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IoT-based smart cities: a bibliometric analysis and literature review

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ABSTRACT
Modern cities face many challenges related to globalisation, metropolisation and digitalisation. The smart city concept, which has been gaining popularity in recent years, is considered an answer to their needs. One of the paradigms of modern smart cities is the Internet of Things. This article aims to identify the main research directions and trends in the scientific literature in the field of Internet-of-Things-based smart cities. The author of the paper conducted a bibliometric analysis of publications from 2012–2021, collected from the Web of Science, Scopus and IEEE Xplore databases. The methodology includes: (i) the selection of databases and key words, (ii) defining search criteria, (iii) data export, creation of an aggregate database and record selection, and (iv) the analysis of the results and identification of the major research trends. The study involved 1019 publications. The last stage of the research process identified the leading countries, institutions, journals, and authors in terms of publication activity, as well as the most frequently occurring terms. The key word analysis allowed identifying five main research directions: IoT application domains in smart cities, IoT architecture for smart cities, energy, security and privacy and data. Within each area, the main research themes have been identified, and selected publications have been reviewed.

KEY WORDS
smart city, Internet of Things, IoT, bibliometric analysis

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Introduction

Cities are complex structures undergoing constant change. They comprise many elements and multidimensional internal and external relations connecting them (Mora et al., 2017; Parysek, 2015; Scott & Storper, 2015). They are centres of service provision, places of creativity development, and innovation and knowledge transfer (European Commission, 2011). Numerous amenities offered by cities (better health care, educational and employment opportunities)

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make them a desirable direction for migrants from rural areas (Gosnell & Abrams, 2009), which results in the dynamic growth of cities and in the depopulation of rural areas. Currently, over 55% of the world's population lives in cities, and this percentage is projected to increase to 68% by 2050 (United Nations Human Settlements Programme, 2020). Rapid urbanisation makes cities catalysts for economic development at all spatial scales (national, regional and local) (United Nations Human Settlements Programme, 2020). However, the constant influx of population requires the development of transport, technical and communication infrastructure, and, thus, involves the need to occupy unused land and undertake tremendous investments. Enormous population growth can also lead to an increase in unemployment and a decrease in the quality of life of urban residents (Habibi & Asadi, 2011). Urban sprawl is also associated with several processes that affect the environment, including increased energy consumption and air pollution, reduced open space, and hindered waste management (Gil-Garcia et al., 2015). Thus, modern cities face new challenges related to management, logistics, communication, and environmental protection, ensuring high quality of life, and involving residents in decision-making processes (Winkowska et al., 2019; Winkowska & Szpilko, 2020). Years of research on cities specificity have led to many concepts of their development. Currently, additional growth factors are identified, among which advanced technologies play a leading role (Stawasz et al., 2012). The penetration of a broader technological trend — the Internet and ICT technologies — into the physical structures of the city has led to the smart city concept (Prado et al., 2016). It is an integrated system that uses advanced technologies to improve the flow of information, increase the quality of life of residents, and ensure sustainable economic development (Rudewicz, 2019). Smart cities constantly evolve, using the latest technological developments, making it difficult to create a single, consistent definition of the concept. Moreover, the fourth industrial revolution has brought new technologies with unprecedented scope and speed of development. It sheds new light on the functioning of smart cities (Ratti, n.d.). One pillar of the fourth industrial revolution is the Internet of Things. It is a vision of an integrated and distributed network of connected and communicating objects equipped with sensors, transmitters, and protocols (Xia et al., 2012; Zanella et al., 2014). IoT solutions allow cities to optimise the use of resources and increase the quality and availability of the services offered while reducing the cost of the activities (Zanella et al., 2014).

There are many publications in the literature addressing smart cities. However, no attempt has been made to provide a comprehensive picture of the current state of research on IoT-based smart cities from a bibliometric perspective. This article evaluates the scientific production in papers on IoT-based smart cities. The study included a bibliometric analysis of publications from 2012 to 2021 available in Scopus, Web of Science and IEEE Xplore databases. Bibliometric analysis is a method that enables the evaluation of scientific research, identification of main research directions and development trends in a given research area. It involves the application of quantitative techniques. The first stage of the study included an analysis of the publications, their subject areas, changes in their number over the years and identification of the most frequently cited articles, the most productive authors, journals, countries and institutions. In the second stage, the most frequently occurring key words in IoT-based smart cities were presented. The publication comprises four parts. The first part presents the theoretical basis of the smart city concept and the Internet of Things paradigm. The second and third parts consist of, respectively, a description of the methodology of the analysis and its results. The final part discusses the results and presents conclusions.

1. Literature review

1.1. Smart cities

Concepts of urban development have changed over the years, depending on current needs and trends (Saad et al., 2014). Since the birth of digital computing in 1950, digital technologies have penetrated cities. Before the beginning of the 21st century, there were already hundreds of publications addressing the digitisation of cities and its impact on urban residents. New concepts have emerged with information technology as the catalyst for urban development, i.e., computable cities or cyber cities (Kitchin et al., 2018). In the '90s, the concept of a smart city appeared in consideration of urban development (Dameri & Cocchia, 2011; Lombardi et al., 2012). Spread of the Internet and the development of information and communication technologies (Mohanty, 2016) allowed for easier creation, analysis, and transmission of information. It increased creativity and innovation and started creating an information society (Yun

& Lee, 2019). The expansion of the existing city model into a new digital dimension (Roberts, n.d.) required the integration of physical and virtual environments.

The potential of new technologies for the efficient and effective functioning of territorial units makes smart cities an attractive vision for researchers, policymakers and urban planners (Yigitcanlar et al., 2019). Besides the smart city concept, related concepts appear in the literature, often used as alternative terms to smart city, i.e., digital city (Dameri & Cocchia, 2011; Ishida, 2017), wired city (Dutton, 2019; Strauss et al., 1996), information city (Hepworth, 1990), ubiquitous city (Shin, 2009), sensing/sensor city (D'Amico et al., 2020), tech city (Nathan & Vandore, 2014), hybrid city (Streitz, 2015) or electronic city (Tohidi & Jabbari, 2011). Undoubtedly, the smart city concept has become the most popular. However, a definite increase of interest in the scientific community occurred after 2011 (Winkowska et al., 2019), when the European Union started promoting the "smart" principle as one of the main directions of urban development (Dameri & Cocchia, 2011; Hajduk, 2016).

Despite its growing popularity, no single, coherent definition of a smart city has yet been created (Min, Yoon, & Furuya, 2019), and the literature provides many descriptions (Albino, Berardi, & Dangelico, 2015; Lima et al., 2020; Bashynska & Dyskina; 2018; Szpilko, 2020). Most often, the city's intelligence is assumed to be demonstrated by the existence of six "smart" dimensions: governance, economy, living, people, mobility and environment (Caragliu, Del Bo, & Nijkamp, 2011; Lombardi et al., 2012; Winkowska et al., 2019). Table 1 presents the description and characteristics of smart city dimensions.

It can be noted that the dimensions of a smart city do not focus only on technological aspects (Table 1). As Caragliu et al. pointed (2011) out, a city can be called smart if the investments (in transport infrastructure, information and communication infrastructure, and social capital) with simultaneous rational management of resources and inhabitants' involvement in the management process, ensure high quality of life and economic growth. Technologies play the role of tools that improve the functioning of the mentioned areas. According to Partridge (2004), a smart city is a place where technology facilitates access to public services, accelerates the flow of information and strengthens freedom of speech. According to Washburn et al. (2010), the concept is to use Smart Computing technologies to create key services and urban infrastructure elements. Bakıcı et al. (2013) defined it as a city having ICT and Web 2.0 technologies integrated with other activities to improve the management and facilitate the identification of new solutions in the field. All the taken actions aim to ensure the sustainable development of the city and the high quality of life for its residents. Although most definitions emphasise that technologies are only a tool to achieve certain goals, they are undoubtedly one of the key elements that prove the "intelligence" of cities (Gil-Garcia et al., 2015).

In recent years, technologies of unprecedented scope and efficiency have emerged. Many researchers emphasise that the changes taking place unequivocally signal the beginning of the next industrial revolution. Devices no longer serve only to connect users to the Internet but integrate the physical world with the digital world, creating cyber-physical systems (CPS) (Borgia, 2014). As Borgia pointed out, CPS are based on four key elements: advanced robotics, autonomous vehicles, knowledge-based work automation, and the Internet of Things. A smart city is

Tab. 1. Characteristics of smart city dimensions

Dimension	Characteristics
Smart people	A city that is socially and ethnically diverse, with highly qualified, experienced, open-minded, creative and engaged citizens.
Smart living	A city attractive to live in, with a high level of social cohesion, whose residents have a sense of security, good housing conditions, high quality medical and educational services, and access to culture.
Smart governance	A city with a transparent system of governance, using services that facilitate management and strengthen public participation, in which various actors are involved in decision-making processes.
Smart economy	A productive, innovative and entrepreneurial city with a flexible labour market and a positive image, undertaking national and international collaborations.
Smart mobility	A city that is communicatively accessible at all scales (local, regional, national and international), equipped with ICT infrastructure in which safe, sustainable and innovative forms of transport are used.
Smart environment	A city with a low level of pollution, where resources are managed rationally, energy consumption is optimised, alternative energy sources are used, and actions are taken to minimise the pressure on the environment.

Source: elaborated by the author based on Giffinger et al., 2007; Sikora-Fernandez & Stawasz, 2016.

one of the application areas of the Internet of Things (Pourghebleh & Navimipour, 2017).

1.2. Internet of Things

The term "Internet of Things" was introduced by Kevin Ashton in 1999. During a presentation for Procter & Gamble (P&G), he spelt out a vision of a world in which physical objects are connected to the Internet through sensors and a platform enabling a two-way exchange of information in real-time (Borgia, 2014). However, this concept gained popularity six years later, when the International Telecommunications Union presented a publication "The Internet of Things". This means that the IoT encompasses all objects, including those that were not previously part of a system (Swan, 2012). It is an integrated network that allows two-way communication between objects and users (human-to-human, thing-to-thing, human-to-things) through the use of embedded sensors, processors and actuators, and communication solutions (e.g., Bluetooth, Wi-Fi, Zigbee) (Group et al., 2015; Yaqoob et al., 2017).

The perception of the Internet of Things depends on the research context. According to Lynn et al. (2020), the literature presents two main conceptualisations of the IoT. The first includes only technical aspects, while the second also considers all interactions between technical and social elements. Based on Sethi and Sarangi (2017), the IoT is not a single technology but a combination of a wide range of integrated technologies and communication protocols. These can include, e.g., cloud computing, fog computing, edge computing, RFID, WSAN, machine-to-machine (M2M) communication, and IPv6 (Lynn et al., 2020). According to Atzori et al. (2010), the difficulties defining the Internet of Things also arise from the two-word structure of this term. It can be defined in two ways, from the perspective of the network (the internet-oriented vision) and things (the things-oriented vision). There is also a third semantic perspective (semantic-oriented vision). Based on Atzori, it is the most accurate view of the IoT as a common element of all three perspectives.

Numerous objects connected to the network generate vast amounts of data. According to Miorandi et al. (2012), the IoT is based on three basic functions of smart objects — traceability, communication, and interaction. Thus, IoT architecture should ensure security, reliability, scalability and interoperability of the entire system. The standard IoT architecture comprises five basic layers — perception (device), network (transmission), middleware, application, and business layer. The first layer includes physical objects and sensors (RFID, infrared sensors, 2D-barcode), which collect data from the environment. The network layer allows the data to be transmitted to the processing system using technologies such as Wi-Fi, Bluetooth, 3G, UMTS or ZigBee (Sethi & Sarangi, 2017). This data is received, stored, processed and analysed by the middleware layer using technologies, such as big data analytics and cloud computing. The application layer manages the IoT application areas (smart homes, smart farming, smart cities, etc.) based on the information extracted from the previous layer. Then, data passes to the business layer, where business models, diagrams, and charts are created to determine possible future courses of action (Khan et al., 2012).

IoT can support many areas of daily life, i.e., smart health, smart education, smart buildings, smart industry or smart agriculture. It can be said that smart cities cover most of the potential application areas of IoT solutions (Romanowski & Lewicki, 2018). Fig. 1 shows examples of application areas of the Internet of Things in different dimensions of a smart city.

IoT improves the functioning of educational and medical services (smart education, smart health), increases the comfort of living (smart homes, smart buildings), strengthens public safety (personal tracking), facilitates resource and waste management (smart waste management), environmental monitoring (air quality, water quality, noise level), and allows for early detection of threats and optimisation of energy consumption. It helps to manage smart transport networks (smart roads, smart parking, smart bike systems, smart public transport, smart vehicles, real-time traffic management). IoT solutions also bring many economic benefits, shaping smart sectors of the urban economy (smart industry, smart retail, smart tourism). They also increase the transparency of city government activities and allow residents to participate in shaping city development (Mehmood et al., 2017; Zanella et al., 2014).

Despite its many benefits, the Internet of Things also brings a number of challenges related to (Elkhodr et al., 2016; Khan et al., 2012):

- ensuring privacy and security of:
  - information, which is related to the use of multiple identification technologies (i.e., RFID, 2D barcode) and risks of private information leakage;

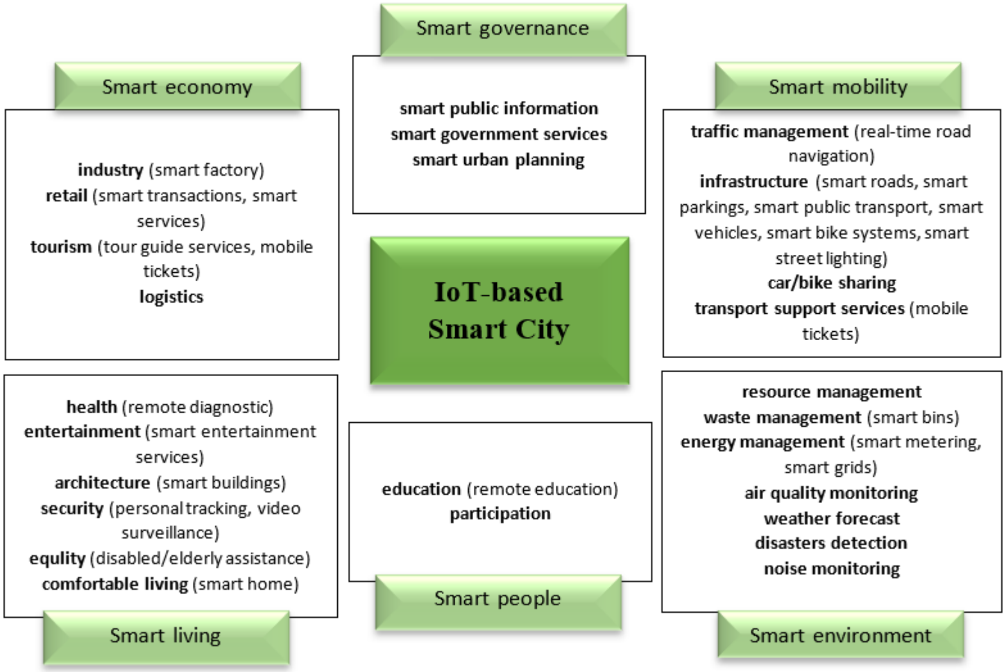

Fig. 1. Applications of IoT in smart cities

Source: elaborated by the author based on Borgia, 2014; Hui et al., 2017; Zanella et al., 2014.

- objects, considering a large number of objects at different locations, posing a risk of unauthorised interference;
- network, dealing with the transmission of vast amounts of data over a wireless network, which can result in an overload and create a risk of unauthorised access;

- data encryption;
- object management (switching on and off, changing target connection networks, detecting failures, updating software);
- identity management — numerous objects connected to the network create problems with their nomenclature and identification;
- integration — connecting multiple devices with different parameters and specifications can make it difficult to achieve interoperability of the entire system;
- optimisation of energy consumption — the increasing number of smart devices and data transfer speeds are associated with higher energy consumption.

The effective implementation of the IoT concept in cities is influenced not only by technological issues but also by social, economic or political aspects. The factors that determine the development of smart cities include the level of digital skills of urban residents, their openness to change, the effectiveness of city authorities in activities aimed at implementing the concept, and the level of investment in research and development activities.

2. Research methods

In an era of the increasing number of publications, the identification, synthesis, analysis and critical evaluation of their content is challenging. This has led to a growing interest in more systematic approaches to the evaluation of scientific production, with a greater emphasis on quantitative methods of data analysis (Ertz & Leblanc-Proulx, 2018; Keathley-Herring et al., 2016). Frequently used methods include bibliometric analysis (Keathley-Herring et al., 2016), which involves the use of quantitative techniques to identify the current state and developmental trends in a research area. Assessments based on bibliometric data are now the basis of research evaluation (Bornmann & Haunschild, 2017; Ellegaard & Wallin, 2015). The aim of the bibliometric analysis is to provide knowledge about the main research directions in a field, research trends, changes in the number of publications over the years, the most productive authors, journals, countries, or research units (Niñerola et al., 2019). Authors use this method both for "mature" research areas (Tran et al., 2019;

Winkowska et al., 2019) and areas with fewer publications (Carrión-Mero et al., 2020; Lim et al., 2021; Tomaszewska & Florea, 2018; Winkowski, 2019). The bibliometric analysis methodology used to achieve the aim of this study is shown in Fig. 2.

The proposed methodology comprises four stages — the selection of scientific databases and key words, the selection of inclusion criteria, data export and aggregate database creation (including their selection), and the analysis of the publication set (Fig. 2). The last stage was divided into two sub-stages. The first involved identifying the most productive countries, organisations, journals, and authors, while the second stage identified the most frequent key words. Then, based on the term analysis, the review of the publication set, and the consultation with an expert, the terms were grouped into thematic clusters depicting the main research directions. Within each cluster, major thematic threads were identified, and selected publications were reviewed.

The bibliometric analysis was performed based on publications available in Web of Science, Scopus and IEEE Xplore databases. It covers publications containing the phrases "smart cit*" and "internet of things" or "iot" in the title. This restriction was made after an analysis of the initial search results, which included publications containing the indicated phrases in the title, abstract, or key words. Next, selected inclusion criteria were applied. The search was conducted for materials published between 2012 and 2021 in English. Articles, conference papers, books, book chapters, reviews and early access were considered. Other publication types (editorial materials, retracted publications, data papers, conference reviews, notes, short surveys, letters, undefined) were rejected. The results of the first search are presented in Table 2.

After searching the terms in titles, abstracts and key words, 4534 records were obtained in the Web of Science, 7809 in Scopus and 4391 in IEEE Xplore

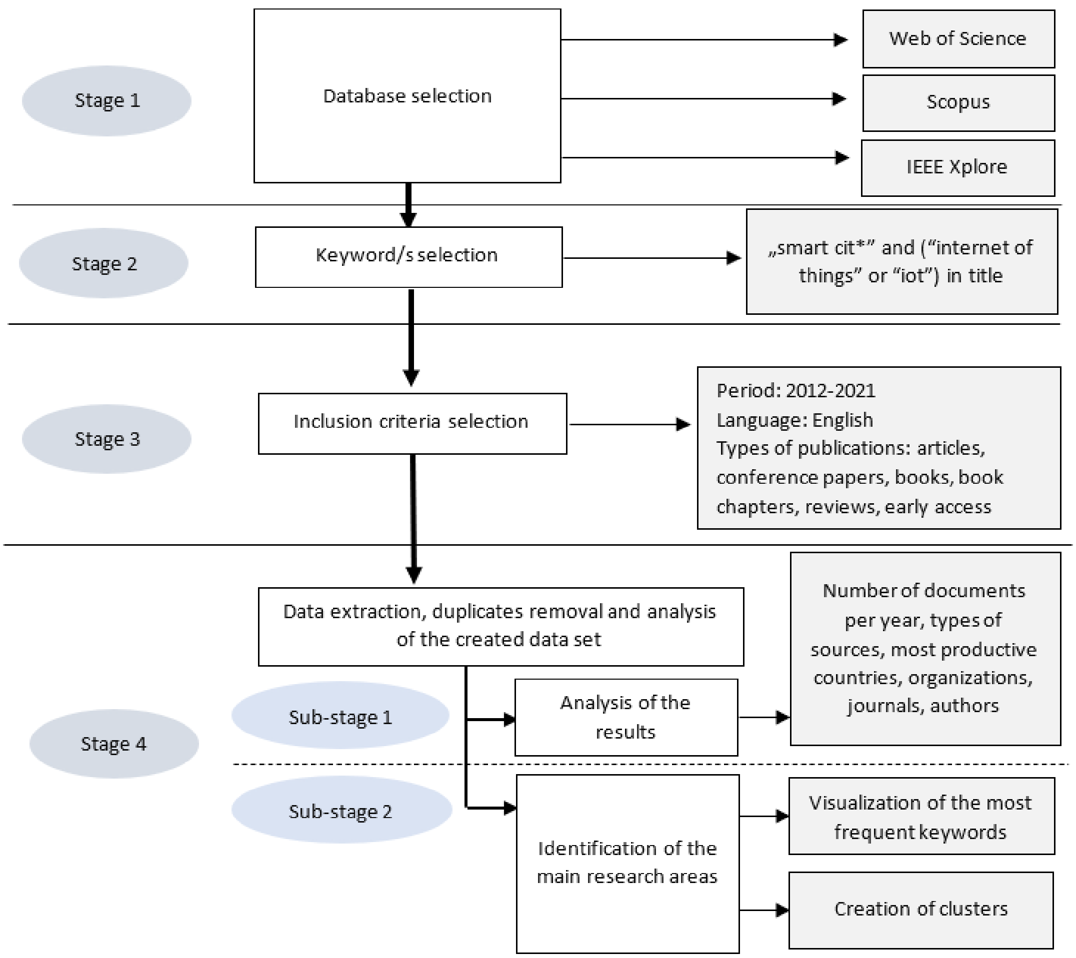

Fig. 2. Proposed methodology for bibliometric analysis

Tab. 2. Results of the first search

Stage	Web of Science	Scopus	IEEE Xplore
Research query	TS=(„smart cit*") AND TS=(„internet of things" OR iot)	TITLE-ABS-KEY („smart cit*") AND TITLE-ABS-KEY („internet of things" OR iot)	„All Metadata": „smart cit*" AND („All Metadata": „internet of things" OR „All Metadata": „iot")
Number of articles before inclusion criteria	4534	7809	4391
Number of articles after inclusion criteria	4482	7451	4389

Source: elaborated by the author based on the Web of Science, Scopus and IEEE Xplore databases.

Tab. 3. Results of the second search

Stage	Web of Science	Scopus	IEEE Xplore
Research query	TI=(„smart cit*") AND TI=(„internet of things" OR iot)	TITLE(„smart cit*") AND TITLE(„internet of things" OR iot)	"Document title": "smart cit*" AND ("Document title": "internet of things" OR "Document title": iot)
Number of articles before inclusion criteria	661	978	459
Number of articles after inclusion criteria	631	945	459

Source: elaborated by the author based on the Web of Science, Scopus and IEEE Xplore databases.

(Table 2). The adoption of inclusion criteria resulted in 4482, 7451, and 4389 records, respectively. The number of publications dated 2021 was 207, 616 and 292, respectively. A preliminary analysis of the results showed that many publications did not serve the aim of the study. Therefore, the search was limited to publications containing the indicated phrases in the title only. Results of the second search are presented in Table 3.

Entering queries yielded 661 records in Web of Science, 978 in Scopus, and 459 in the IEEE Xplore database. Finally, the adopted inclusion criteria resulted in 631, 945, and 459 records, respectively (Table 3). In 2021, 31 publications were registered in the Web of Science database, 72 in Scopus, and 26 in IEEE Xplore.

The file from each of the databases was downloaded. Next, one aggregate file containing 2032 records was created. After removing duplicates and incomplete records, a final set of 1019 records was analysed. The interest in the subject over the years, major research areas, most productive journals, organisations, countries, and authors, and most cited articles were presented. A graphical representation of the most frequently occurring key words and a map which reflects the co-occurrence of key words in the analysed set of publications were showed. The construction of the map in VOSviewer software required a thesaurus file (van Eck & Waltman, 2018).

3. Research results

The first stage of the study comprised the analysis of the interest in the issue over the years, identifying the predominant publication types and the major subject areas. These results were presented separately for each of the three databases. Fig. 3 shows the changes in the number of publications over the years.

For both databases, the number of publications rose during almost the entire period (2012–2019), with a slight decrease in 2020 (Fig. 3). We can observe a definite increase in interest after 2016. The total number of citations for publications indexed in the Web of Science database was 10198, the Scopus database — 16486, and the IEEE Xplore database — 8328. The number of uncited publications was 195, 258, and 163, respectively.

Fig. 4 shows the structure of publications by document type. In the Web of Science database, the largest part was comprised of articles (49.0%) and conference papers (44.6%). In the Scopus database, 50.8% were conference papers, while almost 41% were articles. In the IEEE Xplore, the largest part was

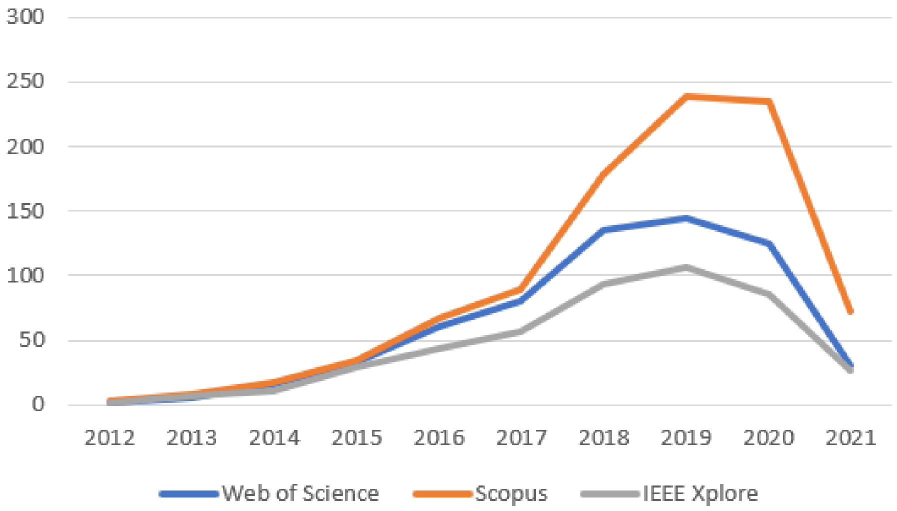

Fig. 3. Number of publications in the field of IoT-based smart cities in the Scopus, Web of Science and IEEE Xplore databases (indexed from January 2012 to March 2021)

Source: elaborated by the author based on the Web of Science, Scopus and IEEE Xplore databases.

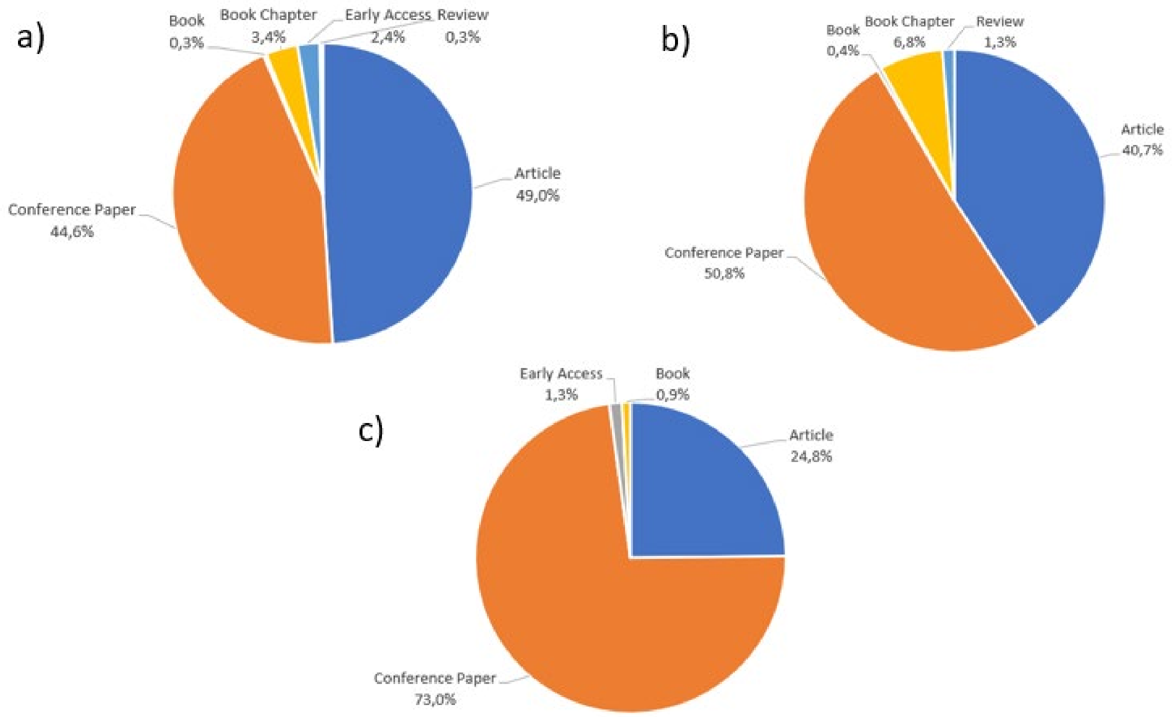

Fig. 4. Type of documents: a) Web of Science, b) Scopus, c) IEEE Xplore

similarly conference papers (73.0%) and articles (24.8%).

Most publications in both databases are assigned to the areas of computer science and engineering, 34.1% and 26.3% in the case of the Web of Science database, and 37.6% and 23.2% in the case of the Scopus database, respectively. A significant proportion of publications in Web of Science are also

Tab. 4. Most productive countries, organisations, journals and authors

No	Item	Np	%ofT	Average citation count		
				WoS	Scopus	IEEE Xplore
	Most productive countries					
1	India	254	24.9%	6.3	6.0	4.5
2	United States	153	15.0%	11.5	14.5	14.6
3	China	133	13.1%	9.8	15.7	7.7
4	Italy	74	7.3%	59.7	71.4	98.8
5	United Kingdom	66	6.5%	25.0	34.4	7.2
6	Spain	58	5.7%	19.1	75.9	113.7
7	Saudi Arabia	57	5.6%	9.0	13.0	11.3
8	South Korea	47	4.6%	22.0	26.3	4.5
9	Pakistan	46	4.5%	9.8	12.1	4.1
10	Germany	39	3.8%	30.7	38.0	17.5
	Most productive organisations					
1	National Institute of Technology Nit System	18	1.8%	14.6	11.8	2.8
2	COMSATS University Islamabad	16	1.6%	15.6	21.2	7.6
3	King Saud University	15	1.5%	25.3	30.6	15.5
4	Commonwealth Scientific Industrial Research Organisation CSIRO	13	1.3%	49.3	74.0	23.8
5	Fraunhofer-Gesellschaft	13	1.3%	19.5	27.8	29.7
6	Universidad de Cantabria	12	1.2%	36.9	53.4	7.6
7	Chinese Academy of Sciences	12	1.2%	10.0	11.0	6.7
8	Indian Institute of Technology System IIT System	10	1.0%	7.5	8.8	1.8
9	Qatar University	10	1.0%	19.8	14.2	8.3
10	Centre National De La Recherche Scientifiquecnrs CNRS	10	1.0%	2.7	5.9	1.4
11	Amity University	10	1.0%	5.8	9.2	5.0
12	ITMO University	10	1.0%	13.8	35.7	30.7
	Most productive journals					
1	IEEE Internet of Things Journal	41	4.0%	116.7	134.8	93.5
2	Sensors	33	3.2%	12.3	18.6	N/A
3	IEEE Access	25	2.5%	8.4	12.5	5.9
4	Future Generation Computer Systems-The International Journal of Escience	17	1.7%	35.4	43.1	N/A
5	Sustainable Cities and Society	15	1.5%	6.8	9.8	13.6
6	IEEE Network	12	1.2%	17.8	24.9	N/A
7	Geopolitics, History, and International Relations	10	1.0%	N/A	2.2	N/A
8	Computer Communications	8	0.8%	2.67	4.71	N/A
9	Journal of Advanced Research in Dynamical and Control Systems	8	0.8%	N/A	1.38	N/A
10	International Journal of Advanced Computer Science and Applications	8	0.8%	0.86	1.38	N/A
	Most productive authors					
1	Zaslavsky, A.	10	1.0%	65.9	96.4	30.7
2	Anagnostopoulos, T.	9	0.9%	10.7	34.9	23.0
3	Guizani, M.	8	0.8%	38.6	83.4	27.7
4	Sanchez, L.	8	0.8%	52.6	72.4	7.5
5	Serrano, M.	8	0.8%	6.7	12.6	6.5
6	Munoz, L.	7	0.7%	59.9	71.6	9.7
7	Sotres, P.	7	0.7%	59.6	83.3	8.3
8	Al-Turjman, F.	7	0.7%	10.2	13.4	N/A
9	Santana J.R.	6	0.6%	69.2	98.6	12.0

Abbreviations: NR — number in ranking, NP — number of publications, %ofT — percentage of the total number of publication (1019), N/A — not applicable.

assigned to the telecommunications area (17.8%). However, it should be noted that the names of the areas vary depending on the database.

To increase the reliability of the results, the author exported records from each database to *.csv files and then merged them. The combined file contained 2032 records. After removing duplicate and incomplete records, 1019 records were obtained.

The next step was to analyse the created set for the most productive countries, journals, organisations, and authors (Table 4). The largest number of publications came from India (254 publications), the United States (153), and China (133). The top ten most productive countries included four European states — Italy, United Kingdom, Spain and Germany. Considering the affiliation of the authors, the highest number of publications came from the National Institute of Technology Nit System network (18), COMSATS University Islamabad (16) and King Saud University (15). The Commonwealth Scientific Industrial Research Organisation CSIRO was ranked fourth (13 publications). Compared to other organisations in the ranking, it had the highest average number of citations in the Web of Science and Scopus databases. In the ranking of the most productive journals, the first position was held by IEEE Internet of Things (41 publications). Articles published in the IEEE Internet of Things Journal also received the highest number of citations in each database. This was followed by Sensors with 33 publications and IEEE Access with 25 publications. Three of the top ten most productive journals were from the Institute of Electrical and Electronics Engineers.

The authors with the highest number of publications were Zaslavsky (10 publications) and Anagnostopoulos (9 publications). Zaslavsky' most cited publication was "Sensing as a service model for smart cities supported by Internet of Things" from 2014. Anagnostopoulos' most cited article was "Challenges and Opportunities of Waste Management in IoT-Enabled Smart Cities: A Survey" from 2017.

Next, the most frequently cited publications were identified (Table 5). The total number of citations was 4890 for the WoS and 6555 for the Scopus. The top

Tab. 5. Ten most cited studies on the Internet-of-Things-based smart cities area

No.	Citation count			Publication title	Author	Journal
	WoS	Scopus	IEEE Xplore			
1	2170	2940	2694	Internet of Things for Smart Cities	(Zanella et al., 2014)	IEEE Internet of Things Journal
2	566	733	653	An Information Framework for Creating a Smart City Through Internet of Things	(Jin et al., 2014)	IEEE Internet of Things Journal
3	446	574	N/A	Sensing as a service model for smart cities supported by Internet of Things	(Perera et al., 2014)	Transactions on Emerging Telecommunications Technologies
4	384	542	500	Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios	(Centenaro et al., 2016)	IEEE Wireless Communications
5	317	384	N/A	SmartSantander: IoT experimentation over a smart city testbed	(Sanchez et al., 2014)	Computer Networks
6	260	370	N/A	Urban planning and building smart cities based on the Internet of Things using Big Data analytics	(Rathore et al., 2016)	Computer Networks
7	230	330	318	Everything You Wanted to Know About Smart Cities The Internet of Things is the backbone	(Mohanty, 2016)	IEEE Consumer Electronics Magazine
8	211	267	259	Enabling Smart Cities through a Cognitive Management Framework for the Internet of Things	(Vlacheas et al., 2013)	IEEE Communications Magazine
9	164	223	107	Internet-of-Things-Based Smart Cities: Recent Advances and Challenges	(Mehmood et al., 2017)	IEEE Communications Magazine
10	142	192	N/A	A Review of Smart Cities Based on the Internet of Things Concept	(Talari et al., 2017)	Energies

Abbreviations: N/A — not applicable.

ten publications included two articles published in IEEE Communications Magazine, IEEE Internet of Things Journal and Computer Networks, and one in Transactions on Emerging Telecommunications Technologies, IEEE Wireless Communications, IEEE Consumer Electronics Magazine, and Energies. The three most cited publications are from 2014. The most cited publication (WoS: 2170, Scopus: 2940, IEEE Xplore: 2694) was the article "Internet of things for smart cities" by Zanella et al. It was followed by the article "An information framework for creating a smart city through internet of things" by Jin et al. (2014). The total number of citations was almost four times less than for the previous publication (WoS: 566, Scopus: 733, IEEE Xplore: 653). Both articles were published in the IEEE Internet of Things Journal. Six articles were from journals of the Institute of Electrical and Electronics Engineers.

The last step of the bibliometric analysis was the identification of the most frequent key words. For this purpose, VOSviewer software was used. The generated set included words having an equal meaning (abbreviations or repetitions) and words that were not related to the subject of analysis. The first set was therefore modified using the prepared thesaurus file. Key words used in search and irrelevant terms were eliminated. Equivalent terms and abbreviations were also replaced. The final set of items contained 54 words. Fig. 5 presents the most frequent terms, while Fig. 6 shows a graphical representation of the links occurring between the individual words.

Among the most frequent key words are terms related to data analysis and processing (cloud computing, big data, fog computing, machine learning) and technologies enabling data collection (sensors, wireless sensor network) (Figs. 5 and 6). Issues related to data security and privacy (security, blockchain, privacy) were also commonly used. These terms also show the most links to other terms. Analysis of the most frequent key words allowed the author to identify five thematic clusters (Fig. 7, Table 6).

The first cluster (yellow) refers to IoT application areas in smart cities (e.g., waste management, environmental monitoring, parking congestion). The red cluster includes terms related to IoT architecture for smart cities. The blue and dark green clusters cover energy issues (energy management, energy efficiency) and security and privacy of IoT use in smart cities (security, privacy), respectively. The last cluster (light green) combines concepts related to data collection and processing in a smart city (e.g., big data, data mining, cloud computing, fog computing, edge computing). Data management issues are closely linked with security and privacy issues, as noted in Fig. 7.

Fig. 5. The most frequently occurring key words

Source: elaborated by the author using WordArt.

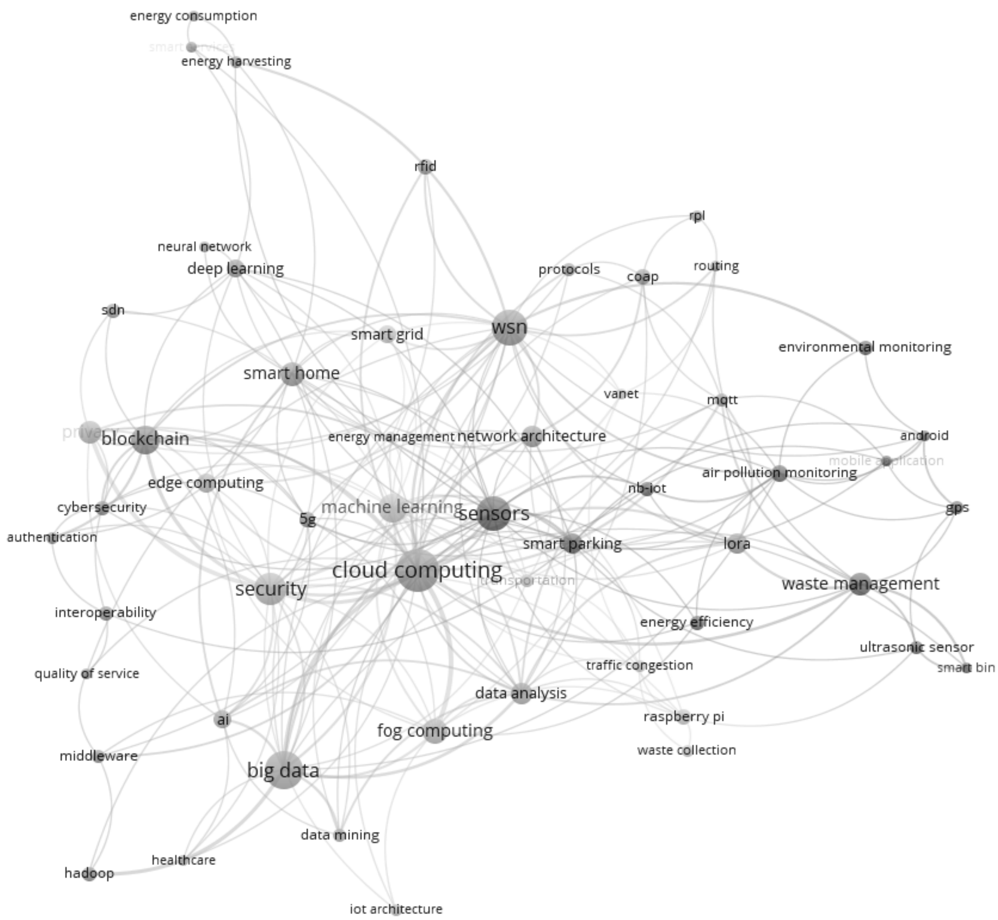

Fig. 6. Key word co-occurrence map

Source: elaborated by the author using the VOSviewer software.

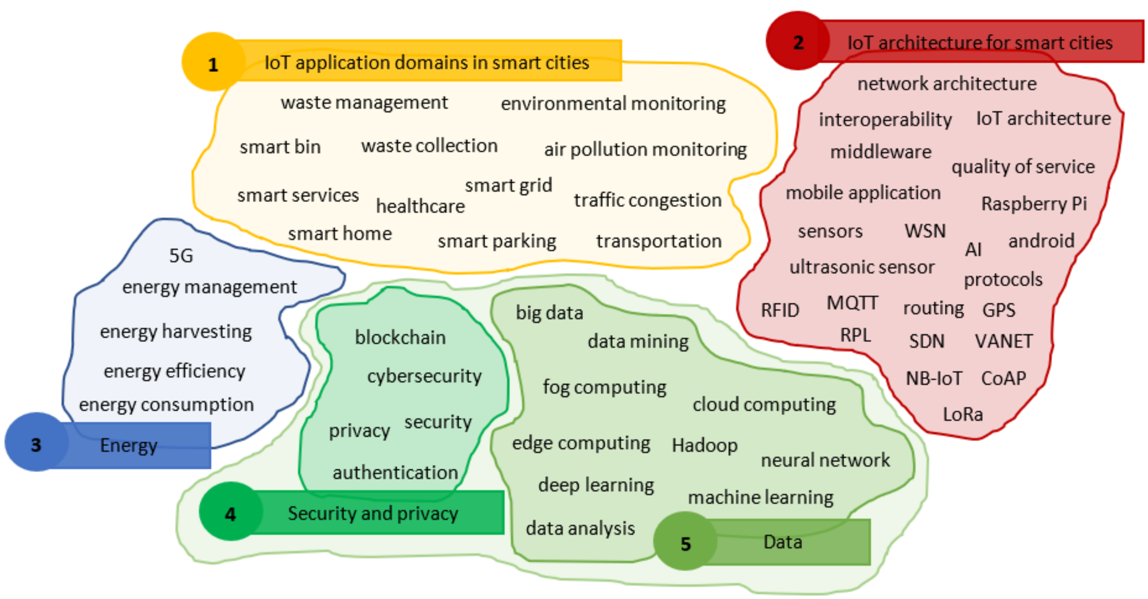

Fig. 7. Subareas of "IoT-based" smart city research

Tab. 6. Subareas of IoT-based smart city research

No.	Cluster name	Words
1.	IoT application domains in smart cities	waste management, waste collection, smart bin, environmental monitoring, air pollution monitoring, smart grid, smart services, smart home, healthcare, smart parking, traffic congestion, transportation
2.	IoT architecture for smart cities	network architecture, IoT architecture, interoperability, quality of service, middleware, routing, Raspberry Pi, sensors, ultrasonic sensor, wireless sensor network (WSN), protocols, MQTT, Vehicular Ad Hoc Network (VANET), Constrained Application Protocol (CoAP), LoRa, Routing Protocol for Low-Power and Lossy Networks (RPL), Software Defined Network (SDN), RFID, android, mobile application, Narrowband IoT (NB-IoT), GPS, artificial intelligence (AI)
3.	Energy	5G, energy management, energy harvesting, energy efficiency, energy consumption
4.	Security and privacy	blockchain, cybersecurity, security, privacy, authentication
5.	Data	big data, data mining, fog computing, cloud computing, edge computing, data analysis, machine learning, deep learning, neural network, Hadoop

4. Discussion of results

Analysis of the most frequently occurring key words allowed the identification of the five major thematic clusters. Table 7 presents the thematic threads within each of these clusters, along with examples of publications.

It can be noted (Table 7) that the first research area refers to potential application areas of the Internet of Things in smart cities. The key word analysis shows five major research trends in this area — transportation, waste management, environmental protection, smart buildings, and healthcare. Each of these subareas presents different issues analysed by the authors. The subarea one (transportation) explores such issues as traffic management (Masek et al., 2016; Rizwan et al., 2016), parking management (Gandhi, 2016; Sadhukhan, 2017), and accident management (Bhatti et al., 2019). As Masek et al. (2016) indicated, the capabilities of current traffic management systems are insufficient for future needs. Future traffic management systems should integrate current systems, manage effectively under diverse infrastructure and allow to visualise and simulate urban traffic. They should also determine traffic conditions more precisely and respond to emergencies more effectively (Masek et al., 2016). The improvement of existing systems is a frequent research area (Masek et al., 2016; Misbahuddin, 2015). Various authors also analyse elements of the traffic management process, including accident management. IoT can improve the speed and efficiency of response of automated accident detection and emergency services notification systems. An example of such a system is the Accident Detection and Reporting System (ADRS) developed by Bhatti et al. (2019). An Android smartphone (equipped with four sensors: noise, pressure, speed, and accelerometer) can be used to identify the accident site, the nearest hospital, and notification of the appropriate hospital ward. Accident information is sent when defined threshold values are exceeded (Bhatti et al., 2019). IoT can also improve the parking space management process by enabling remote monitoring of parking space availability, reservation, payment, and identification of damage-inflicting offenders or stolen vehicles (Gandhi, 2016; Sadhukhan, 2017).

Waste management is another identified subarea. It is one of the biggest challenges facing modern cities due to dynamic urbanisation, excessive consumption of goods, ineffective waste management systems and mechanisms (collection, selection, collection, disposal and recycling), and low use of modern technologies (Ali et al., 2020). Smart waste management systems are based on the use of different sensors (e.g., weight, pressure, temperature) that allow monitoring of the fill level of waste containers in real-time. The system users receive timely information about the need to empty containers, allocate resources, optimise waste collection routes and schedules, or about potential fire hazards.

The collected data enables the creation of reliable statistics and forecasts, which facilitate decision-making for city authorities (Ali et al., 2020; Anagnostopoulos et al., 2017; Sharma et al., 2020). As Sharma et al. (2020) pointed out, the main implementation barriers of intelligent waste management systems in cities are the lack of connectivity, standardisation, and legal regulations. Anagnostopoulos et al. (2017) reviewed and characterised ICT-based waste management models. According to a proposed taxonomy, the authors classified the identified models and compared them in terms of key components (physical infrastructure, software analytics and IoT technology).

Tab. 7. Main research areas and subareas in IoT-based smart cities research

No.	Research areas	Main research Subareas	Selected publications
1	IoT application domains in smart cities	Transport	(Bhatti et al., 2019; Gandhi, 2016; Ji et al., 2014; Masek et al., 2016; Rizwan et al., 2016; Sadhukhan, 2017)
		Waste management	(Ali et al., 2020; Anagnostopoulos et al., 2017; Bharadwaj et al., 2016; M. Sharma et al., 2020)
		Environmental monitoring and protection	(Duangsuwan et al., 2018; Indhumathi & Dineshkumar, 2019; Malche et al., 2019; Shah & Mishra, 2016)
		Homes	(Dutta & Roy, 2017; Dwivedi et al., 2021; Hui et al., 2017)
		Healthcare	(Abril-Jiménez et al., 2020; Bryant et al., 2017; Dawood & Sah, 2021; Poongodi et al., 2021)
		Disaster prevention	(Loftis et al., 2018; Sakhardande et al., 2016; Shah et al., 2019; A. Sharma et al., 2020)
		Lightning	(Rossi et al., 2016; Sikder et al., 2018, 2018; Tambare et al., 2016; Xu & Wang, 2020)
2	IoT architecture for smart cities	IoT framework for smart city	(Abreu et al., 2017; Cerchecci et al., 2018; Ganchev et al., 2014; Gaur et al., 2015; Nitti et al., 2017)
		Green IoT	(Alsamhi et al., 2019; Kaur et al., 2018; Sarkar & Gul, 2021)
3	Energy	Energy management	(Brundu et al., 2017; Ejaz et al., 2017; Khajenasiri et al., 2017; Mahapatra et al., 2017)
4	Security and privacy	Data security and privacy	(Al-Turjman et al., 2019; Gheisari et al., 2019; Shen et al., 2019)
		Cyberattacks detection	(Alrashdi et al., 2019; Li et al., 2019; Qureshi et al., 2020; Rashid et al., 2020)
		Blockchain	(Fan et al., 2020; Gong et al., 2019; Yetis & Sahingoz, 2019)
5	Data	Data management and analysis	(Cheng et al., 2018; He et al., 2018; Mohbey, 2017; Moreno-Cano et al., 2015; Romero et al., 2016; Zahmatkesh & Al-Turjman, 2020; Zhang, 2020)

The third subarea covers the issues related to environmental monitoring and protection. The increasing number of vehicles and intensive industrial activities cause a high level of air pollution in urban areas, which is a major threat to human health (Duangsuwan et al., 2018). As indicated by Malche et al. (2019), to avoid the negative effects of environmental pollution, it is necessary to develop effective systems for monitoring and disseminating information about its status. This issue is addressed by numerous authors (Indhumathi & Dineshkumar, 2019; Orłowski et al., 2017; Shah & Mishra, 2016). The developed systems differ in terms of used methods and technologies but bring similar benefits. They allow monitoring of certain parameters in real-time, provide accurate and reliable information and signal the appearance of deviations. An example is a system proposed by Malche et al. (2019) that detects and signals elevated levels of harmful gases and noise. It consists of sensors, a microcontroller board, and a cloud-based server. As shown by the authors, in the future, it can be extended to features such as monitoring dust, water pollution levels, ultraviolet radiation, soil moisture, or detecting aerosols (Malche et al., 2019).

Smart homes are a key component of smart cities. They ensure automatic and remote control of devices and systems, which allow them to operate efficiently while reducing operating costs (Dutta & Roy, 2017). Smart homes can significantly increase the comfort of living and improve user safety through features such as remote control of parameters (e.g., temperature, light intensity), device management and control, presence detection or simulation, and identification of potential threats. They also allow adapting particular functions to the user's individual preferences. Researchers both consider the functioning of an intelligent building as an integrated system and analyse individual subsystems (e.g., burglary prevention systems or measurement systems). As Hui et al. (2017) pointed out, despite significant progress in smart home research, the rate of adoption by the public is relatively low, which is due to the lack of incentives to modernise traditional homes. The authors have identified and characterised several requirements that smart buildings must meet (including heterogeneity, extensibility, usability, self-configurable, intelligence, context-awareness, and security and privacy protection).

Smart homes are extremely important from a smart healthcare perspective. IoT improves the efficiency of traditional medical systems by ensuring the personalisation of services, remote monitoring of patient conditions, and signalling of life-threatening emergencies (Poongodi et al., 2021). Smart healthcare is also a response to issues posed by the ageing population. IoT technologies can support the elderly in daily activities, increasing their independence. They also enable real-time monitoring of health status, which affects the speed of response and effectiveness of action in the event of a health or life threat. As showed by Abril-Jiménez et al. (2020), smart city infrastructure can support preventive health care and provide personalisation of medical services by collecting behavioural data without disrupting the daily lifestyle of the elderly.

The analysis of the records allowed the author to distinguish two more frequently addressed issues — disaster management (natural and man-made) and lighting management in a smart city. The first deals with the development of complex hazard monitoring and detection systems (Shah et al., 2019) as well as systems intended for specific types of hazards (Loftis et al., 2018; Sharma et al., 2020). Natural disasters are an enormous threat to human life, the environment, infrastructure, and the economy. The use of IoT can minimise the risk of its occurrence and increase the efficiency of rescue operations (Sakhardande et al., 2016). Thus, IoT can play a key role in the emergency management process in smart cities. Gaining, processing, and providing timely and accurate data increase with the speed of response when an emergency occurs (Shah et al., 2019).

The second subarea includes smart lighting systems, which enable automatic control of indoor and outdoor lighting. IoT solutions ensure remote control of lighting installations, signalling irregularities and real-time monitoring of electricity consumption. Smart lighting systems increase the efficiency of the lighting management process, enable cities to reduce their electricity expenses, and improve the safety of residents (Rossi et al., 2016; Sikder et al., 2018; Tambare et al., 2016). An example is the self-cleaning urban streetlight system proposed by Xu and Wang (2020). A smart street lamp has sensors that allow the users to monitor specific factors (brightness, ambient temperature) and remote control of the lamp operation (Xu & Wang, 2020).

Cluster two covers issues related to the Internet of Things architecture for smart cities (Fig. 7). Cities are complex structures with their own unique identities and individual characteristics. Each city has different goals and priorities and operates in a unique environment. This means that diverse factors influence their development. Therefore, the Internet of Things architecture must meet the needs of the city. The analysis of the publication set allowed the author to distinguish two main thematic threads within this subarea. The first thread concerns general issues related to the IoT architecture. This topic was addressed, among others, by Abreu et al. (2017), who highlighted the need to ensure the reliability of communication between devices and applications. According to the authors, one of the key issues, in this case, is to ensure that the system (network and services) can be automatically restored in the case of a failure (Abreu et al., 2017). The authors in this area deal both with the design of the IoT architecture for smart cities (Abreu et al., 2017; Ganchev et al., 2014; Gaur et al., 2015) as well as with the creation of a framework for specific processes and services (Cerchecci et al., 2018; Nitti et al., 2017).

The use of the Internet of Things (IoT) in urban environments, apart from its undeniable advantages, also comes with many risks like increased consumption of energy, materials, water and chemicals, as well as production of hazardous waste. According to Kaur, Tomar and Singh (2018), the key issue is to design IoT-based systems to be environmentally friendly at all stages of their life cycle. All areas of IoT applications in smart cities (smart homes, waste management systems, transportation systems, etc.) should therefore be "green" (Kaur et al., 2018). Green IoT is a relatively new research trend in the field of IoT-based smart cities (Sarkar & Gul, 2021). A review of current research on Green IoT and potential supporting technologies was conducted by Alsamhi et al. (2019). They indicate that research focuses on "greening" elements of IoT-based systems (e.g., communication, design, deployment, IoT services and application areas). According to the authors, future research directions should focus on drone technology, data transmission, M2M communication, Green IoT design, energy balancing, green Quality of Service (QoS) and security, and green big data. They identified RFID, wireless sensor networks (wsn), machine-to-machine communication (M2M), Internet, communication network, cloud computing, and data centre among the major ICT technologies to enhance Green IoT capabilities (Alsamhi et al., 2019). A proposal for a Green IoT architecture based on a cloud platform was presented by Kaur (2018), among others.

The growing number of networked devices and increasing data transfer rates result in higher energy consumption. Efficient management of energy production, distribution and consumption are, therefore, one of the biggest challenges that smart cities must face. As Ejaz et al. demonstrated, energy management in smart cities focuses on two issues — energy harvesting processes and energy-saving solutions. The first issue aims to prolong the lifetime of the equipment. The second includes scheduling optimisation, energy forecasting, and cloud-based approaches, among others (Ejaz et al., 2017). Energy issues are addressed within each of the identified research areas. The increasing demand for energy creates a need to optimise energy consumption in all areas of smart city operations (Ejaz et al., 2017).

Networked devices generate a vast amount of diverse data (big data), which poses problems for data collection, processing, selection, and analysis. As Mohbey (2017) pointed out, IoT, big data, and cloud computing are three key and interrelated components of smart cities. Data analysis also relies on the use of artificial intelligence, including self-learning systems — machine learning and deep learning, that automatically identify and remember interdependencies in analysed datasets. To meet the challenges of growing data volumes, solutions enabling data collection and processing in virtual space (cloud computing, edge computing, fog computing) are used. They allow for real-time computing, cost reduction and energy efficiency improvement.

Big data also comes with many challenges. Talebkhah et al. (2021) indicated the lack of standards, insufficient digital literacy of the population, high costs, the need to integrate disparate data, and security and privacy issues. The security of data, devices and networks is a key issue not only from the perspective of the city government but also from the residents' perspective, as it affects their openness and trust for new technologies. Among the most important security and privacy issues, Al-Turjman et al. (2019) mentioned cybersecurity, botnet activity (computers with malware), threats from the use of autonomous vehicles, and leaks of private data. As the researchers point out, the risk of threats can be eliminated or minimised using blockchain technology, cryptography, biometrics, machine learning, and data mining etc. It is also necessary to create mechanisms and regulations for security and privacy within smart systems (Al-Turjman et al., 2019). As Gheisari et al. (2019) claimed, the main drawbacks of the methods used to protect data privacy from IoT devices are the simultaneous transmission of whole data, the use of a single static privacy-preserving method for the whole system, and the lack of understanding of the context of a situation. Besides general research on systems, methods, and tools for security and privacy, authors often address the use of blockchain technology (Fan et al., 2020; Gong et al., 2019) and the prevention and detection of cyberattacks (Alrashdi et al., 2019; Qureshi et al., 2020; Rashid et al., 2020).

Conclusions

The vision of smart cities based on the Internet of Things paradigm is slowly becoming a reality. Effective implementation of the IoT paradigm in the urban environment can bring many benefits, e.g., streamline processes, facilitate decision-making, save time and minimise costs in almost all areas of human activity. However, its implementation is associated with many challenges, both of engineering and scientific nature. This publication aimed to analyse and evaluate the scientific output and identify the main research directions over the last ten years in the area of "IoT-based smart cities". Five main thematic clusters were identified — IoT application areas in smart cities, IoT architecture, energy, security and privacy, and data. These areas are closely related and intertwined. A smart city is an integrated and coherent system, providing data exchange and communication between the various components. All subsystems must be properly designed, enabling optimisation of energy consumption and guaranteeing data security and privacy. Although the smart city is based on the use of modern technologies, many authors point out that they cannot be treated as the only factor that proves the "intelligence" of cities. Technologies should be only the tools for improving actions taken in a city. Their use is justified only if they help solve actual problems of cities and their inhabitants. However, the analysis showed that issues, such as the involvement of citizens in designing visions for the development of smart cities or the possibility of using IoT solutions to activate them, are rarely addressed in research.

An advantage of the conducted study is the integration of data from three databases (Web of Science, Scopus and IEEE Xplore), which significantly increased its scope allowing for a comparison of the results. The strictly structured methodology for the implementation of the bibliometric analysis allowed the author to obtain reliable results. It should be noted that the bibliometric analysis is a very broad method, and the choice of its methodology depends on the researcher and the type of issue analysed. The limitations of the present study result mainly from the specificity of the method used. The analysis of extensive collections of materials is associated with the possibility of the appearance in the analysed set publications that do not correspond to its purpose. In this study, the author limited the analysed set of publications to materials containing the selected key words only in the title. This increased the reliability of the study, but at the same time, it is one of its limitations since the rejected set could also contain relevant publications. Another limitation arises from the ranking by the number of publications. Authors or journals with many publications could be rarely cited. Moreover, in the case of ranking journals, authors or organisations, one publication with numerous citations may determine a high position in the ranking. Therefore, although the rankings were created based on the number of publications, the data on citations were also included. This study is preliminary, and its results may constitute the basis for further research, i.e., a systematic literature review or subsequent, separate bibliometric analyses of the areas identified in this publication.

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