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Systematic Review

Research Trends in the Use of the Internet of Things in Sustainability Practices: A Systematic Review

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Abstract: This article discusses the role of technological advancements, particularly in the IoT domain, in promoting economic, productive, and social development in the context of environmental sustainability. The research focuses on identifying specific trends in the application of these systems for sustainable practices through a bibliometric analysis using PRISMA. The text presents an evaluation of global scientific productivity, highlighting the significant contributions of countries such as China and the United States. It also emphasizes India's prominent role in the efficiency of the agri-food supply chain. The study further examines thematic evolution, keyword networks, and their co-occurrence, as well as the relationship between validity and frequency. The article proposes a research agenda that concludes the exponential growth of IoT research in sustainable cities since 2016. The research agenda focuses on energy efficiency, cloud computing, and big data. Additionally, the article identifies smart cities and sensor usage, along with the creation of new decentralized networks, as priority research areas that will remain relevant in the future. The article emphasizes the importance of security and privacy in these areas.

Keywords: Internet of Things; sustainability; smart cities; sensors; PRISMA

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1. Introduction

In the past, there was a direct correlation between technological progress and the degradation of the environment. Some academic and social positions viewed economic and industrial growth as a threat to the natural ecosystem [1]. As a result, sustainability has become a primary concern on the agendas of countries worldwide. However, current technological advances enable us to contribute to economic, productive, and social development without harming the environment. Sustainability involves integrating environmental, social, and economic resources to promote healthy growth and meet various demands to satisfy human needs simultaneously [2]. Environmental preservation refers to the protection of natural resources to maintain social equity and economic stability, creating a healthy community for present and future generations [2].

To address the challenges of environmental degradation and climate change, innovative solutions such as Artificial Intelligence (AI), IoT, and big data have been developed [2,3]. The Internet of Things (IoT) is gaining popularity and is being adopted in various fields, ranging from industry to everyday life [4]. This is attributed not only to the use of wearable devices, which enable constant health monitoring and are utilized in many aspects to enhance quality of life [5], but also to new urbanization methods and trends. These include the use of green infrastructure technologies and designs supported by IoT tools and devices [3]. In order to improve sustainable construction through the adoption of appropriate technologies in the fourth and fifth industrial revolutions [6], it is important to consider the use of IoT.

Another field where IoT has been extensively researched and implemented is agriculture. As the world confronts a changing climate, agriculture must develop more efficient and sustainable food production systems. However, traditional farming methods consume significant amounts of energy and are largely manually controlled, resulting in suboptimal production. The use of IoT, for example, enables controlled production through the use of sensors in greenhouses [7].

The IoT has become an essential tool in the pursuit of sustainable solutions across various fields. Studies, such as that by Pecunia, Occhipinti, and Hoye [8] explore emerging photovoltaic technologies for indoor applications. They suggest the potential to integrate renewable energy generation into IoT devices, promoting energy self-sufficiency and reducing carbon footprints. Meanwhile, Alsamhi et al. [9] examined the use of unmanned aerial vehicles (UAVs) in B5G networks for green IoT applications. They point out how sustainable mobility can improve energy efficiency and connectivity in IoT environments.

Additionally, the integration of Industry 4.0 and IoT technologies in the construction industry offers opportunities to improve efficiency and sustainability in infrastructure projects. Big data analytics in industrial IoT systems also presents challenges and opportunities to optimize manufacturing operations in a more sustainable manner, as discussed in [10,11]. Finally, Nižetić et al. [12] emphasize the opportunities and challenges of IoT in creating a smart and sustainable future. They stress the importance of addressing aspects such as security, privacy, and data management in the implementation of IoT solutions.

Furthermore, Reyana et al. [13] demonstrated the potential of fog computing to enhance fault tolerance and energy efficiency in IoT systems. Their study highlights the role of cloud computing in creating sustainable and efficient IoT environments. These and similar studies demonstrate the importance of addressing security, energy efficiency, and sustainability challenges in the context of the IoT. Technological innovation plays a critical role in finding comprehensive and viable solutions to these problems. Research at the intersection of IoT and sustainability is essential to the development of a more sustainable and resilient future.

Solutions often involve flexible, printed, or wearable electronics. Therefore, the selection of materials and the provision of an eco-friendly power source are crucial [4]. Some researchers have also explored the use of low-power devices [14]. Recently, green algorithms have been proposed to reduce energy consumption by modifying network algorithms and protocols [1].

For instance, Morchid et al. [15] demonstrated how IoT is being used to tackle sustainability challenges in agriculture. IoT-based systems for irrigation monitoring optimize water use, reducing waste. Additionally, this technology enables precise nutrient distribution for fertilizer management, increasing agricultural productivity sustainably. Early detection of crop diseases through IoT systems enables effective responses, minimizing losses and supporting the economic sustainability of production. Early detection of fires in agricultural areas is crucial to prevent loss of crops and natural resources. Real-time monitoring of weather conditions through IoT devices can assist farmers in making informed decisions.

Additionally, Wen-Cheng et al. [16] suggest that smart buildings, which are part of the IoT, can reduce the cooling and heating loads required to maintain spaces at a comfortable temperature, thereby reducing operating costs and energy consumption. This example demonstrates how IoT is being used to address environmental and economic sustainability challenges by optimizing energy consumption in smart buildings. It also showcases the integration of physical and computer systems to improve efficiency and accuracy in various environments, such as smart cities, homes, and transportation.

This article exclusively focuses on the IoT due to its significant implications in promoting sustainable practices, despite the existence of other technologies such as AI and big data that also play a role in sustainability. The IoT provides solutions to environmental and climate challenges while promoting energy efficiency, resource conservation, and emissions reduction. This article aims to demonstrate the central role of the IoT in achieving sustainable solutions and a more resilient and ecologically balanced future.

Therefore, researchers are investigating the impact of power conversion efficiency (PCE) of RF energy harvesters on the performance of wireless IoT devices. IoT devices include sampling frequency and data security [17]. The IoT paradigm plays a crucial role in enhancing smart city monitoring applications and managing city operations in real time [18]. Therefore, there is a significant research gap in IoT applications for sustainability [3]. This research aims to identify research trends in the use of the IoT in sustainability practices through a bibliometric analysis according to the PRISMA statement. The following questions are proposed:

RQ1: What are the years in which there has been the most interest in the use of Internet of Things techniques in sustainability practices?

RQ2: What kind of growth is there in the number of scientific articles on the use of the Internet of Things in sustainability practices?

RQ3: What are the main research references on the use of the Internet of Things in sustainability practices?

RQ4: What is the thematic evolution derived from the scientific production on the use of the Internet of Things in sustainability practices?

RQ5: What are the main thematic clusters on the use of the Internet of Things in sustainability practices?

RQ6: What are the growing and emerging keywords in the research field of the use of the Internet of Things in sustainability practices?

RQ7: Which themes are positioned as protagonists for the design of a research agenda on the use of the Internet of Things in sustainability practices?

2. Materials and Methods

To achieve the research objective, we propose a bibliometric analysis based on the international PRISMA declaration (Supplementary Materials). The aim is to obtain clear, detailed, and replicable methods using the parameters of the PRISMA-2020 update, as detailed in [19].

2.1. Eligibility Criteria

This bibliometric analysis examines the use of the Internet of Things in sustainable practices. Eligibility requirements are defined based on terms related to the IoT and sustainability. The requirements apply mainly to article titles, which are considered key metadata for selecting relevant studies.

The process of selecting relevant studies for this bibliometric analysis involves three stages of exclusion. The first stage involves discarding records with erroneous indexing to ensure the accuracy and quality of the data included in the analysis. In the second stage of exclusion, documents that are not fully accessible are removed. It is important to note that this second phase is only applicable to systematic literature reviews. For other types of documents analyzed in this bibliometrics analysis, the available metadata are considered sufficient. In the third phase of exclusion, conference proceedings, non-relevant texts, and documents with incomplete indexing are discarded to ensure the inclusion of quality and relevant studies in the bibliometric analysis.

2.2. Information Sources

The Scopus and Web of Science databases were selected as the main sources of information due to their wide recognition as excellent sources of scientific and academic information. They offer extensive coverage in different disciplines and thematic areas [20], providing a global and accurate perspective of research related to the IoT and sustainability. This comprehensive and representative approach ensures a balanced view of the field.

2.3. Search Strategy

To conduct a search in the Scopus and Web of Science databases, we developed two specialized search equations that were adapted to the established inclusion criteria and search functionalities of each database. The equations were created using key terms related to the IoT and sustainability, as well as their synonyms, to ensure the retrieval of relevant studies in the area of interest. In addition, we considered Boolean operators and truncation functions specific to each database to enhance the precision and completeness of the results. Our goal in designing these specialized search equations was to establish an effective and rigorous search strategy that would ensure a representative selection of studies for subsequent bibliometric analysis. It is important to note the following:

- For the Web of Science database: (TI = (“internet of things” OR “IoT” OR “smart devices” OR “connected devices” OR “smart objects”) AND TI = (sustainability OR sustainable));
- For the Scopus database: (TITLE (“internet of things” OR “IoT” OR “smart devices” OR “connected devices” OR “smart objects”) AND TITLE (sustainability OR sustainable)).

2.4. Data Management

During the development of this bibliometry, we used Microsoft Excel® to extract, store, and process information from the selected databases. Excel® provided a flexible and efficient platform to organize the collected data and perform bibliometric calculations and statistical analyses. Additionally, we used two tools to visualize the results and create graphs of the different bibliometric indicators, namely VOSviewer®, a software utilizing a linked approach [21], reached version 1.6.20 on 31 October 2023. This latest iteration is freely accessible on its official website and was developed by the Centre for Science and Technology Studies at Leiden University in The Netherlands, in its version 2402, was released as part of the Microsoft Office 365 Products. These tools enable the visual representation of relationships between articles, authors, institutions, and other relevant elements, facilitating network analysis and identification of significant patterns in IoT and sustainability research. During the writing process, we utilized the ChatGPT artificial intelligence in its free version 3.5 provided by Open AI on its official website, which was used to generate keyword orientation. However, it is important to note that the content was written autonomously by the authors, without the use of generative tools, to ensure the originality and coherence of the text.

2.5. Selection Process

In accordance with the PRISMA 2020 statement, as highlighted in [19], it is important to disclose the use of an internal automated classifier in the selection process, as well as any internal or external validation performed to assess the risk of omitting studies or making incorrect classifications. The researchers in this study utilized an internally developed automation tool in Microsoft Excel®. Each researcher independently used this tool to apply the inclusion and exclusion criteria. The goal was to minimize the risk of omitting relevant studies or making incorrect classifications by converging the results. This rigorous and precise selection of studies included in the bibliometrics reduces bias and guarantees the validity of the obtained results. The methodological design of the research is shown in Figure 1.

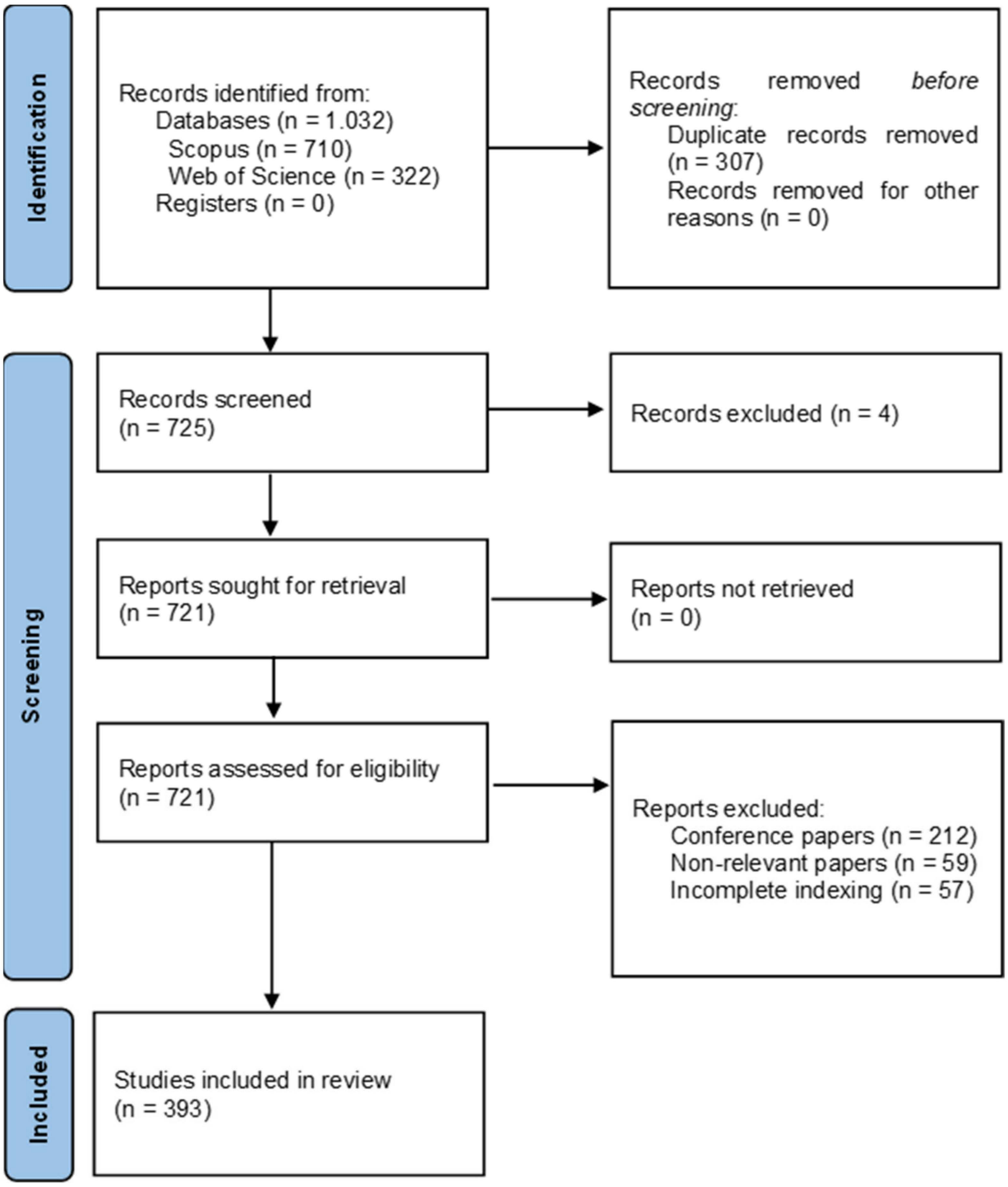

Figure 1. PRISMA flow chart. Own elaboration based on Scopus and Web of Science.

The flow chart illustrates the initial step in which 1032 documents were identified. Out of these, 307 duplicate documents were removed. Subsequently, three exclusion phases were conducted based on the established criteria, resulting in a total of 393 documents that were analyzed using bibliometric methods.

2.6. PRISMA Registration Number

This research study, although following the guidelines outlined by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), does not possess a PRISMA registration number. Nevertheless, rigorous methodology and transparency were maintained throughout the investigation to ensure the integrity and reliability of the findings.

3. Results

The metric 'publications per year' displays the trend of the number of works published in a specific research field over time. Figure 2 illustrates the studies conducted since 2012, with an exponential growth of approximately 98% until 2023. It is noteworthy that the most significant years were 2021 and 2022, with 2022 having the highest number of scientific publications on the IoT and sustainability. One notable publication is [22], which presents a smart IoT framework enabled by blockchain and artificial intelligence for the development of sustainable cities. Similarly, another study proposed a sustainable smart photobioreactor for the continuous cultivation of microalgae using IoT technology [23].

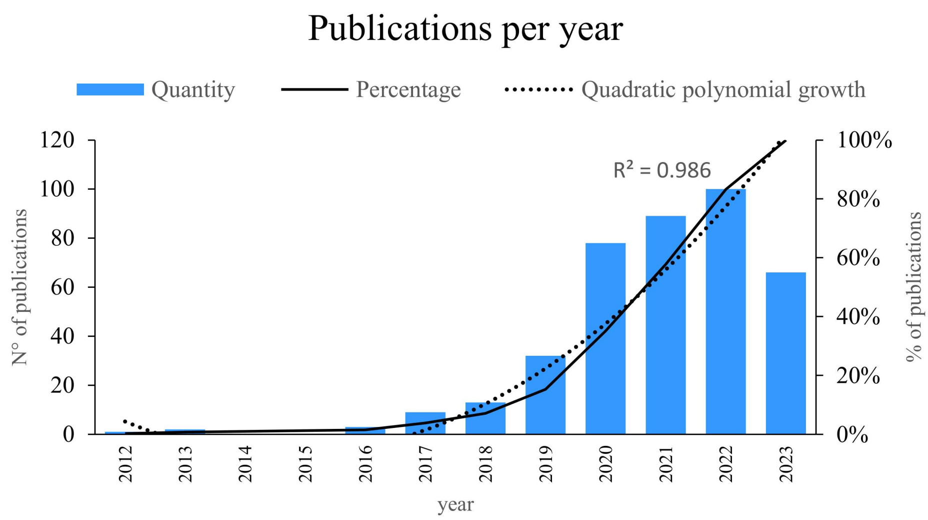

Figure 2. Publications by year. Own elaboration based on Scopus and Web of Science.

Research on this topic continued to grow in 2021. One noteworthy study is [24], which examines the role of companies in promoting the United Nations Sustainable Development Goals through the use of IoT and blockchain technology. Another relevant article is [25], the authors of which conducted a comprehensive review of applications and communication technologies for sustainable smart agriculture based on the IoT and unmanned aerial vehicles.

In 2020, there was a notable increase in scientific publications related to the use of the IoT in sustainability practices. Some studies explored the convergence of blockchain and artificial intelligence in IoT networks for the development of sustainable smart cities [26]. Another significant publication was [27], which proposed blockchain-based trust models for sustainable healthcare IoT systems.

It is expected that there will be a significant increase in scientific publications on this topic in 2023. Two relevant publications have been identified to date. The first publication [28] presents a super-efficient GSM triplexer for 5G-enabled IoT deployments in sustainable smart grid and metaverse edge computing. The second relevant paper [29] proposes a trust-based secure parking allocation model for IoT-enabled sustainable smart cities.

The analysis that follows measures the number of articles and citations of the main authors, as shown in Figure 3, to determine the main research references. Lăzăroiu G stands out as one of the main references in terms of scientific productivity and academic impact in the field of IoT use in sustainability practices. The scientific community widely recognizes his contributions due to the high number of publications and citations he has accumulated throughout his career. Some of his studies relate to his scientific productivity, conducting extensive research on Internet of Things sensing infrastructure and data-driven planning technologies in the governance and management of sustainable smart cities. The author's research offers valuable insights into how IoT capabilities can optimize decision-making processes and improve efficiency in city management [30].

In terms of academic impact, ref. [31] has made significant contributions in terms of addressing the use of AI-based decision-making algorithms, IoT sensing networks, and sustainable cyber–physical management systems in big data-driven cognitive manufacturing. The research emphasizes the significance of incorporating these technologies into manufacturing processes to enhance efficiency, sustainability, and competitiveness in the industry.

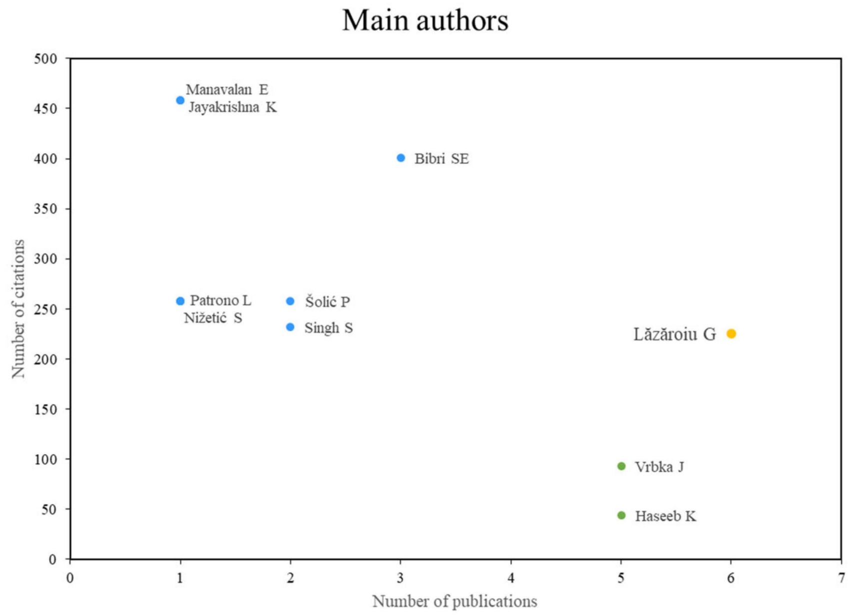

Figure 3. Main authors. Own elaboration based on Scopus and Web of Science.

Similarly, Manavalan and Jayakrishna, as well as Bibri, are acknowledged as key references in terms of academic impact in the area of using the IoT in sustainability practices, despite not having a high number of publications to support their scientific productivity. The scientific literature recognizes the contribution of [32] in conducting an exhaustive review on the application of IoT in sustainable supply chains to meet the requirements of Industry 4.0. Their study provides a comprehensive view of how IoT integration can improve efficiency, traceability, and sustainability in supply chains.

Similarly, ref. [33] makes an important contribution to the field of sustainable smart cities, particularly in the field of IoT. The paper presents an analytical framework for sensor-based big data applications, with the goal of promoting environmental sustainability in future cities. The research emphasizes the significance of utilizing IoT and sensor-generated data to make informed decisions and enhance quality of life in urban environments.

Finally, Vrbka and Haseeb are recognized as key references for their scientific productivity in using the IoT for sustainability practices, despite having a low number of citations to support their impact. Vrbka's contribution is highlighted by his high scientific productivity, publishing numerous relevant articles in the field. The author's studies have explored business process optimization, cognitive decision-making algorithms, and AI-driven IoT systems in sustainable smart manufacturing. The research provides valuable insights into how these technologies can improve the efficiency and sustainability of production systems [34].

Additionally, ref. [35] emphasizes the significance of IoT integration, big data-based decision-making, and digitized mass production in Industry 4.0-based manufacturing systems. His research highlights how these technologies can contribute to sustainability and the development of more efficient manufacturing systems.

On the other hand, Haseeb has made significant contributions in the area of sustainable cities, focusing on security and intelligence in edge computing. Her research proposes an edge-enabled smart and secure computing model using green IoT to promote sustainability in cities. The author emphasize the significance of utilizing eco-friendly and efficient technologies to attain sustainable urban development [36]. Additionally, ref. [37] proposed a secure and sustainable predictive framework for IoT-based multimedia services utilizing machine learning techniques. This study underscores the significance of considering security and sustainability in the implementation of IoT services.

Figure 4 displays an analysis of the primary scientific journals that disseminate knowledge about the use of the IoT in sustainability practices. The journals Sustainability and the Journal of Self-Governance and Management Economics are widely recognized in the scientific field for their outstanding productivity and academic impact related to the use of the IoT in sustainability practices. Sustainability has made significant contributions to research in this area. An example of relevant research is presented in [38], the authors of which developed a deep learning-based predictor for sustainable precision agriculture using IoT systems. This study provides innovative insights into how advanced technologies can improve efficiency and sustainability in the agricultural sector. Other studies propose a secure and sustainable IoT-based framework for multimedia services using machine learning. The authors emphasize the significance of tackling security and sustainability issues when implementing IoT-based services, making a valuable contribution to the academic community [37].

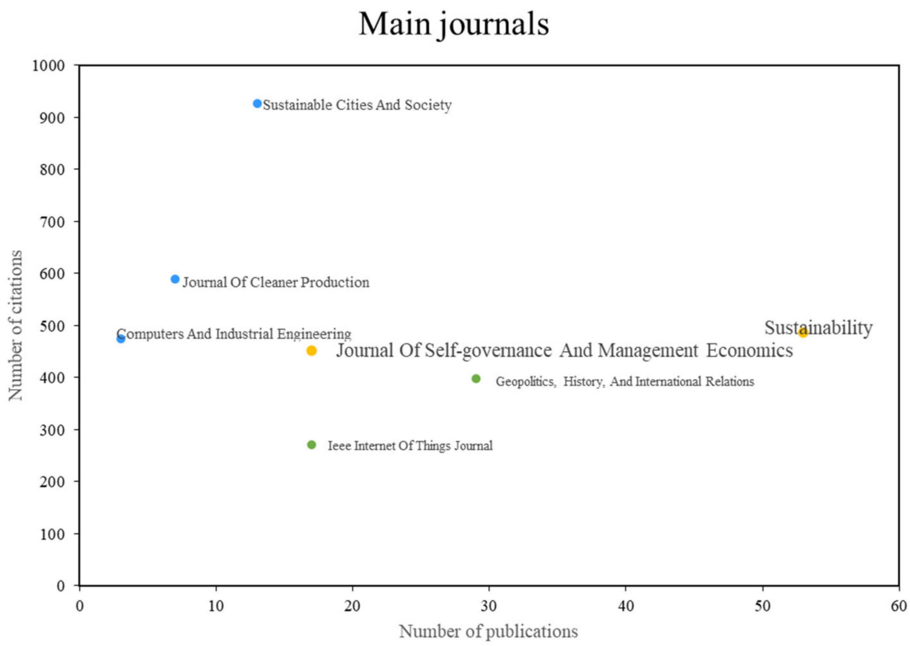

Figure 4. Major journals. Own elaboration based on Scopus and Web of Science.

Additionally, the Journal of Self-Governance and Management Economics has been instrumental in generating knowledge on the IoT and sustainability. In a previous article published in this journal [39], the authors investigated the performance of smart factories, cognitive automation, and industrial big data analytics in IoT-based sustainable manufacturing. Their study provides an in-depth understanding of how IoT technologies can be implemented in the manufacturing sector to improve sustainability and operational efficiency.

The journals Sustainable Cities and Society and the Journal of Cleaner Production have established themselves as references in the field of research on sustainable practices related to the use of the IoT, thanks to their outstanding academic impact and the high number of citations they have received. Although not recognized for high scientific productivity in terms of the number of publications, they are highly regarded in the academic community. The authors of [40] propose IoT and machine learning-based approaches to predict traffic congestion in cities. This research provides valuable insights to address urban mobility challenges and contributes to the development of more efficient and sustainable strategies for traffic management in urban environments [40].

On the other hand, ref. [12] in the Journal of Cleaner Production analyzes the opportunities, issues, and challenges related to the IoT in building a smart and sustainable future. The study provides a comprehensive view of the key aspects and potential impacts of the IoT on environmental, social, and economic sustainability. Its critical and reflective approach contributes to the academic debate on how to harness the potential of the IoT in a responsible and sustainable way.

The journal Geopolitics, History, and International Relations is known for its remarkable scholarly productivity in the field of sustainable practices related to the IoT. While it may not be widely recognized for its scholarly impact in terms of citations, its high number of publications is noteworthy. This journal features articles that comprehensively address the intersection of geopolitics, history, international relations, and the use of the IoT in building smart and sustainable cities. For instance, ref. [41] discusses how to address the COVID-19 crisis by leveraging IoT sensors and machine learning algorithms in data-driven smart cities. This study offers insight into how emerging technologies can contribute to crisis management and building more resilient and sustainable cities. The journal Geopolitics, History, and International Relations has played an important role in providing a space for the publication of relevant and novel research in this area, although its academic impact in terms of citations may be limited.

Another article published in this journal [42] focuses on the response to and recovery from the COVID-19 pandemic in the context of governance and management of smart and sustainable cities. The study emphasizes the critical role of data-driven IoT systems and machine learning-driven analytics in addressing the challenges posed by the pandemic and promoting urban resilience. Although this article may not have received a high number of citations, it contributes to the advancement of knowledge and offers valuable perspectives on how emerging technologies can drive sustainability and efficiency in city management.

Figure 5 identifies the main countries producing knowledge around the use of the IoT in sustainability practices, comparing the number of citations and publications on the topic. India, China, and the United States stand out as the main references in terms of scientific productivity and academic impact in the field of sustainable practices related to IoT. The article by Yadav et al. [43] demonstrates India's significant contributions in this area. This article presents a model for achieving global sustainability in the multi-tiered agri-food supply chain through the use of IoT technology, particularly in the context of natural epidemic outbreaks. The study addresses key challenges in combining the IoT with sustainable supply chain management and provides valuable insights for improving resilience and efficiency in this critical sector. Additionally, the article highlights India's commitment to promoting sustainable practices through the use of emerging technologies.

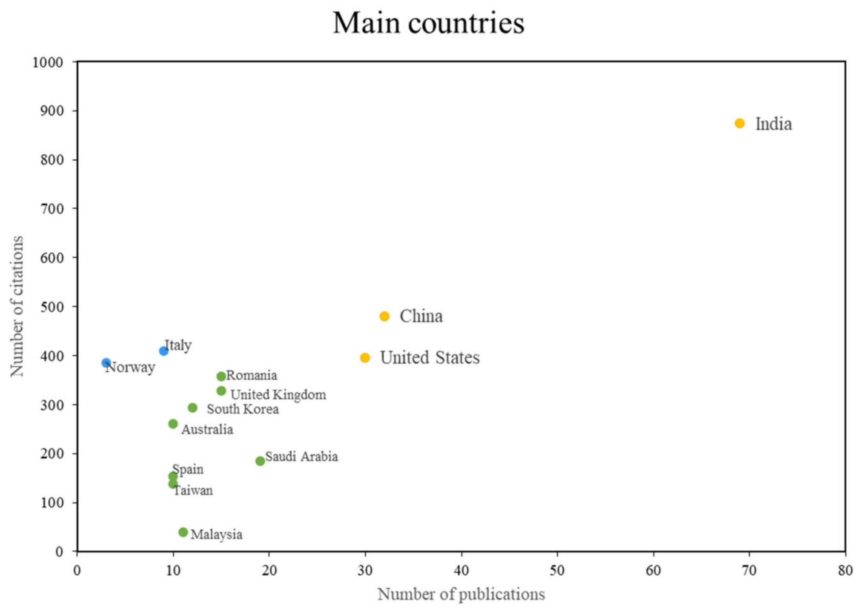

Figure 5. Main countries. Own calculations based on Scopus and Web of Science.

Similarly, in 2019, Manavalan and Jayakrishna conducted a literature review to identify trends and explore the potential of implementing the IoT in the sustainable supply chain for Industry 4.0. They proposed a conceptual model from five supply chain management (SCM) perspectives. The purpose of this work is to evaluate the readiness of supply chain management (SCM) for sustainable growth in the context of Industry 4.0. The focus is on business, technology, sustainable development, collaboration, and management strategy perspectives. The goal is to provide a basis for transformation to an Industry 4.0 organization, ultimately becoming a digital enterprise that operates and interacts in digital organizational ecosystems. The above statement presents favorable opportunities but also acknowledges limitations such as lack of security in information technologies, low-skilled labor, and difficulty for small businesses to adopt technologies and adapt to changes. These limitations pose a major challenge for small businesses [32].

China has made significant progress in IoT and sustainability research. One study presented a hybrid electromagnetic/triboelectric generator that enables autonomous flow velocity detection in IoT-based environmental monitoring, demonstrating China's commitment to developing sustainable and efficient solutions through the integration of innovative technologies. The article highlights China's significance in IoT research and its application in environmental monitoring to promote sustainability [44].

The article by Zhao et al. [45] demonstrates the United States' significant contributions to the importance of the Environmental Internet of Things in planning, constructing, and managing sustainable cities in China. The article also highlights the United States' leadership in promoting technological solutions to address urban sustainability challenges. The research presents a comprehensive perspective on the necessity of integrating the IoT in the planning and management of sustainable cities. It also emphasizes the potential impact of these solutions on sustainable urban development.

Additionally, Italy and Norway, despite having a lower number of publications, are acknowledged as significant contributors to the scientific impact of the IoT in sustainability practices. The article by Belli [46] emphasizes the significance of IoT-enabled smart cities in addressing sustainability challenges in Italy. The study analyzes the challenges and approaches required to develop sustainable smart cities, providing a comprehensive vision of the topic. Despite its lower scientific productivity, Italy demonstrates its ability to contribute to the academic discussion on the use of the IoT in the context of sustainable smart cities.

On the other hand, Norway is notable for its academic impact, as demonstrated in [47]. This research explores the enabling technologies and practical applications of IoT and big data analytics in sustainable smart cities. The article emphasizes Norway's significance in sustainable smart city research and offers a comprehensive understanding of the technologies and applications driving the field. Norway is making a significant contribution to knowledge on the use of IoT and big data analytics in the context of sustainable cities.

Saudi Arabia, Romania, and the United Kingdom are also notable for their scientific productivity in the field of IoT use in sustainability practices, despite their lower citation counts. Regarding Saudi Arabia, some studies have addressed IoT vulnerability assessment for sustainable computing. For example, [48] analyzes the threats, current solutions, and open challenges related to IoT security. Despite its lower scientific impact, Saudi Arabia has demonstrated its ability to produce a significant amount of research in the field of IoT vulnerability assessment.

Romania contributes to scientific productivity in the field of sustainability through an article by Nica et al. [49]. The study focuses on IoT-based real-time production logistics, sustainable industrial value creation, and AI-driven big data analytics in cyber–physical smart manufacturing systems. Despite its lower scientific impact, Romania demonstrates its commitment to research at the intersection of the IoT and sustainable manufacturing.

Finally, a paper by Peoples et al. [50] evaluates the performance of green data center management in the United Kingdom to support sustainable IoT growth. The study examines how data centers can adopt more sustainable practices to support IoT growth. Despite its lower scientific impact, the United Kingdom demonstrates its commitment to sustainable data center research and its contribution to building a more sustainable IoT.

4. Discussion

Research on sustainability has developed in response to social, economic, and academic priorities. Investigative approaches are tailored to the demands and needs of the time. Figure 6 shows the thematic evolution of research on IoT and sustainability over time. The thematic evolution can be observed by analyzing the most frequently used keyword for a given year. In 2012, the most common term was ‘system level approaches’, which investigates the role of the Internet of Things in agricultural systems. The focus was on using the IoT to facilitate sustainable agriculture, understand and support biodiversity management, and manage natural resources such as irrigation water. Finally, ref. [51] presents recommendations for the future development of policies and research strategies to enhance the use of ICT in the agricultural sector.

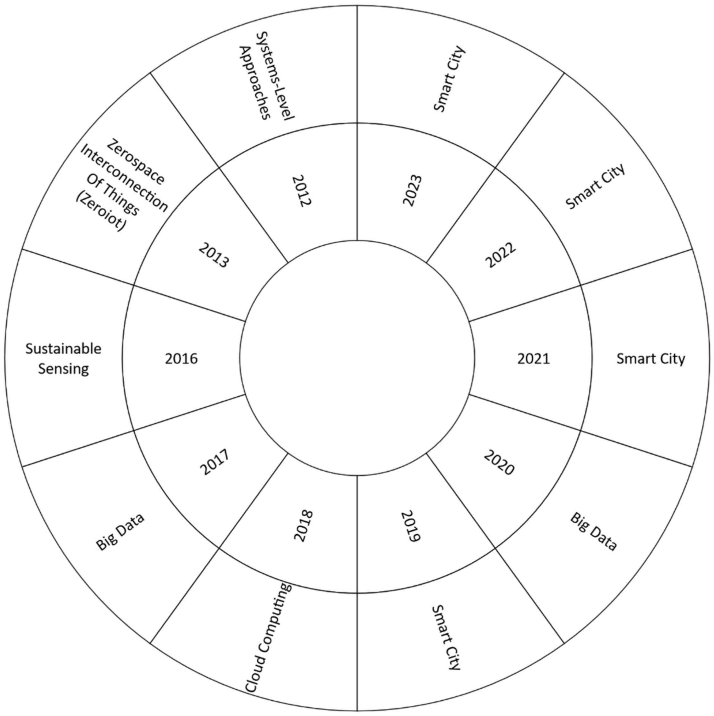

Figure 6. Thematic development. Own elaboration based on Scopus and Web of Science.

In 2013, researchers introduced the term ‘zerospace interconnection of things’ (zroiot), proposing that the IoT could eventually collect, transport, process, model, predict, and provide early alerts for the application of information in the shortest possible time and space. Zeroiot aims to minimize the time and space intervals in its operational process, as well as reduce error and uncertainty [45]. In 2016, the most commonly used term was ‘sustainable sensing’, which emphasizes the importance of using efficient, high-quality, and sustainable sensors. The transmission of data from these sensors is crucial for providing better services, including device authentication. The LEACH routing protocol was emphasized for its ability to transmit sensor data by measuring energy and dynamically assigning groups of sensors, despite its shortcomings, such as key vulnerability, attack eavesdropping, and attack relaying [52].

In 2017 and 2020, research focused on the use and exploitation of big data technologies. The term ‘Big Data’ was used because its analysis became an essential element in obtaining valuable information from the large and diverse data generated by the Green IoT (G-IoT). The obtained knowledge allows for easier decision-making, forecasting, and other activities related to smart city services, contributing to the continuous improvement of G-IoT technologies [53]. Thus, the IoT is associated with big data analytics due to its pervasiveness in many urban areas, making it one of the prevailing computing paradigms of information and communication technology (ICT) for the optimization of energy efficiency and the mitigation of environmental impacts [33].

In 2018, cloud computing became relevant for research in the field of IoT and sustainability. For this thematic axis, cloud computing is integrated with big data to achieve data processing in the cloud, providing a sustainable and environmentally friendly computing system [54]. Cloud computing is a technological solution that enables the integration of smart and sustainable tools and devices [55].

Beginning in 2019 and especially between 2021 and 2023, the use of the IoT for smart and sustainable cities has become increasingly relevant. The term 'smart city' became the most commonly used term during this period. The IoT is considered an emerging technology for smart cities, connecting different digital devices through the Internet and providing innovative facilities for academia, industry, health care, and business [56]. The development of a sustainable smart city involves various aspects, including electronic government, electronic commerce, electronic healthcare systems, construction automation, and others. These elements require the use of the IoT to support the technological infrastructure [57]. However, while the terms 'smart city' and 'big data' are prevalent in current discourse, scientific advancements offer various methods to facilitate a sustainable transition in areas such as sustainable agriculture, urban infrastructure, and Industry 4.0. The literature discusses the relevance of the IoT in transforming the habitat and dynamics of citizens, posing new challenges for technological adoption in the path of process automation, data collection, and storage. It covers production systems, cybersecurity, business, urban dimensions, and territorial development. Research in the field leaves a series of questions that draw new frontiers for knowledge and advancement of research, development, and innovation.

Figure 7 displays the association between concepts based on thematic clusters of different colors for the topic of IoT and sustainability. The term 'smart city' is the main thematic node, showing a stronger relationship with terms such as governance, sensors, and environment [58], in coherence with the thematic evolution. Various research studies have focused on developing models, strategies, and technologies for the construction and evolution of smart cities integrated into urban ecosystems [56].

The following cluster of keywords is centered around the term big data: industry 4.0, food security, and sustainable smart city. Research in this area is focused on agricultural systems supported by the Internet of Things. Some studies have concentrated on modeling a sustainable multi-level system for the agri-food supply chain managed by various emerging applications of IoT technology [43].

The cluster centers around artificial intelligence and includes terms such as blockchain, sustainable computing, security, machine learning, privacy, deep learning, health care, and edge computing. These terms represent the latest technologies that are part of the recent industrial revolution and enable the integration of IoT devices in various industrial sectors and urban development [59]. These technologies are primarily integrated to develop models that collect data and generate predictive intelligent models. Therefore, in this case, they function as enabling technologies in smart cities [40].

The following network has cloud computing as its main term, accompanied by terms such as energy efficiency, energy storage, and data analytics. The literature describes research on the development of smart and sustainable cities using cloud-based network architecture and IoT devices supported by other technologies that enable constant monitoring and control based on network data [2]. Research has investigated the use of radio frequency energy due to the prevalence of wirelessly connected devices and the potential for wireless energy storage to promote sustainability [14].

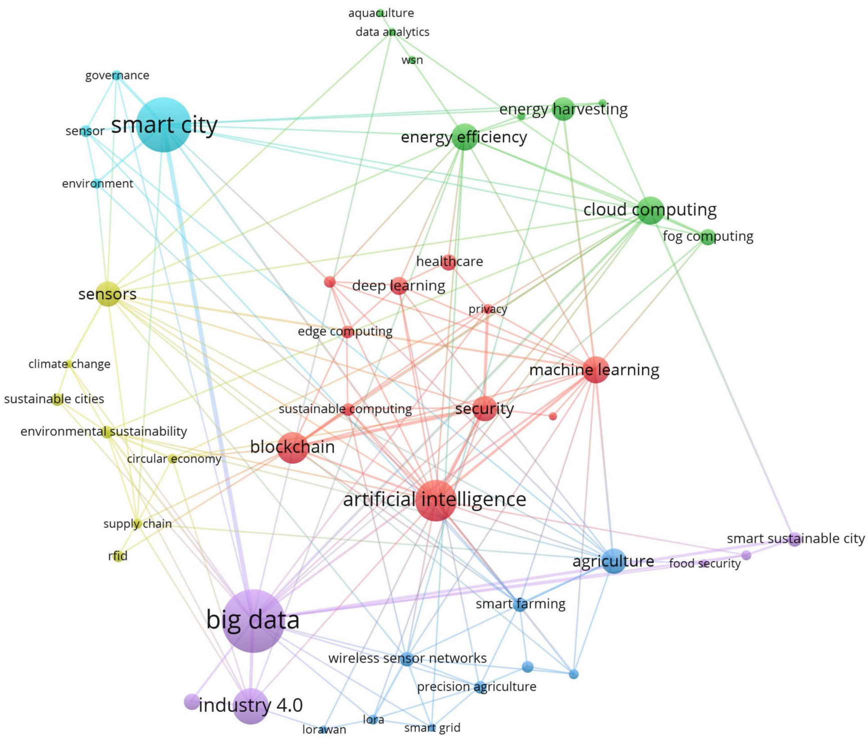

Figure 7. Keyword co-occurrence network. Own elaboration based on Scopus and Web of Science.

The following section focuses on agriculture, with keywords including smart farming, wireless sensor networks; smart cells; precision agriculture; LoRa (long range); and LoRaWan, which refers to long-range WAN networks. This cluster comprises these terms because of the various studies conducted to achieve sustainable agricultural development through continuous monitoring of farms, crops, and other related factors. This facilitates agricultural work without causing significant harm to the soil [60]. This is accomplished through the use of integrated sensors that employ various artificial intelligence techniques to enable remote sensing of smoke, heat, and other necessary factors in the field [61].

The last cluster is headed by the term sensors and is accompanied by words such as climate change, sustainable cities, sustainable environment, circular economy, supply chain, and RFID (Radio Frequency Identification). These terms are grouped in the development of research that proposes the use of different types of wireless sensors for the constant monitoring of factors that intervene in climate change; in this way, it has been possible to integrate these aspects in the construction of sustainable cities [5,62–64].

Figure 8 shows the validity of the key terms discussed in the document using a 2×2 matrix. This graph displays the behavior of keywords, considering their temporality and frequency of use in research on the studied topic. The first quadrant contains the most recent and established terms. Regarding the topic of sustainable cities and the IoT, the term used to describe the first quadrant is smart city. This term is used throughout the document, and the research focuses on the use of IoT devices and how to improve them for use in the construction of smart and sustainable territories [1,6,65].

Between the first and second quadrants lies the term ‘artificial intelligence’. Some research has proposed using this technology to develop intelligent systems in sustainable cities. These models can use data to predict and monitor various factors. Recent research has focused on using this technology to develop energy-efficient networks [2,66] or optimize data-based networks for ecological IoT use [67], among other applications.

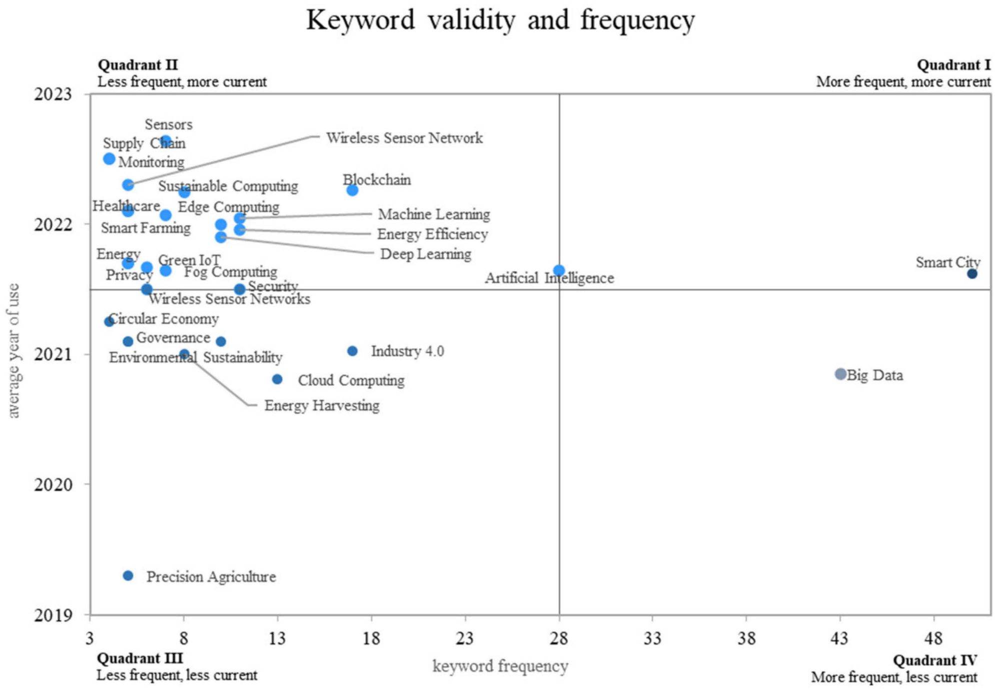

Figure 8. Validity and frequency of keywords. Own elaboration based on Scopus and Web of Science.

The second quadrant groups less common but emerging terms in the field of study. The text mentions various terms, such as sensors, wireless sensor network, blockchain, supply chain monitoring, smart farms, and energy efficiency [2]. For instance, smart agriculture is a development that has emphasized the use of information and communication technology (ICT) in machinery, equipment, and network-based high-tech farm monitoring cycles, with sensors embedded in the IoT [68]. Some research has investigated the use of IoT and AI technology to improve productivity and product quality in agricultural farms, including crops, aquaculture, and livestock [69].

In the context of sustainability, the text highlights several crucial intersections between technological terms. The big data cluster emphasizes the importance of terms such as food security and sustainable smart cities, indicating their fundamental role in creating sustainable systems within the agri-food supply chain. The artificial intelligence cluster emphasizes sustainable computing, machine learning, and deep learning as important concepts for the promotion of sustainability, particularly in the development of smart cities.

The cloud computing cluster highlights energy efficiency and data analytics as key components for building smart and sustainable cities, with a particular focus on cloud-based architecture and IoT devices. The agriculture cluster employs terms such as smart farm, precision agriculture, and wireless sensor networks to achieve sustainable agricultural development through continuous monitoring supported by integrated sensors and AI techniques.

The sensors cluster emphasizes the use of wireless sensors to monitor factors related to climate change and integrate them into the construction of sustainable cities. These developments emphasize the integration of cutting-edge technologies that prioritize sustainability in agriculture, urban development, and environmental monitoring. The 2×2 matrix analysis further reinforces the importance and prevalence of terms such as 'smart city' and 'artificial intelligence' within the broader sustainability discourse, highlighting their relevance over time and the frequency of their use.

Other terms found in this group of words include 'health care' [5]. This field is more focused on using wearable technology (wearables) to monitor various factors related to individuals' health status [70]. Additionally, there is research on security and privacy, with the latter investigating ways to improve network security [71,72]. Finally, this document also mentions fog computing, edge computing, and machine learning, which are related to the development of smart and sustainable cities.

The third and fourth quadrants include previously discussed terms such as security and wireless sensor networks. Additionally, there are terms such as circular economy, governance, Industry 4.0, sustainable environment, energy storage, and cloud computing. These terms are well-established in the research on sustainable cities and the Internet of Things. Additionally, the term precision agriculture, which involves using devices to monitor and control factors related to agricultural production, is also located in the third quadrant. In the fourth quadrant, there is the term 'big data', which is a basic concept that facilitates the analysis of data necessary for the use of technologies in different areas of smart city construction. However, it is also a decreasing term in the field of knowledge on sustainable cities and the IoT.

There is a clear trend towards integrating emerging technologies such as artificial intelligence, wireless sensors, blockchain, and cloud computing. These advances reflect a reality where research and practice aim to create more efficient, safer, and sustainable urban environments. For instance, smart agriculture emphasizes the use of the IoT and AI to improve agricultural productivity. This illustrates how theory is materializing into concrete practices that transform traditional agriculture into a more technological and efficient sector.

Similarly, there is a growing interest in security and privacy issues. This suggests a concern with respect to addressing the ethical and legal challenges associated with the proliferation of data and connected devices in urban environments. This trend signals the need to balance technological progress with the protection of individual privacy and information security. The research shows a trend towards implementing IoT-based solutions to promote sustainability in cities. It emphasizes the need to address ethical and legal aspects to ensure equitable and responsible urban development.

Figure 9 displays the main concepts, their recent usage, and the most significant year for each concept. This information can be used to develop a research agenda for the future. For instance, monitoring, supply chain, and fog computing are the most recent terms that were used significantly in 2022. These terms may be of interest for future research on sustainable cities and the IoT. Monitoring based on the use of IoT devices may require novel network structures and sensors connected to the network that transmit data.

The most frequently mentioned terms between 2021 and 2022 were blockchain, sustainable computing, energy efficiency, artificial intelligence, machine learning, deep learning, energy, Internet of Things, wireless sensor network, and fog computing. These terms are integrated because of the ongoing effort to reduce energy consumption in smart devices and sustainable spaces. However, due to the large amount of data exchanged and the potential distances and data sources involved, a data storage model outside the cloud and closer to the source may be beneficial for future network and wireless sensor architectures [1,13,73]. During the same time period, the terms 'smart farms', 'health care', and 'smart cities' emerged. These terms became more prevalent in 2021, but their potential for improving IoT device performance, particularly in adverse weather conditions, through enhanced connectivity and response times, remains to be explored. Additionally, energy storage solutions, such as energy harvesting, will be investigated in locations where traditional energy sources are not feasible.

On the other hand, the terms cloud computing, Industry 4.0, big data, security, and agriculture mainly refer to technology and its applications. These terms emerged around 2019 and were primarily used in research between 2019 and 2020. However, they may no longer be valid. While a research agenda can be proposed, it should primarily focus on cloud computing, privacy, and security and propose strategies for the use and storage of data in the cloud or elsewhere. Finally, some terms that are no longer valid include 'circular economy', which was popularized around 2017 and reached its peak between 2020 and 2021 and is still being researched in 2022. Similarly, the term 'governance', which emerged in 2019, was maintained until 2021. The concept of 'precision agriculture' remained in research for about 10 years, from 2012 to 2022, and was included in research on sustainable cities and the IoT, mainly between 2018 and 2019. The terms 'sustainable environment', 'cyber–physical system', and 'agriculture' are no longer current in the research agenda of sustainable cities and the IoT.

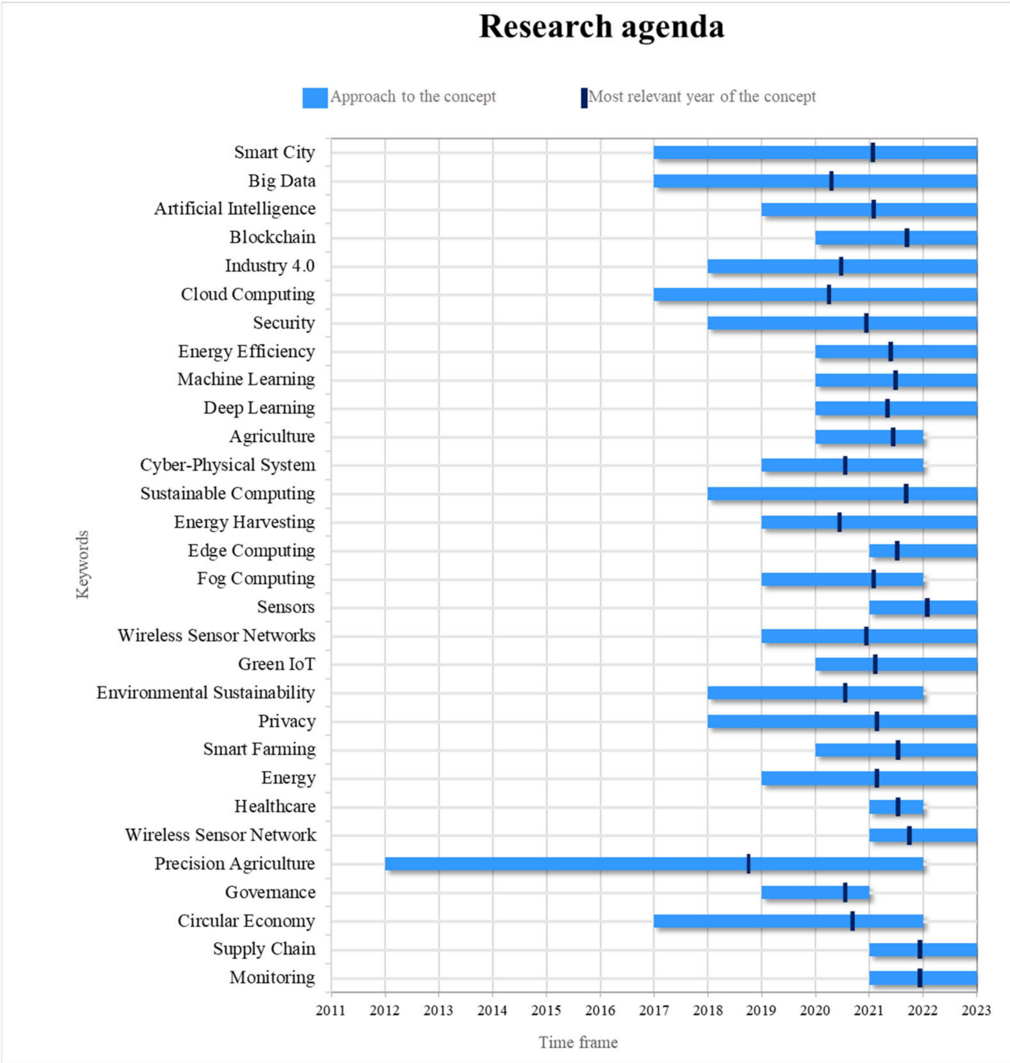

Figure 9. Research agenda. Own elaboration based on Scopus and Web of Science.

The successful implementation of the IoT in sustainability initiatives faces several fundamental challenges that go beyond simple technological adoption. One of these challenges is the integration of emerging technologies, which involves harmonizing disparate devices to ensure smooth and seamless operation. This situation leads to the generation of a significant amount of data, which requires a scalable storage system to process the information detected by sensors. To address this challenge, the integration of cloud and IoT technology has been proposed to enable the storage and processing of data in an environment that can accommodate the growth of information [74].

However, addressing concerns related to data security is also linked to managing energy efficiency, adding another layer of complexity to the impact of the IoT on sustainability outcomes. Optimizing energy efficiency is critical to maximize the performance of IoT systems and ensure secure transmission for users. Therefore, it becomes a multi-objective problem that includes optimizing transmission power, power allocation, and antenna selection [75].

Collecting and analyzing information from various sources requires a strategic approach to extract meaningful insights. Comprehensive access to data enables more sustainable systems, promising a new vision for government data in smart cities. However, device interoperability presents a significant challenge due to the variety of technologies and protocols hindering effective communication between different devices. The absence of standard protocols or methods for representing data and expressing services, combined with the private ownership of many current systems, impedes cooperation between different technologies, devices, services, and systems [76].

In this context, ensuring privacy is a critical concern, particularly when attempting to enhance the effectiveness of environmental monitoring without compromising the confidentiality of information [77]. To overcome these challenges, it is essential to establish clear regulatory frameworks that provide the necessary structure to support the ethical and secure implementation of the IoT. At the same time, cross-sector collaboration can lead to more comprehensive and effective solutions by converging knowledge and resources from different sectors. A holistic approach that embraces the principles of environmental sustainability—not just operational efficiency—can be adopted. This includes promoting sustainable business models that integrate environmentally friendly practices at their core [78].

Based on the evolution of the terms and their relevance in the research on sustainable cities and the IoT, several comprehensive recommendations can be derived to guide future research agendas. It is crucial to focus on the most recent and promising concepts, such as monitoring, supply chain, and cloud computing, which have emerged strongly in recent years. For these terms, it is suggested to investigate innovative models of IoT networks and sensors that allow for efficient data transmission and precise monitoring, especially in constantly changing urban environments.

For relevant but less recent terms such as blockchain, artificial intelligence, machine learning, energy efficiency, and smart cities, it is recommended to continue exploring new strategies to integrate these technologies into the construction of sustainable spaces. This could include developing data storage models outside the cloud and closer to the source, as well as optimizing the connectivity and response times of IoT devices, especially in adverse weather conditions.

Finally, it is suggested to archive terms that have lost relevance, such as circular economy, governance, and precision in agriculture. Efforts should be focused on more relevant and emerging topics. However, it is important not to lose sight of the underlying principles of sustainability and efficiency, even as new concepts and technologies are explored. A comprehensive research agenda should prioritize innovation in critical areas, optimization of existing technologies, and adaptation to the changing needs of a world that is constantly evolving towards sustainability.

5. Practical Implications

Bibliometrics has practical implications for the development of policies and strategies in urban environments and socio-economic systems. The shift from system-level approaches to a more detailed analysis of aspects related to smart cities and big data management represents a significant conceptual evolution. This evolution necessitates a more comprehensive and specific approach to addressing the challenges and opportunities presented by the implementation of the IoT in the construction of sustainable urban environments.

The thematic cluster analysis reveals a conceptual connection among terms such as smart city, governance, sensors, and environment. This suggests an inherent relationship between technology, urban management, and environmental sustainability. These findings have practical implications for the formulation of policies and strategies that promote the effective integration of IoT technologies in urban planning and sustainable development.

An analysis of the frequency and usage of keywords indicates emerging and declining trends in the utilization of terms associated with the IoT and sustainability. Notably, the relevance of concepts like big data is decreasing, while terms such as sensors, wireless sensor networks, blockchain, supply chain monitoring, smart farms, and energy efficiency are becoming more prominent. These trends indicate the necessity of concentrating research and policy on emerging areas that require more attention and technological development to promote urban sustainability.

Additionally, this study can help identify gaps and areas of opportunity in research. By analyzing gaps in the literature, researchers and policymakers can focus their efforts on underrepresented areas that may be critical to advancing the effective implementation of the IoT. In sustainability practice, a more accurate understanding of research needs can guide resource allocation and strategic planning.

Additionally, bibliometrics can provide valuable insights into collaborations and research networks in the field of the IoT and sustainability. Identifying successful collaborations and strong research networks can foster interdisciplinary collaboration and knowledge transfer between different sectors and disciplines. This collaboration has the potential to stimulate innovation and expedite the development and implementation of sustainable technological solutions.

Finally, there may be practical implications for policy formulation and decision-making. By understanding research trends and researcher preferences, policymakers can design policies and programs that promote research and innovation in areas crucial to the IoT and sustainability. Additionally, bibliometric evidence can support data-driven policy-making and provide a framework for evaluating and monitoring IoT initiatives in sustainability practices at local, national, and international levels.

6. Limitations

One limitation of this study is that it did not include other relevant databases, such as IEEE. This exclusion may have limited the search coverage and potentially missed relevant studies on the application of the Internet of Things in sustainability practices. Focusing solely on the Scopus and Web of Science databases may result in the exclusion of relevant works, limiting the comprehensiveness of the results and the representativeness of the research landscape in this field.

One limitation of this study is the lack of a formal analysis of the risk of bias in study selection. Although a rigorous selection process based on predefined criteria was implemented and an internal automation tool was used to minimize the omission of relevant studies or incorrect classifications, no explicit risk of bias assessment was conducted. The inclusion or exclusion of certain studies may have been influenced, which could have impacted the integrity and validity of the bibliometric results obtained.

7. Conclusions

Research on the use of the IoT in sustainable cities began in 2012. However, it only gained relevance in 2016 and showed exponential growth until 2022, when the largest number of studies was presented. It is important to note that 2024 is still ongoing. The publications are mainly found in journals that focus on sustainability or research related to climate and environmental policies. Additionally, the primary authors who have contributed to these same journals have taken a more technical approach, focusing on how data can aid in the creation of sustainable cities. They emphasize the use of technological advancements and data in territorial development.

Based on the literature, the development of sustainable cities using IoT technology requires further investigation in various fields of knowledge. The text avoids subjective evaluations and uses clear, concise language with a logical flow of information. Technical terms are explained when first used, and the formal register is maintained throughout. The text is free from grammatical errors, spelling mistakes, and punctuation errors. No changes in content were made. One of the main areas of ongoing research in this field is the efficient use of energy required for these devices. Although this topic has been studied for several years, there are still various gaps that need to be investigated, particularly in energy storage and the use of cloud computing and big data to generate machine learning models that can identify different ways to improve energy consumption.

India is one of the main references on the subject, with authors from the country being the greatest reference. This may be due to the country's concern about its conditions as an emerging country with a worrying demographic situation, leading to the search for sustainable solutions. In terms of thematic evolution, the most recent concept is smart cities. Scientific progress has shown that technology is a valuable tool for achieving social and economic development and growth in cities. Therefore, the terms 'smart cities', 'big data', and 'artificial intelligence' emerge as the main thematic clusters.

The use of the IoT in sustainable and efficient agricultural systems is an important aspect. In this context, the IoT refers specifically to sensors that can monitor and identify factors such as humidity, heat, climate, and others in the field through deep learning or other machine learning methods. The research agenda is focused on designing new devices for health monitoring that can predict health conditions. Additionally, new governance models are being developed that prioritize health, including the incorporation of new technologies to facilitate user services in smart and sustainable cities. It is important to consider the validity of keywords and one of the aspects found on the agenda, which is wireless sensor networks. Security and privacy are important and relevant discussions in research. Additionally, future research could explore the characteristics of wireless sensor networks and their potential use in fog computing for storage of sensor data.

In conclusion, the research analysis indicates clear trends that outline the future path of IoT research in the context of sustainable cities. There is a growing interest in energy efficiency, where energy storage and the application of technologies such as cloud computing and big data analytics emerge as key areas for future research. In the coming years, considerable attention will be required to develop machine learning models that optimize energy consumption and improve resource management. The research suggests a wider application of the Internet of Things across multiple sectors, including agriculture and health. This technology has the potential to revolutionize the monitoring and management of resources and services. Priority research areas include the development of devices and systems for sustainable agriculture, health monitoring, and improving governance in sustainable urban environments. Similarly, security and privacy are critical issues in the context of wireless sensor networks that require significant attention. Exploring technologies such as fog computing to address these challenges and ensure data integrity will be fundamental to advancing research in this area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16072663/s1, The PRISMA 2020 Checklist.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviation	Meaning
IoT	Internet of Things
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
AI	Artificial intelligence
UAVs	Unmanned aerial vehicles
WPCN	Wireless communication network
PCE	Power conversion efficiency
SCM	Supply chain management
ICT	Information and communication technology

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