more specific approach. For instance, Adeleke et al. [25] investigated the available literature on the use of IoT exclusively for optimizing the food fermentation process, while Luo et al. [26] collected research related to food safety within the food supply chain up to 2022. Additionally, Mohapatra et al. [27] conducted a bibliometric analysis on the applications of blockchain in the agri-food system, offering valuable insights into the integration of emerging digital technologies.

However, to the best of the author's knowledge, this is among the first attempts to provide a comprehensive analysis of the intellectual structure of the literature up to 2024, focusing specifically on IoT applications in food safety. This is where the novelty and originality of the present research lies, as it aims to fill this gap by offering an up-to-date and in-depth mapping of this evolving research area.

3. Methodology

The main objectives of this research paper are to assess the productivity of global research in this scope of analysis, examine the trends and international growth of research on this topic, and identify the main research interests and application areas.

In light of these objectives (RQ1), a bibliometric analysis was conducted to examine the existing body of literature systematically. To guide this process, the review followed the methodological framework proposed by Rowley and Slack [28], which provides a structured approach for identifying key themes within a research area and highlighting potential directions for future investigation.

This approach unfolds through five distinct phases, each described in detail in the following sections. The first phase involved selecting the most appropriate academic database for the study (see Subsection 3.1). In the second phase, the search strategy was defined through the careful formulation of keywords and search terms (see Subsection 3.2). The third phase focused on refining the dataset by applying inclusion and exclusion criteria to ensure that selected publications are relevant and of quality (see Subsection 3.3). In the fourth phase, the collected data were analyzed using bibliometric techniques (see Subsection 3.4). Finally, the fifth phase consisted of presenting and interpreting the results obtained from the analysis, which are discussed in detail in Section 4.

3.1 Database Selection

First of all, Scopus and Web of Science (WoS) were explored because they are among the most popular bibliographic databases and in order to ensure data collection from high-quality sources. According to records (journals, books and conference proceedings), more than 29,200 journals (of which more than 27,800 are peer-reviewed) are listed in Scopus. In WoS, only 21,900 are listed. Furthermore, with over 94 million publications, Scopus has 2.4 billion citations versus 2.2 billion citations listed on WoS. Given its better coverage, Scopus was chosen for data collection in this research.

3.2 Research and Data Collection Strategies

The search strategy was built around the keywords "Internet of Things" and "Food safety", aiming to capture all relevant literature at the intersection of these two fields. To ensure a comprehensive retrieval of documents, the search also included commonly used acronyms and variations of these terms. This broad approach allowed for the identification of a wide range of research contributions. The initial query returned a total of 580 documents, the vast majority of which (577 items) were published within the last 13 years, between 2012 and 2024, reflecting the growing academic interest in this area during the past decade.

3.3 Inclusion and Exclusion Criteria

Regarding the inclusion criteria, the analysis focused uniquely on peer-reviewed journal articles—both published and in press—as well as review papers, in line with the definition of certified knowledge proposed by Ramos-Rodríguez and Ruíz-Navarro [29]. This initial selection resulted in 263 research items. In keeping with this approach, other types of documents such as conference proceedings, book chapters, theses, duplicates, and non-English publications were excluded to ensure consistency and quality in the dataset. After applying these filters, the final number of documents considered for analysis was 252.

Given that the final version of this research was completed in July 2025, only articles published up to December 2024 were included to maintain a clear and relevant temporal boundary. For each of the 252 selected documents, all available metadata—including citation information, bibliographic details, abstracts, keywords, and references—were downloaded from the Scopus database for subsequent analysis.

3.4 Data Analysis Plan

The bibliometric methodology relies on the use of quantitative techniques (such as citation analysis and other bibliometric tools) to examine bibliographic data like publications and citations [30]. Two main approaches are typically employed in this type of analysis: performance analysis and science mapping.

Performance analysis focuses on evaluating the contributions of various components within a research field and is widely regarded as a cornerstone of bibliometric studies [29, 31, 32]. It is commonly used not only in bibliometric research but also in many literature reviews that do not incorporate science mapping, because it offers a structured way to assess the productivity and influence of research constituents such as authors, institutions, countries, and journals. The number of publications is generally used as a proxy for productivity, while citation counts serve as indicators of impact and influence. Additional metrics—such as *h*-index—combine both publications and citations to provide a more nuanced assessment. Although inherently descriptive, performance analysis can offer valuable insights into the role and standing of various contributors within a given field of study.

The second approach that will be carried out in this paper—science mapping—seeks to uncover the relationships among topics, disciplines, articles, journals, or authors, offering a view of the cognitive structure and evolution of a research domain over time [33-35].

Some techniques commonly employed in this approach are citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship analysis [31].

In summary, performance analysis will be conducted in order to measure the individual contributions of research components, while science mapping will be conducted in order to explore the relationships and interconnections among those components, offering a deeper understanding of the structure and development of a research field, exploring the bibliometric and intellectual landscape of a discipline [32, 35].

4. Results and Discussion

This section presents the main findings related to RQ1, offering a snapshot of the current state of the research field. In particular, this analysis will be useful to highlight the volume and evolution of scientific production over time, offering insights into both the quantity and scope of the publications analyzed.

4.1 Performance Analysis Techniques

4.1.1 Articles

The annual scientific output on this topic is shown in Fig. 1. As you can see, the earliest relevant contributions began to emerge around 2012. However, research in this area has experienced a notable acceleration starting from 2019, with a significant and sustained increase in the number of publications. The field has recorded an impressive annual growth rate of 43.3%, indicating a rapidly expanding scholarly interest in the intersection of the Internet of Things and food safety.

Table 1 presents the top 10 most influential research items within the scope of this bibliometric analysis, ranked based on total citation count (TC). The table includes key bibliometric indicators for each paper such as the total number of citations and the average citations per year (TC/Y).

Among the most cited articles, Feng et al. [36], published in the *Journal of Cleaner Production*, leads the ranking with a total of 539 citations, averaging nearly 90 citations per year. This is closely followed by Zhao et al. [37], published in *Computers in Industry*, with 511 citations. Notably, Misra et al. [38] demonstrates the highest average citations per year (103.5), reflecting its strong impact in a short time span.

Other notable contributions include papers by Brewster et al. [39] and Rateni et al. [40], both of which are foundational works published in *IEEE Communications Magazine* and *Sensors*, respectively. This table also highlights the multidisciplinary nature of this research field, with articles published in journals spanning engineering, food science, communication, and environmental studies.

These highly cited papers serve as key references in the literature and underscore the growing scholarly attention toward the application of IoT in food safety and related domains.

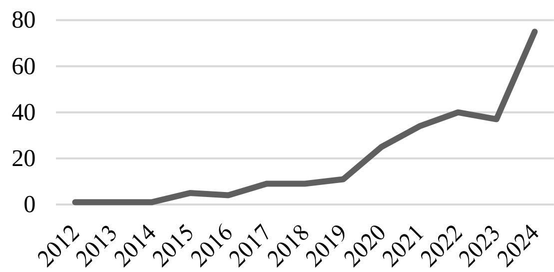

Fig. 1 Annual scientific production.

Table 1 Top 10 cited items.

References	Title	TC	TC/Y
Feng et al. [36]	Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges	539	89.83
Zhao et al. [37]	Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions	511	73.00
Misra et al. [38]	IoT, Big Data, and Artificial Intelligence in Agriculture and Food Industry	414	103.50
Brewster et al. [39]	IoT in Agriculture: Designing a Europe-Wide Large-Scale Pilot	279	31.00
Rateni et al. [40]	Smartphone-Based Food Diagnostic Technologies: A Review	252	28.00
Bouzembrak et al. [15]	Internet of Things in food safety: Literature review and a bibliometric analysis	227	32.43
Alonso et al. [41]	An intelligent Edge-IoT platform for monitoring livestock and crops in a dairy farming scenario	217	36.17
Yin et al. [42]	Recent development of fiber-optic chemical sensors and biosensors: Mechanisms, materials, micro/nano-fabrications and applications	198	24.75
Thibaud et al. [43]	Internet of Things (IoT) in high-risk Environment, Health and Safety (EHS) industries: A comprehensive review	198	24.75
Han et al. [44]	A comprehensive review of cold chain logistics for fresh agricultural products: Current status, challenges, and future trends	195	39.00

Table 2 Top 10 author impact.

Authors	Items	Citations	*h*-index	*g*-index	PY
Zhang X	5	675	5	5	2020
Liu Y	5	161	4	5	2018
Singh R	5	337	4	5	2017
Ayyasamy A	3	103	3	3	2019
Balamurugan S	4	106	3	4	2019
Huang X	3	208	3	3	2020
Khan S	3	70	3	3	2021
Kumar A	5	114	3	5	2022
Liu S	4	552	3	4	2018
Luthra S	3	114	3	3	2022

4.1.2 Authors

The analysis of author productivity is based on Lotka's Law. It reveals that out of 1,064 authors contributing to this research area, the vast majority (983 authors) have published only one article. Meanwhile, 59 authors have contributed two publications each, and only 13 authors have authored three papers on this topic. This distribution reflects a typical pattern in scientific publishing, where a small group of researchers tends to produce multiple contributions while most authors publish less frequently.

To gain deeper insights into the influence of these contributors, an author impact analysis was conducted. This analysis considers several bibliometric indicators, including the *h*-index, *g*-index, total citations, number of publications, and the year of the author's first publication in the field (PY). These metrics offer a detailed view of both the productivity and the scholarly impact of key contributors to the evolving field of IoT applications in food safety.

As you can see in Table 2, among the most impactful authors, Zhang stands out with an *h*-index of 5, a *g*-index of 5, and a total of 675 citations across five publications since 2020. Similarly, Liu and Singh both have an *h*-index of 4 and have maintained strong citation records, reflecting their significant contributions since 2018 and 2017, respectively. Other notable researchers include Ayyasamy, Balamuruga, and Huan, each with an *h*-index of 3 and publication activity beginning around 2019 and 2020.

4.1.3 Journals

The analysis of the publication items shows that, among 169 journals contributing to this research area, only eight have published at least four articles on this topic. Table 3 lists the top 10 journals ranked by publication count. Leading the list is *Sensors* (MDPI) with 17 articles, followed by *IEEE Access* (IEEE) and *Sustainability* (MDPI), each with eight publications. Other notable journals include *Trends in Food Science and Technology* and *Food Control*, both published by Elsevier, which have contributed seven and six articles, respectively.

To gain a clearer understanding of the influence and impact of these key journals, a more-in-depth bibliometric analysis was conducted. Table 3 provides a summary of the main journal-level metrics, such as the *h*-index, *g*-index, total citations, number of publications (items), and the year when each journal was first published in this area (PY). Based on these metrics, *Sensors* is the most influential source, with an *h*-index of 13 and nearly 1,000 citations across 17 publications since 2017. *IEEE Access* and *Sustainability* both demonstrate significant impact, each with an *h*-index of 6 and numerous citations. Other journals such as *Food Control*, Foods, and *Trends in Food Science and Technology* show solid contributions with notable citation records. Additionally, local source impact analysis confirms *Sensors* and *IEEE Access* as the most cited journals, underscoring their central role in disseminating research on IoT applications in food safety. This distribution highlights the concentration of research outputs within a relatively small set of journals, a finding further supported by the source clustering analysis based on Bradford's Law.

Table 3 Top 10 journals.

Journal (Publisher)	Items	Citations	*h*-index	*g*-index	PY
Sensors (MDPI)	17	978	13	17	2017
IEEE Access (IEEE)	8	410	6	8	2017
Sustainability (MDPI)	8	268	6	8	2017
Trends in Food Science and Technology (Elsevier)	7	507	5	7	2019
Food Control (Elsevier)	6	307	5	6	2015
Foods (MDPI)	6	246	5	6	2021
Applied Sciences (MDPI)	5	283	4	5	2021
Journal of Food Process Engineering (Wiley)	4	48	2	4	2021
Biosensors (MDPI)	3	14	1	3	2023
IEEE Internet of Things Journal (IEEE)	3	423	2	3	2022

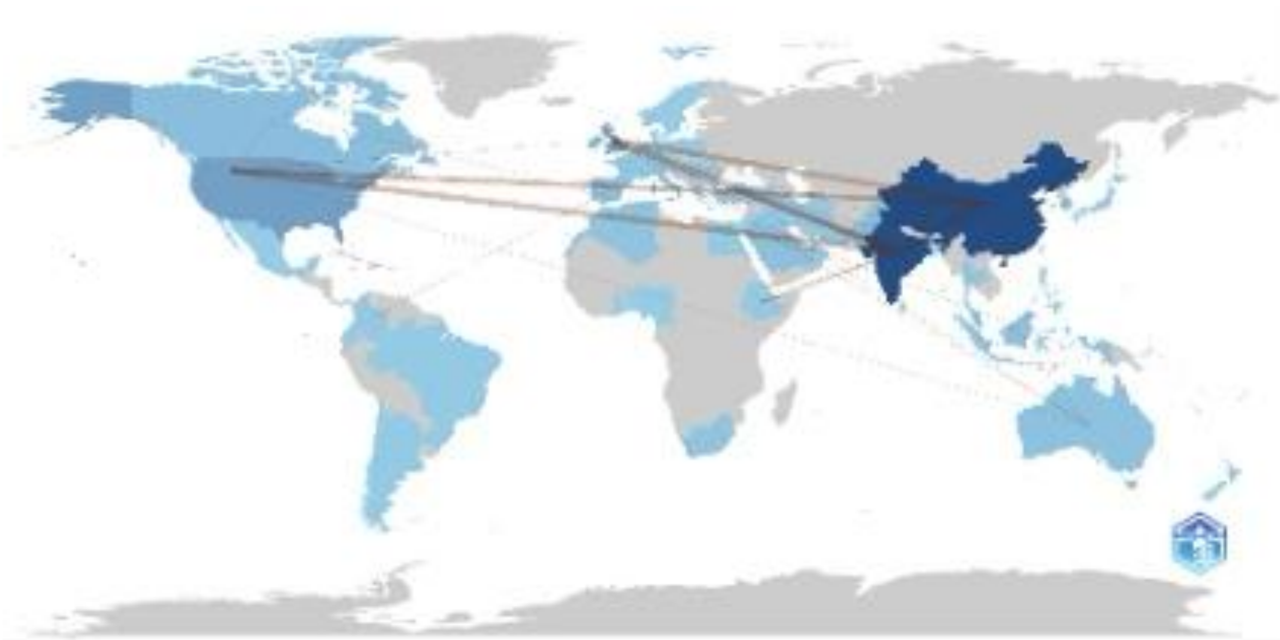

Fig. 2 Country analysis and collaboration.

4.1.4 Countries

The subsequent analysis focused on the contributions of different countries to the research field. As illustrated in Fig. 2, China leads with the highest number of research items, totaling 291 items, followed by India with 228 research items, and the United Kingdom (UK) with 63. When examining international collaborations, the strongest partnership is observed between India and the UK, with a total of eight joint research efforts, highlighting a significant collaborative link between these two countries.

4.1.5 Keywords

This study analyzed the top 20 keywords, as shown in Table 4. Unsurprisingly, "IoT" stands out as the most frequently occurring keyword, reflecting its central role in the research field. What is particularly striking is the broad interest spanning the entire food supply chain.

From a technological perspective, alongside IoT, significant attention has been given to its integration with blockchain and robotics. Several studies also explore the combination of IoT with AI, incorporating deep learning and ML techniques to enhance functionality. Additionally, cloud computing and Radio Frequency Identification technologies continue to be important components within this technological ecosystem.

Table 4 Top 20 keywords.

Keyword	Occurrences
Internet of Things	190
Food Supply Chain	110
Food Safety	106
Blockchain	64
Industry 4.0 (Robotics)	42
Deep Learning/Machine Learning	39
Food Quality	39
Accident Prevention	29
Human Activities	26
Cloud Computing	23
Traceability	19
Sustainable Development	17
Food Industries	17
Artificial Intelligence	16
Environmental Monitoring	13
Radio Frequency Identification (RFID)	10
Genetic Procedures	8
Health Risks	8
Precision Agriculture	8
Biosensing Techniques	7

Regarding applications and objectives, key themes include food safety and quality assurance, as well as the prevention of accidents and health risks. Noteworthy areas of application also encompass traceability, environmental monitoring, precision agriculture, genetic procedures, and biosensing techniques, underscoring the diverse potential of IoT and related technologies in transforming the food sector.

The thematic map analysis (Fig. 3) was performed on 250 keywords, selecting those with a minimum occurrence of five across nearly one thousand documents. This analysis identifies 13 thematic clusters, with each circle's size representing the number of associated keywords [31]. These clusters are assessed based on two primary axes: centrality and density. Centrality reflects the level of interaction between a cluster and others in the research landscape, serving as a measure of the theme's relevance and influence [31, 45]. Instead, density indicates the internal consistency and maturity of the cluster, offering insight into how developed and self-contained a topic is over time [31, 45].

The resulting strategic diagram is split into four quadrants, each representing a different thematic area. In the upper-right quadrant, "Motor Themes" are located, representing themes that are highly developed and strongly connected to the broader research network. These encompass well-established and influential topics such as monitoring, food preservation, biosensors, and food quality assurance. The lower-right quadrant contains "Basic Themes", which are marked by high centrality but lower density. This suggests they are crucial but still developing. Noteworthy examples here include IoT, Blockchain, and Food Safety topics that are central to current discourse but continue to evolve as technological innovations emerge in the agri-food sector.

In the upper-left quadrant, there are "Niche Themes", which show strong internal growth but limited connections to other clusters. Topics such as privacy and security fall into this category, indicating a high level of specialization with a narrower scope of influence. Finally, the lower-left quadrant includes "Emerging or Declining Themes", marked by low centrality and density. These represent areas that may be at an early research stage or gradually becoming less significant in the field.

Overall, this map provides valuable insights into the structure and trajectory of research on IoT applications in food safety, highlighting both well-known topics and areas with high potential for future research.

4.1.6 Three-Field Plot

This analysis (Fig. 4) was conducted using three key parameters: the author's country, keywords, and journals. In this Sankey diagram-based analysis, the size of each rectangle is proportional to the number of occurrences, illustrating the flow and connections among these elements [46].

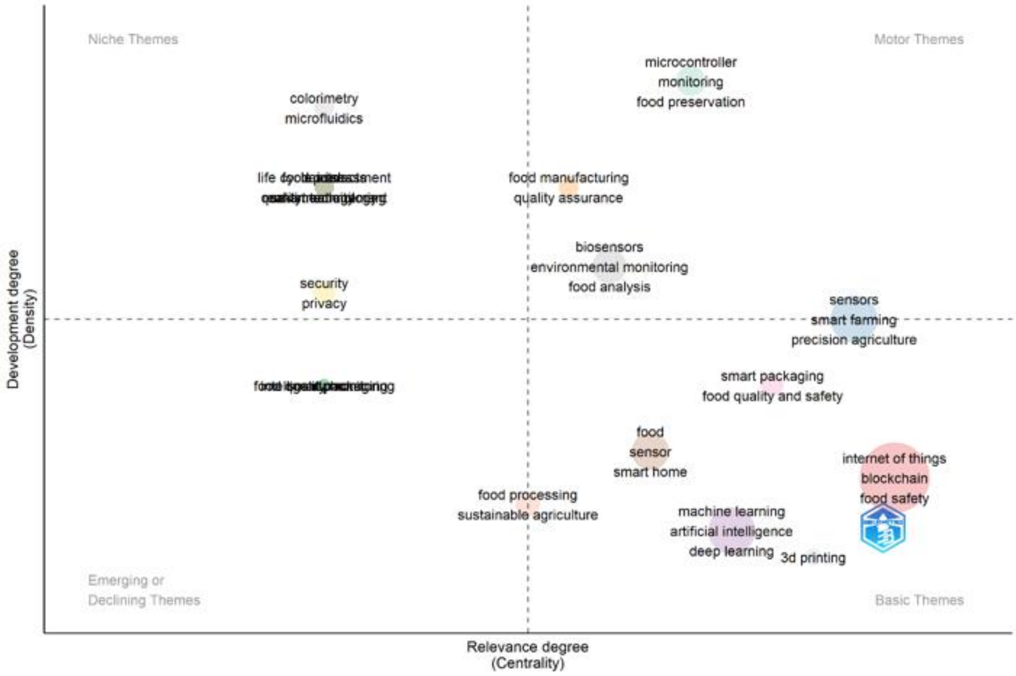

Fig. 3 Thematic map.

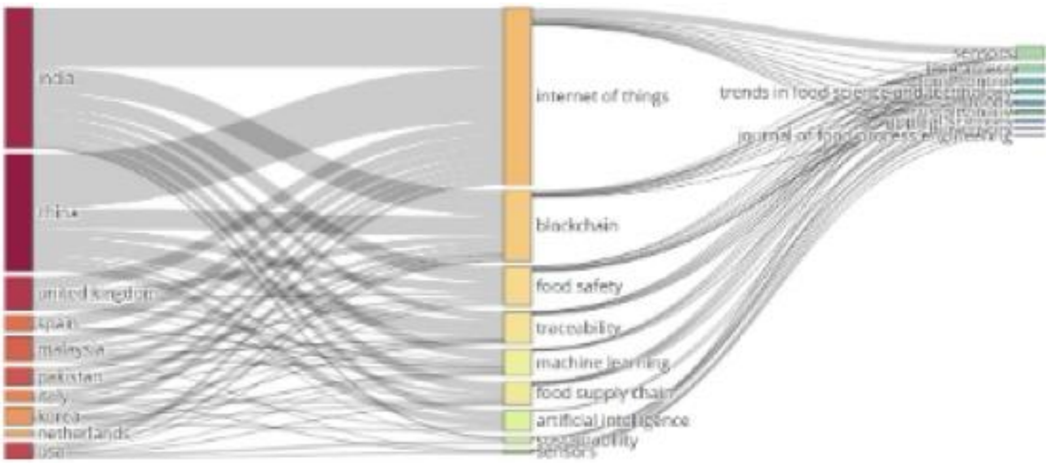

Fig. 4 Three-field plot.

The rectangles on the left represent the countries of affiliation of the authors. India and China are the countries with the highest number of research items, dominating the research in the fields represented in the graph. The United Kingdom, Spain, Malaysia, Pakistan, Italy, Korea, the Netherlands and the USA contribute to a lesser but significant extent. It is noticeable that the research on these topics is not exclusive to a single country, but is well distributed among several nations. However, Western countries such as the United States and Italy have a smaller presence than India and China.

In the middle, we find the keywords (main themes) covered in the research items. The breadth of connections between countries and these themes indicates how much a given country contributes to a specific area. IoT is the most connected topic, indicating a strong global interest in the use of IoT in the food and agricultural sector. Food safety is considered as an essential element to ensure quality and safety in the agri-food sector. Sensors are proposed to monitor food quality and product safety. Traceability is also important for monitoring the food supply chain and fighting food fraud. Blockchain is proposed as a tool for food traceability and safety, showing how it can contribute to the improvement of the food supply chain, understood as the study of logistics and distribution in the food sector. New technologies such as Machine Learning (ML) and Artificial Intelligence are investigated as tools for quality control and data analysis. Among these topics, we also see sustainability, which is an emerging theme linked to the reduction of the environmental impact of the food supply chain.

On the right, we find the main scientific journals in which these studies are published. The most relevant are: *IEEE Access* which indicates a strong engineering component in the research; *Sensors* which highlights the importance of sensors in food safety and quality; *Trends in Food Science and Technology* which investigates the application of these technologies in the food sector; *Food Control* which delves into food safety and regulation; *Journal of Food Process Engineering* which analyzes the importance of innovation in food processing processes; *Applied Sciences* investigates the interest of the broader scientific community for these technologies.

4.2 Science Mapping Techniques

4.2.1 Citation Analysis

This science mapping technique (Fig. 5) assumes that citations reflect the intellectual connections between research items if a research item cites another one [47]. In this way, you can identify the impact of a research item through the number of citations received.

This analysis led to the identification of the most influential research items in a field. Even though there are different metrics, this is considered the most objective and direct impact measure [48].

Therefore, using citations, the most influential publications can be analyzed to investigate its intellectual dynamics of a research field. The citation analysis highlighted that out of 252 documents, 99 have at least 20 citations. Only 46 items are connected each other. In particular, three relevant studies have emerged in this domain of analysis [36-38]. Feng [36] is the most cited and impactful publication in the research network. Being in the center with many connections, it is probably a reference article in the field. Misra [38], Brewster [39], Han [44], Raten ì [40] have nodes of significant size, suggesting that their articles are also important and frequently cited.

4.2.2 Co-citation Analysis

This method, introduced by Small [49], is used to map the structure of a research field by examining pairs of publications that are frequently cited together, based on the assumption that such works share thematic similarities [50, 51]. In this approach, two research items are connected if they are listed together in the reference list of a third research item. Using the centrality index, Newman [52] explains that the domain under study can be organized into distinct clusters.

One of the main advantages of this analysis is its ability to identify the thematic clusters and highlight the most influential items within a field. Widely applied in the literature to define the boundaries of research areas [53], it is also valuable for uncovering knowledge communities [54], emerging research frontiers [55], and for exploring various scientific disciplines [31].

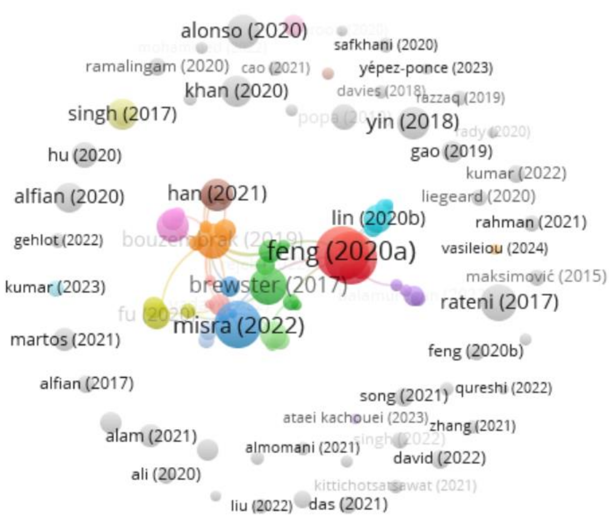

Fig. 5 Citation analysis.

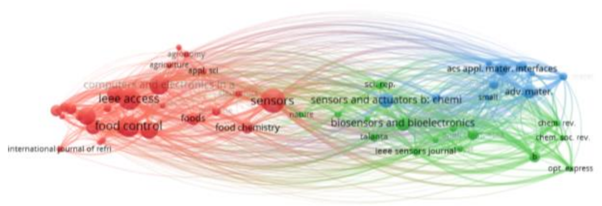

Fig. 6 Co-citation analysis with cited sources.

For this study, the analysis was conducted using the "full counting" method, focusing on cited sources with a minimum threshold of 20 citations. This resulted in a dataset of 53 cited sources. The analysis, illustrated in Fig. 6, revealed the presence of three main clusters, differentiated by three colors.

Cluster 1 includes 53 journals, with prominent titles such as *Sensors* (link strength = 9,997), *Food Control*, and *IEEE Access* (highlighted in red). This cluster centers on technological and engineering applications within the agri-food sector, covering research on food quality control, food safety, and preservation technologies.

Cluster 2 consists of 15 journals, led by the highly cited *Biosensors and Bioelectronics* (shown in green). The focus here is on the use of sensors to monitor food quality, detect contaminants, and enhance food processing, with biosensors and bioelectronics forming the core themes.

Cluster 3 contains 10 journals, including *Sensors* and *Actuators B: Chemical* (depicted in blue). This group leans towards research on novel materials and nanotechnologies for sensing and bioelectronic applications, highlighting connections to the development of advanced biosensors and cutting-edge devices.

4.2.3 Co-authorship Analysis

Co-authorship analysis explores the collaborative relationships between authors within a research field. In fact, it represents a formal form of intellectual partnership among researchers, providing valuable insights into how scholars interact, both within institutions and across countries. This understanding is increasingly important, as the increasing complexity and variety of research methodologies and theories have driven a surge in collaborative efforts among academics [56].

Fig. 7 illustrates the co-authorship network of authors in the dataset who have co-authored at least two publications and have been cited at least ten times during the analyzed period. The analysis identified a total of 1,132 authors, visually organized into clusters distinguished by different colors, representing collaborative groups. Of these, only 45 authors met the specified thresholds, highlighting the core group of active and influential collaborators in this research area.

Fig. 8 presents the co-authorship network based on the country of affiliation, with at least 5 publications in the period under analysis and at least 10 citations. The 23 (out of 73) countries that exceeded the threshold were divided into 6 clusters and India had the highest link strength.

This analysis is used to show academic collaborations between countries based on shared research items. The United States, India, and China are the main nodes of the network, suggesting that they are among the largest academic collaborators at the international level. European countries (Italy, Netherlands, Spain) are less central than China and India, but still present in global academic collaborations. Connections between Asia and the Middle East appear particularly strong, which may reflect collaborations in specific sub-sectors.

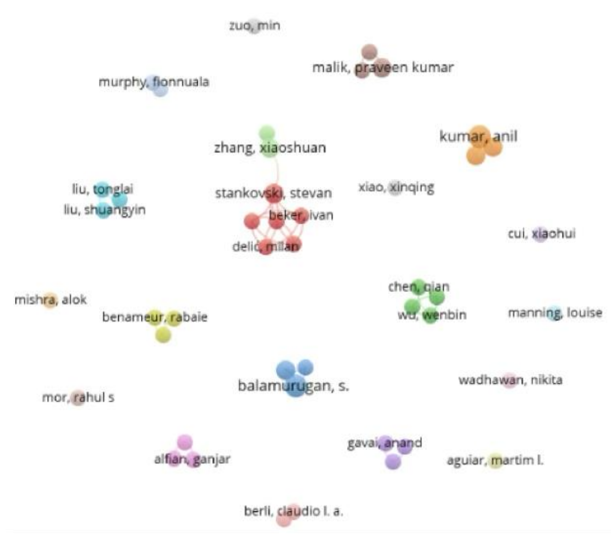

Fig. 7 Co-authorship analysis by author network.

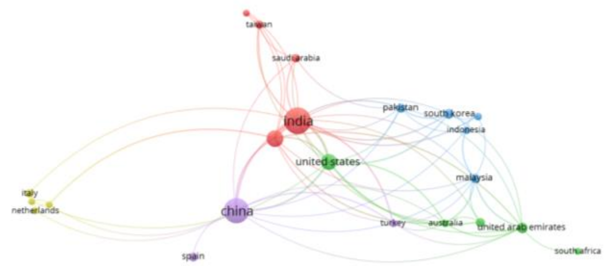

Fig. 8 Co-authorship analysis by country network.

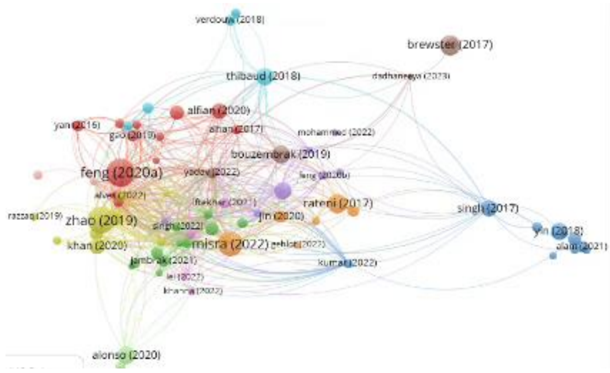

Fig. 9 Bibliographic coupling.

4.2.4 Bibliographic Coupling

In science mapping, bibliographic coupling is a technique that is based on the assumption that two research items share similar content if they have common references [57]. In this analysis, research items are grouped into thematic clusters characterized by shared references [58].

Only 79 research articles with significant interconnections were considered, applying a minimum citation threshold of 30. These items were then organized into 11 distinct clusters, as shown in Fig. 9, highlighting the main thematic areas and relationships within the research items.

4.2.5 Co-occurrence Analysis

In order to identify a thematic flow, co-occurrence analysis based on author-keywords was carried out to better understand the prevailing search trends in our field of analysis. Initially, a total of 794 keywords were extracted from the documents. In this analysis, the author-keywords were set to at least 5 occurrences. Fig. 10 illustrates this network. This analysis produced 22 keywords, grouped into 5 clusters (represented by a different color), and 111 links are identified and the total link strength is equal to 391.

The analysis of the author's keywords offers some useful information. IoT is the key concept, represented by the largest and central node, from which multiple related topics branch out. The image (Fig. 10) shows 5 main clusters that derive from IoT.

The red cluster is related to food safety (keywords: biosensors, cloud computing, big data, industry 4.0, COVID-19). This cluster highlights how IoT helps improve food safety through the use of smart sensors and biosensors that monitor food quality in real time. In addition, cloud computing enables the collection and the analysis of large amounts of data (big data) related to food production and preservation. The connection with COVID-19 suggests that the pandemic has accelerated the adoption of IoT technologies to improve traceability and supply chain security while Industry 4.0 highlights the integration of IoT with automation and digitalization in food production processes.

The yellow cluster refers to traceability and supply chain (Keywords: food quality, food, big data, supply chain). This cluster highlights how IoT is crucial for food traceability (temperature, humidity and location of products), allowing monitoring each phase of the supply chain and ensuring that food quality standards are guaranteed. Big data are useful to analyze large volumes of information on the supply chain, improving supply chain management.

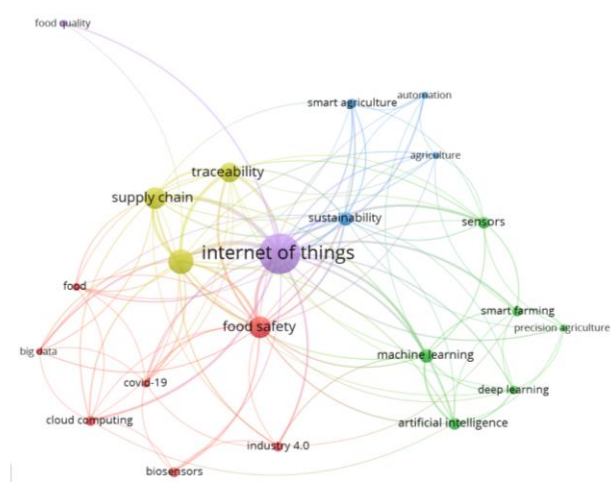

Fig. 10 Co-occurrence analysis.

The blue cluster summarizes the relationship between smart agriculture and sustainability (Keywords: automation, agriculture, sustainability, sensors, smart agriculture). IoT is in fact a key element of smart agriculture, thanks to the use of sensors and automated systems that monitor soil, air and crop conditions. Sustainability becomes a central factor and, through the IoT, the use of resources (such as water, fertilizers, pesticides) can be optimized, contributing to the reduction of waste and environmental impact. The connection with automation highlights how IoT devices can control irrigation, fertilization and harvesting systems autonomously.

The green cluster (Keywords: machine learning, deep learning, smart farming, precision agriculture, sensors, artificial intelligence) allows us to understand that IoT provides real-time data that can be analyzed with AI and ML to optimize decisions in agriculture and supply chain management. Deep learning is applied to analyze satellite images or drones, detecting problems in crops before they become serious. Precision agriculture uses IoT sensors to optimize cultivation based on collected data, improving production yield. Smart farming is the integration of all these technologies for more efficient and data-driven agriculture.

The purple cluster highlights how IoT contributes to sustainability by monitoring and optimizing resources in the food and agricultural sector. Smart sensors and devices can reduce waste of water, energy and raw materials, improving efficiency and reducing environmental impact. Food quality is closely linked to traceability and food safety. IoT allows data to be collected on food production, storage and transportation, ensuring higher quality standards. IoT, through real-time monitoring, helps prevent food spoilage and contamination, improving consumer confidence in the food supply chain.

5. Application Domains and Technological Solutions of IoT in Food Safety

Starting from the analyses conducted in paragraph 4, a content analysis allows identifying several distinct thematic areas of application within the research field. These thematic areas not only highlight the main directions and focus points of the existing literature but also provide a clear framework for addressing Research Question 2 (RQ2). Analyzing clusters and their features helps us better understand the main topics, technologies, and challenges explored in the domain, providing a comprehensive answer to RQ2.

5.1 Smart Agriculture and Food Production

IoT is a key component of smart agriculture, with applications including real-time crop monitoring, precision irrigation, automated harvesting and post-harvest management [41]. Distributed sensors, drones, and edge gateways help optimize resource use, improve agricultural productivity, and reduce environmental impacts [59]. The most common solutions use environmental sensor networks to monitor soil temperature, moisture, pH, solar radiation, and atmospheric conditions, feeding data into cloud-based decision systems [60]. Specific cases include smart greenhouses, precision viticulture, vertical farming, and hydroponic systems. Here, IoT manages light, nutrients, temperature, and irrigation to create ideal growing conditions [43]. The integration of data analytics and IoT has also enabled the creation of digital twins, predictive models that simulate crop growth under varying environmental scenarios to optimize planning and output [61]. Based on the above, it is reasonable to say that IoT deployment improves crop cycle management, supports targeted interventions, and enables disease prediction. In addition, in rural or low-income areas, the use of low-cost and open-source solutions is essential. In fact, several contributions present sensor systems built on platforms, featuring modular components and mobile apps for ease of use [62, 63].

5.2 IoT Sensors and Real-Time Monitoring

In the domain of IoT for food safety, the use of IoT-based sensors for monitoring environmental conditions within food systems is among the most established and rapidly evolving applications. In fact, smart sensors allow the detection of key parameters such as temperature, humidity, volatile gases, and light, allowing continuous and automated control along the food supply chain, from production to distribution [64]. As a matter of fact, several studies suggest integrating sensors with wireless networks and low-power microcontrollers to monitor food quality in real time, enabling the early detection of spoilage [65]. For example, systems capable of detecting ammonia or carbon dioxide levels in refrigerated environments have been developed to identify anomalies and activate predictive alerts [66]. Furthermore, in storage and transportation settings, integrating these sensors with cloud platforms enables real-time monitoring of environmental data, improving operational efficiency and minimizing waste [63]. Many studies highlight wireless technologies such as LoRa, ZigBee, and NB-IoT, which ensure reliable data transmission even in rural or low-coverage areas [67]. Smart packaging also attracts attention. These systems incorporate sensors into food packaging to monitor freshness through biochemical and optical detection of spoilage indicators like volatile organic compounds [68]. Bluetooth and Near Field Communication based low-cost sensors have demonstrated effectiveness for small-scale monitoring in retail settings [69]. Several authors propose modular and scalable architectures, where multiple sensors collect data processed through edge computing algorithms, reducing latency and improving energy efficiency [59]. Experimental validation is increasingly common, with real-world applications (e.g., produce, dairy, meat) measuring tangible impacts on shelf-life, waste reduction, and hygiene improvements [63, 70].

5.3 Traceability and Blockchain in the Food Supply Chain

The convergence of IoT and Blockchain has significantly improved food traceability, enhancing transparency, data integrity, and trust throughout the supply chain [71]. RFID tags, environmental sensors, and distributed ledgers allow each event in a product’s lifecycle to be recorded immutably and shared among stakeholders [72]. Smart contracts automate quality checks, temperature validation, and logistics, and can trigger alerts for anomalies [73, 74]. Blockchain provides tamper-proof visibility to all actors—producers, processors, retailers, and consumers—helping prevent fraud and increase accountability [61]. Some works explore blockchain-AI integration to evaluate risk levels and prioritize inspection or recall activities [75]. Challenges include scalability, high computational costs, and lack of standards, particularly in large-scale supply chains [76].

5.4 Quality and Freshness in Processed Foods

IoT is increasingly utilized to ensure the microbiological safety and freshness of processed food products such as meat, seafood, dairy, and baked goods. A key objective is to prevent spoilage through continuous monitoring of critical parameters during processing and storage [76]. Technologies include gas and optical sensors that detect spoilage-related volatiles (e.g., nitrogen compounds), either embedded in packaging or positioned in refrigerated units [68]. These systems transmit data to cloud platforms for analysis and visualization. In the seafood sector, combined use of temperature sensors and olfactory sensors, along with predictive algorithms, supports early detection of deterioration and improves decision-making on shelf life and recalls [77]. Active packaging is also gaining popularity, incorporating sensors that monitor oxygen, humidity, and microbial indicators within the sealed environment [63]. Some studies use machine vision and deep learning for visual inspection of defects in processed foods, ensuring fast and precise quality control [70].

5.5 Information Systems, RFID, and Data Security

As IoT systems grow more complex, data security emerges as a crucial concern in smart food safety. Protecting the confidentiality, integrity, and availability of data is essential for maintaining trust in digital infrastructure [78]. Many solutions utilize RFID and NFC for automated data collection, coupled with cloud platforms offering end-to-end encryption and secure authentication [79]. Some propose private blockchain networks for confidential yet auditable sensor data logs. Research highlights the importance of interoperability, access control, and cyber-resilience. Decentralized frameworks distribute computation between edge devices, gateways, and cloud systems to reduce vulnerabilities [80]. Compliance with international standards (e.g., ISO 22005, GS1) is emphasized to harmonize data collection and promote cross-platform integration. Advanced architectures often include distributed logs and digital signature verification to improve data security [81].

5.6 Adoption Challenges

A large part of the literature focuses on barriers to IoT adoption within the food supply chain. These challenges are technical, economic, social, and regulatory, often differing by region or industry. Major obstacles include system complexity, lack of interoperability, and connectivity issues in rural areas [36, 82]. High initial costs, lack of technical training, and data privacy concerns also restrict adoption [83]. Some studies highlight the importance of human factors, organizational culture, and institutional support to try to overcome these obstacles [63]. Researchers promote sustainable business models and public policies to support digital transformation, especially for smallholders and in developing economies [84]. The availability of cloud infrastructure, reliable electricity, and mobile access is a prerequisite for successful implementation [76]. Additional studies point to emerging trends such as AI integration, open-source platforms, and hybrid edge-cloud architectures [85]. Comparative analyses across countries or food systems show that digital maturity strongly influences adoption levels [86]. Standardizing communication protocols, data formats, and performance indicators is crucial for scalability and interoperability [81]. Some propose architectural frameworks that integrate sensors, edge devices, and cloud platforms within heterogeneous environments [75].

6. Research Limits and Future Research Trajectories

The main goal of this paper was to gain a clearer understanding of how mainstream literature on IoT for food safety has evolved over time. However, like many studies in this field, it has some limitations that are worth noting. To address the research questions, data were collected exclusively from the Scopus database, which means relevant publications indexed elsewhere may have been overlooked. Future research could minimize this bias by incorporating multiple databases for a more comprehensive view.

Another limitation lies in the focus solely on IoT technology. Upcoming studies might expand their scope to explore other emerging technologies and techniques, such as Digital Twins and green, energy-efficient communication systems. Among the themes observed, IoT and Blockchain stand out as the most widespread and transversal across countries. Meanwhile, Artificial Intelligence and Machine Learning are gaining momentum as vital tools for enhancing the food supply chain and merit further detailed investigation.

Particularly promising areas for future research are found in the Motor and Basic Themes quadrants, as these represent both relevant and rapidly evolving topics. Basic Themes (including IoT, Blockchain, Machine Learning, Deep Learning, AI and 3D Printing) are highly significant but still developing, offering ample opportunities for research, especially related to automation and digitalization within the agri-food sector. Motor Themes, such as Microcontrollers, Food Monitoring and Preservation, Biosensors, Environmental Monitoring, and Food Analysis, are already well established yet remain fertile ground for innovations, new applications, and integration with emerging technologies (for example, combining biosensors and AI for enhanced food quality monitoring).

Given the relative novelty of this research topic, similar bibliometric studies should be repeated in the next two to three years to track its evolution further, especially considering upcoming EU food safety policies. Despite the limitations outlined, this study provides a comprehensive overview and generates valuable ideas for future investigations to deepen understanding in this rapidly growing area.

7. Final Remarks

This study offers a comprehensive bibliometric overview of the potential role of IoT in enhancing food safety, elucidating key research trends, applications, and prevailing challenges. As IoT technologies continue to advance, their significance in fostering safer, more transparent, and more efficient food systems is expected to grow substantially. Distinct from previous investigations, this research incorporates publications up to 2024, providing an updated analysis of the intellectual landscape. Temporal trend analysis reveals the dynamic evolution of research interests, highlighting phases of intensified focus on emerging technologies, particularly since 2019, when scholarly attention markedly accelerated. Further examination of primary publication sources underscores the interdisciplinary nature of this research domain, with significant contributions from both engineering and food science journals. Notably, publications are evenly distributed between technology-focused outlets such as *IEEE Access* and *Sensors*, and food science journals including *Trends in Food Science and Technology* and *Food Control*, illustrating the convergence of technological innovation and food safety concerns. Author impact metrics identify the leading and most influential scholars driving this field, while country-level analysis reveals that India and China are at the forefront of research output, signaling their prominent scientific leadership in IoT applications within the agri-food sector. Keyword and thematic map analyses delineate the intellectual structure by distinguishing foundational themes, marginal topics, nascent areas, and motor themes. Among these, IoT, Blockchain, and AI emerge as particularly promising, poised to drive future advancements in the agri-food industry. The accelerating digitalization of the food supply chain is anticipated to further enhance the deployment of these technologies, improving traceability, quality control, and overall food safety.

Mapping the research landscape across six core application areas, this paper provides a foundation for scholars and practitioners in order to navigate the complexities of IoT in food safety and to identify priorities for innovation, deployment, and policy-making. As a matter of fact, this research offers valuable insights for both academics and practitioners by delivering a holistic understanding of the current state of literature alongside practical applications and benefits.

From an academic perspective, this paper significantly contributes to the multidisciplinary discourse at the intersection of agri-food systems and advanced technologies. By providing a detailed bibliometric mapping of IoT applications in food safety, it bridges gaps between engineering, computer science, and food science research communities. This integrative approach fosters cross-sectoral dialogue, encouraging scholars to explore innovative synergies and address complex challenges in food safety and supply chain management. Furthermore, the identification of emerging themes and influential authors offers a foundation for future research, stimulating new theoretical frameworks and methodological advancements. Consequently, this work enriches the academic debate by promoting a comprehensive understanding of how technological innovation can sustainably transform the agri-food sector.

From a practical perspective, the findings are especially relevant to stakeholders within the agri-food sector, including sustainability managers, technology developers, and policymakers. Sustainability managers may leverage these insights to guide strategic investments in new technologies, fostering integrated approaches that enhance efficiency, sustainability, and resilience over the long term. For technology developers, the study highlights the imperative to create interoperable solutions that seamlessly integrate emerging technologies, thereby promoting innovation as a key driver of sustainability.

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