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Article

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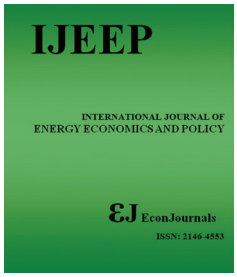

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New Insights into the Research Landscape on the Application of Artificial Intelligence in Sustainable Smart Cities: A Bibliometric Mapping and Network Analysis Approach

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ABSTRACT

Humanity's quest for safe, resilient, and liveable cities has prompted research into the application of computational tools in the design and development of sustainable smart cities. Thus, the application of artificial intelligence in sustainable smart cities (AISC) has become an important research field with numerous publications, citations, and collaborations. However, scholarly works on publication trends and the research landscape on AISC remain lacking. Therefore, this paper examines the current status and future directions of AISC research. The PRISMA approach was selected to identify, screen, and analyse 1,982 publications on AISC from Scopus between 2011 and 2022. Results showed that the number of publications and citations rose from 2 to 470 and 157 to 1,540, respectively. Stakeholder productivity analysis showed that the most prolific author and affiliation are Tan Yigitcanlar (10 publications and 518 citations) and King Abdulaziz University (23 publications and 793 citations), respectively. Productivity was attributed to national interests, research priorities, and national or international funding. The largest funder of AISC research is the National Natural Science Foundation of China (126 publications or 6.357% of the total publications). Keyword co-occurrence and cluster analyses revealed 6 research hotspots on AISC: Digital innovation and technologies; digital infrastructure and intelligent data systems; cognitive computing; smart sustainability; smart energy efficiency; nexus among artificial intelligence, Internet of Things, data analytics and smart cities. Future research would likely focus on the socio-economic, ethical, policy, and technical aspects of the topic. It is envisaged that global scientific interest in AISC research and relevant publications, citations, products, and services will continue to rise in the future.

Keywords: Bibliometric Mapping, Research Landscape Analysis, Artificial Intelligence, Internet of Things, Smart Cities, Sustainable Cities
JEL Classifications: C4, C5, R3

1. INTRODUCTION

Global interest in the application of computational methods such as artificial intelligence has increased in recent times owing to their potential for addressing myriad human and environmental challenges (Abduljabbar et al., 2019, Nishant et al., 2020). Historically, the term artificial intelligence (AI) was reportedly coined by John McCarthy of the Massachusetts Institute of Technology (MIT) in 1956 (Rajaraman, 2014). Over the years, the concept has metamorphosed in reputation, importance, and impact resulting in numerous definitions and applications worldwide. In principle, AI is broadly defined as the field of science concerned with the design and development of intelligent machines (Luxton, 2016). AI refers to software that can process or analyse information similar to or beyond human cognition (Powell and Hopkins, 2015). It is also described as a computational technology designed to

simulate, extend, or expand the intelligence of humans using machines (Voda and Radu, 2019).

From a system perspective, AI is described as the process of creating computers that can carry out a range of human-intelligence-based tasks, including learning, perception, reasoning, and decision-making (Sheth and Thirunarayan 2021, Wang et al., 2022). Typically, AI is designed around machine learning (ML) algorithms or techniques (such as decision trees and neural networks) that utilise numerical techniques to enable computers to learn and improve their performance using pre-imputed data (Pereira et al., 2020; Sánchez-Morales et al., 2020). Consequently, AI-based systems that can perform simple to complex tasks have soared with applications in various sectors such as transportation (Abduljabbar et al., 2019; Iyer, 2021), finance (Buckley et al., 2021; Cao, 2022), business (Enholm et al., 2022; Loureiro et al., 2021), manufacturing (Chien et al., 2020; Zeba et al., 2021), and others. In recent years, there have been growing calls for the application of AI in tackling socio-economic and environmental problems relating to sanitation, energy, healthcare, and housing, among other things.

One of the major challenges facing humanity is the lack of safe, resilient, and sustainable cities and communities around the world (MacDonald et al., 2018; Thomas et al., 2021). Thus, the United Nations (UN) established the Sustainable Development Goals (SDGs) initiative in 2015 to set an agenda for inclusive, global, and sustainable cities and communities worldwide (Carlsen and Bruggemann, 2022). Among the 17 SDGs is SDG 11 with targets that include providing affordable yet safe housing, sustainable transportation, and green public spaces, enhancing air and water quality, disaster resilience, urbanization, and industrialization, and safeguarding natural and cultural legacies worldwide (Abastante et al., 2021). Given the complex nature of the goals, analysts have proposed the use of computation tools such as AI, ML, deep learning (DL), and the Internet of Things (IoT) to collect, organise, and analyse the complex data required to tackle such socio-economic and environmental challenges facing humanity (Elsawah et al., 2020; Halkos and Tsilika, 2021; Song et al., 2017).

The concept of sustainable smart cities has been mooted among scientists and policymakers in response to the global quest to achieve the targets of SDG 11. A smart city (SC) is defined as any urban metropolis or area that consists of an interconnected network of computer-based devices used to monitor and optimize urban systems using data (Maignant and Staccini, 2018). Similarly, an SC is described as a digital area or region that is characterised by large numbers of connected wireless sensor networks (WSN) or distributed networks (Obaidat, 2022). The integration of WSN and IoT are considered the building blocks of SC, which are typically utilised to maximise the quality of life and health of the city's inhabitants whilst preserving resources or minimizing resource utilisation (Maignant and Staccini, 2018). However, the design and development of SC require comprehensive research on the intricacies of current cities around the world. Hence, computational tools have been proposed to collect and analyse complex data on cities using AI, IoT and ML, among others.

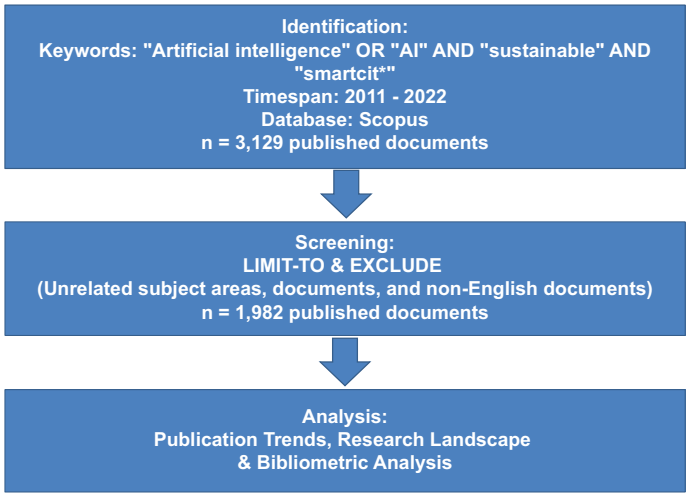
Given these dynamics, numerous studies have examined the application of AI in the design, development, and operation of SC, which has given rise to the concept of AISC research. Some researchers have sought to investigate the merits and demerits of adopting and executing AI in SC. Others have investigated the ethical concerns, residents' accessibility, and impacts of AI on public safety, urban planning, transportation, citizen engagement, and the environment in SC. In addition, studies on AISC research have sought to tackle socio-economic inequalities and environmental factors that influence the approval and execution of SC as well as barriers to AI in SC. Therefore, AISC research is considered an important aspect of sustainable governance and humanity's quest for safe, resilient, and liveable cities worldwide.

Hence, it is critical to map the current progress on the application of AI in SC based on publications in the scientific literature. This will potentially improve the understanding of the current status and help shape future research on the topic. Therefore, the Scopus database and bibliometric analysis have been employed to collect, examine, and analyse publications, stakeholders, and funding data on AISC research using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) technique.

2. METHODOLOGY

This section of the paper presents the various methods and tools adopted for mapping the research landscape on the application of AI in SC research globally. To accomplish this objective, the scientific publications on the topic of artificial intelligence in sustainable smart cities (AISC) research were identified in the Scopus database. The related documents on AISC research were identified using the search query developed from the subject keywords to recover scientific publications indexed in Scopus from 2011 to 2022. This study approach is loosely based on the evidence-based minimum approach of the PRISMA technique (López-Rodríguez et al., 2022). Figure 1 shows the methodology used to identify, screen, and analyse the scientific publications on AISC research over the 12 years examined in this paper.

Figure 1: Flowchart methodology for the selection, screening, and analysis of publications on artificial intelligence in sustainable smart cities research (2011-2022)



On the 5th of March 2023, an advanced search was executed in the Scopus database to recover related scientific publications on the topic based on the query: TITLE-ABS-KEY ("Artificial intelligence" OR "AI" AND "sustainable" AND "smart cit*") AND PUBYEAR > 2010 AND PUBYEAR < 2023. The results were subsequently screened to remove unrelated, unconventional document types and non-English publications from the list of recovered documents. The screening query was executed using the LIMIT-TO and EXCLUDE functions in Scopus. The screening query executed in this study was as follows: (LIMIT-TO [DOCTYPE, "cp"] OR LIMIT-TO [DOCTYPE, "ar"] OR LIMIT-TO [DOCTYPE, "re"]) AND (LIMIT-TO [LANGUAGE, "English"]) AND (LIMIT-TO [SRCTYPE, "p"] OR LIMIT-TO [SRCTYPE, "j"]) AND (EXCLUDE [SUBJAREA, "ARTS"] OR EXCLUDE [SUBJAREA, "ECON"] OR EXCLUDE [SUBJAREA, "HEAL"] OR EXCLUDE [SUBJAREA, "IMMU"] OR EXCLUDE [SUBJAREA, "NURS"] OR EXCLUDE [SUBJAREA, "Undefined"]) AND (EXCLUDE [EXACTKEYWORD, "current"]).

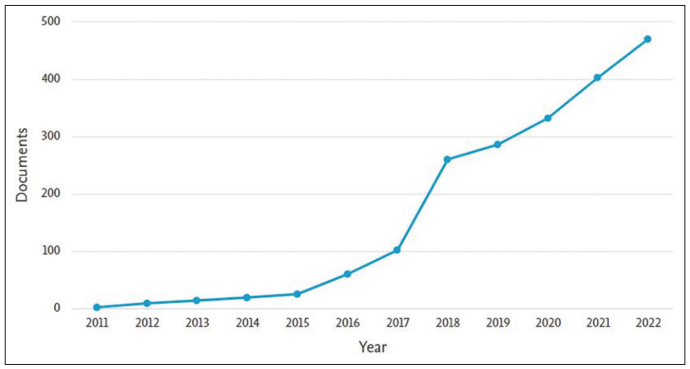
The identification and screening of the scientific publications on AISC research resulted in a total of 1,982 documents. The resulting document data were subsequently analysed using Microsoft Excel (version 2016) spreadsheets to scrutinise the publication trends, document types, sources, subject areas, and most cited publications on AISC over the years. Next, the productivity of the major stakeholders in the research area namely, key authors, affiliations, countries, and research funding bodies were critically analysed to elucidate their impacts on the technological growth and scientific development of the topic. Next, bibliometric analysis (BA) was performed on the publications data to examine the impact of collaborations/co-authorships, citations, and keyword co-occurrences on the topic. BA is a widely used statistical method for analysing the research landscape in any field or topic of research (Ajibade et al., 2023). The technique helps researchers identify and map the social networks of the key stakeholders, documents, citations, and hotspots in any given field of research using specialised bibliographic software (Donthu et al., 2021). In this study, the VOS viewer software was used to map the research/publications on AISC based on publications indexed in Scopus between 2011 and 2022.

3. RESULTS AND DISCUSSION

3.1. Publication Trends

Figure 2 shows the publication growth trends on AISC research based on the published documents recovered from Scopus from 2011 to 2022. A total of 1,982 publications were recovered based on the executed search query. As observed, the number of publications showed an incremental trend. The trend shows that the total number of publications increased from 2 in 2011 to 470 in 2022. Likewise, the number of citations increased from 157 to 1,540 during the same period, whereas the h-index of the topic increased from 1 to 18.The findings reveal that there has been growing scientific interest in the topic over the years. Also, the high productivity indicates that the topic has significant effects on humanity, with a social impact as well as a high scientific influence among researchers and stakeholders in academia, industry, and policy circles. This research productivity is largely due to the growing applications of AI for enhancing the standards of living and efficiency in cities and urban centres worldwide. Over the years, humanity has experienced the impact of AI in various sectors, such as smart infrastructure, energy and waste management, traffic control, as well as human health and public safety. In recent years, AI has been deployed to monitor public infrastructure such as bridges, roads, and buildings, in addition to the optimisation of waste management and disposal in cities around the world. Other applications include reducing traffic congestion, energy consumption, societal crime, and crime rates in towns and cities globally.

Figure 2: Publication growth trends on artificial intelligence in sustainable smart cities research (2011-2022)



Given this scenario, numerous studies have been conducted over the years with findings that have resulted in several documents published on various platforms. Further analysis shows that publications on AISC research consist largely of conference papers (1116), articles (773), and reviews (93), which account for 56.31, 39, and 4.7% of the total publications (TP), respectively. The Scopus data also reveals that publications on AISC research are indexed in various subject categories ranging from computer science to material/environmental sciences and chemical engineering to psychology. The findings showed that the top 5 categories (with total publications in brackets) are computer science (1,578), engineering (925), social sciences (385), decision sciences (307), and energy (290).

The existence of non-STEM categories, such as business, humanities, and arts, suggests that AISC is a wide and multidisciplinary field of research characterized by significant levels of collaboration between specialists from various areas. The data shows collaborations among computer scientists, engineers, urban planners, and stakeholders in policy and social circles. In practice, computer scientists create algorithms and software that are utilised to collect, process, and analyse complex data using sensors, devices, and the internet (collectively termed Internet of Things, IoT). Next, the data are utilised by urban planners and policymakers to fashion out sustainable smart cities strategies or initiatives that assess and address current issues or improve the quality of life of city dwellers.

With the span of collaborations and research productivity in the field, numerous publication sources have emerged on the topic.

The analysis of the most important sources that publish findings on AISC research was examined. The results from the Scopus database indicate that the top 5 sources of publications (with TP in brackets) on the topic are *ACM International Conference Proceeding Series* (68), *IEEE Access* (56), *Sustainability* (45), *Ceur Workshop Proceedings* (32), and *Sensors* (31). As observed, 2 of the top sources are conference proceedings, whereas 3 are journals. The *ACM International Conference Proceeding Series* (ACM-ICPS) is a publisher of conference papers as well as contents of technical conventions and workshops. Established in 2002, the ACM-ICPS is managed by the Association for Computing Machinery (ACM) whose digital library contains 45,000 research papers from 1,350 conferences. On the other hand, *IEEE Access* is a journal published by the Institute of Electrical and Electronics Engineers (IEEE).

Lastly, *Sustainability* and *Sensors* are open access (OA) journals published by the Multidisciplinary Digital Publishing Institute (MDPI) based in Switzerland. OA journals play a crucial role in enhancing the accessibility, visibility, and impact of publications. In addition, OA journals help rapidly disseminate publications, reduce the cost of accessing novel up-to-date studies, and impact research findings. This increased the popularity and relevance of such journals among academics. Studies have also shown that OA can positively influence the citation of published research papers (MacCallum and Parthasarathy, 2006). Hence, OA articles tend to receive more citations over time than those published in established subscription-based journals, which, along with other factors, has resulted in numerous highly cited publications.

3.2. Highly Cited Publications (HCP)

Table 1 presents the list of the top 10 most highly cited publications (i.e., publications with 200 or more citations) on AISC research in the literature. The analysis of HCP is critical to understanding the impact, relevance, and value of the researchers' works or ideas on any given subject area (Mei et al., 2016). In addition, the analysis presents insights into the degree or level of productivity, innovation, and development of the research. HCP could be utilised by up-and-coming researchers to identify the fundamental concepts, theories, and methods that currently, or could potentially, determine the direction of research in their field. As observed in Table 1 the most HCPs on AISC consist of 8 articles, and 2 conference papers, which have gained between 48 and 393 citations (or 114.5 on average) over the years. As deduced from the Scopus database, the most HCP is the article "On Big Data, Artificial Intelligence and Smart Cities" by Allam and Dhunny (2019) with 393 citations, which was published in the journal *Cities*. In the study, the authors demonstrated that AI and big data (BD) could be utilised to enhance the design, management, and liveability of urban centres, although this is dependent on their synergy with the culture, metabolism, and governance of such conurbations. The authors concluded that the effective integration of AI into city planning could stimulate economic growth and opportunities in cities around the world. The use of blockchain and IoT in sustainable smart city studies has also attracted significant attention. In the study by Singh et al. (2020), which has been cited 200 times, the potential of utilising AI and blockchain technology for the development of sustainable ecosystems was highlighted in detail. The authors posited that the convergence of both technologies could revolutionise the network architecture of future sustainable smart cities, provided that intrinsic problems (such as the security of such systems) are tackled effectively. The third most HCP on the topic is the study "Energy Sustainability in Smart Cities: Artificial Intelligence, Smart Monitoring, and Optimization of Energy Consumption" published in the OA journal *Energies* (MDPI) by Chui et al. (2018) with 104 citations.

Other highly cited publications on the topic have focused on the application of AI in various sectors (e.g., transportation, renewable energy, microgrids, safety, and security) of sustainable smart cities (SC). In the study by Nikitas et al. (2020), the authors examined the various dimensions of applying AI in the transportation sector to enhance the urban landscape and transport systems of SC. The authors introduced the concept of AI-based mobility and highlighted the conditions for successful implementation in SC. Similarly, Cugurullo (2020) proposed a research agenda to examine and highlight the potential of AI in the management of urban services in SC using Masdar City as a case study. Serban and Lytras (2020) reported that AI presents unique opportunities for enhancing the development, efficiency, structure, and management of projects with the renewable energy chain. The study also revealed the potential of utilising AI to enhance labour productivity in the renewable energy sector compared to the economy in general. The application of AI in the development, operation, and maintenance of microgrids in SC has also been reported in the literature. The study by Khan et al. (2018) revealed that the utilization of AI-enabled microgrids is a critical building block that not only provides distributed energy generation for smart cities but also addresses the problems associated with such energy networks. The study highlighted the potential of the BluWave-ai framework that leverages deep learning, AI, and IoT sensors to address smart city microgrid challenges. Lastly, Srivastava et al. (2017) examined the potential of applying AI to boost the security of SC. The authors reported that AI has the potential to provide transformative solutions for addressing safety and improving security challenges in sustainable smart cities. Given the growing importance of the topic, numerous agencies, organizations, and governments have invested significant funds in the development of cutting-edge AISC research.

3.3. Funding Organisations

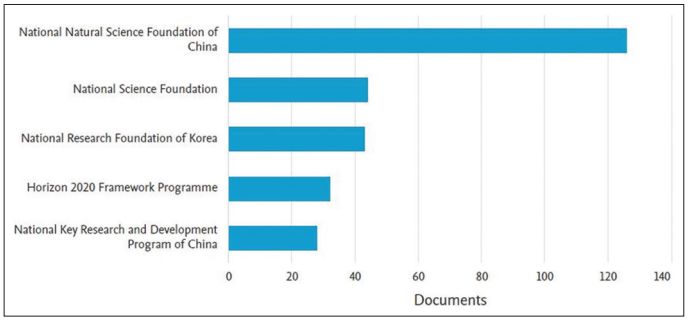
Funding plays an integral role in the growth and development of any research endeavour (Ajibade and Adediran, 2016). Typically, research funds provide the necessary resources and support that researchers require to obtain equipment, personnel, and other resources crucial to their research (Ajibade and Ojeniyi, 2022). In addition, funding supports the development of new technologies, products, and discoveries, and it provides a venue for collaboration and networking. Funding could also be used to examine the degree of research interest in any given area of research (Nyakuma et al., 2021). In this study, the top funders of AISC research were examined, based on data in the Scopus database. Figure 3 shows the top 5 research funding organisations along with the total publications they funded over the years.

The top 5 funders have supported a total of 273 publications or 13.77% of the total publications (TP) on AISC research over the

Table 1: Top ten most highly cited publications on AISC Research (2011-2022)

Authors	Title	Source title	Cited by	Document type
Allam and Dhunny (2019)	On big data, artificial intelligence and smart cities	*Cities*	393	Article
Singh et al. (2020)	Convergence of blockchain and artificial intelligence in IoT network for the sustainable smart city	*Sustainable Cities and Society*	200	Article
Chui et al. (2018)	Energy sustainability in smart cities: Artificial intelligence, smart monitoring, and optimization of energy consumption	*Energies*	104	Article
Nikitas et al. (2020)	Artificial intelligence, transport and the smart city: Definitions and dimensions of a new mobility era	*Sustainability* (Switzerland)	100	Article
Cugurullo (2020)	Urban artificial intelligence: From automation to autonomy in the smart city	*Frontiers in Sustainable Cities*	72	Article
Guo et al. (2018)	Artificial intelligence-based semantic Internet of Things in a user-centric smart city	*Sensors* (Switzerland)	66	Article
Serban and Lytras (2020)	Artificial intelligence for smart renewable energy sector in Europe-smart energy infrastructures for next generation smart cities	*IEEE Access*	59	Article
Falco et al. (2018)	A master attack methodology for an AI-based automated attack planner for smart cities	*IEEE Access*	52	Article
Srivastava et al. (2017)	Safety and security in smart cities using artificial intelligence - a review	*2017 7th International Conference on Cloud Computing, Data Science and Engineering – Confluence*	51	Conference Paper
Khan et al. (2018)	Artificial intelligence framework for smart city microgrids: State of the art, challenges, and opportunities	*2018 3rd International Conference on Fog and Mobile Edge Computing, (FMEC)*	48	Conference Paper

Figure 3: Top research funding bodies for artificial intelligence in sustainable smart cities research (2011-2022)



years. Further analysis shows that 2 out of the top 5 funders are based in China; the other 3 funders are based in Asia, Europe, and North America. The top funder of AISC research is the National Natural Science Foundation of China (NSFC) with 126 publications or 6.357% of the total publications (TP) on the topic. This lead is followed by the National Science Foundation of the United States with 44 publications, which account for 2.21% of the TP. The National Research Foundation of Korea has 43 publications or 2.16% of TP. The European-based Horizon 2020 Framework Programme and the National Key Research and Development Program of China has 32 and 28 publications, respectively.

The significant interest of NSFC in AISC research in China stems from the nation's quest to prioritise AI-based sustainable smart city developments in the coming years (Wang et al., 2021, Yang et al., 2021). In 2017, the Chinese government introduced the New Generation Artificial Intelligence Development Plan to position China as the global frontrunner in AI with an estimated value of $150 billion by the year 2030 (Wu et al., 2020; Zhao et al., 2019). Furthermore, Chinese-based internet and technology companies such as Huawei and Alibaba have established programs such as the "Intelligence Operations Centre" and "City Brain" systems to operate, monitor, and control various public transport, energy, safety, and infrastructure in the country (Rabbi et al., 2022). With such policies and financial backing from agencies such as NSFC, China aims to become the premier global AI innovation centre in the years to come (Al-Sayed and Yang, 2019; Fischer, 2018).

Similarly, the United States has prioritised AI research for numerous applications such as SC design, operation, and development. In 2019, the Donald Trump administration issued a Presidential Directive to support the development and application of AI in the US. The strategic move was followed by the promulgation of the National Artificial Intelligence Initiative Act of 2020 on 1st January 2021, which in turn oversaw the establishment of the National AI Initiative Office (NAI) on 11th January 2021. The objective was to oversee the nation's coordinated strategy to develop and implement world-class R&D in AI. The Republic of Korea has also invested significant resources in AI-based sustainable smart city infrastructure and technologies. For example, the country has invested in AI-based intelligent transportation systems, energy management, public safety, and healthcare services over the years. These developments are evident in the Song do International Business District smart city near Seoul along with the AI sustainable smart city infrastructure being built by the nation's

conglomerates such as SK Telecom, Samsung and Hyundai, among others. As a result, the AI market in South Korea is estimated to rise to US$ 44 billion by the year 2025. Such significant government investments have resulted in high research activities, which have prompted significant industry and academic publications, collaborations, products, and technology developments.

3.4. Authors

The examination of the authors, affiliations, and countries in BA provides readers with insights into the research landscape and identifies top stakeholders (Donthu et al., 2020; Wong et al., 2020). Furthermore, it enables current and future researchers to understand research trends, evaluate research impact, and inform policy decisions on any given topic (Ajibade et al., 2022; Wang et al., 2021). Figure 4 shows the top 5 authors involved in AISC research from 2011 to 2022.

The top author of AISC research as observed in Figure 4 is Tan Yigitcanlar based at the Queensland University of Technology in Brisbane, Australia, with 10 publications that have received 518 citations (*h*-index = 9) to date. The author's most notable publications include "Contributions and Risks of Artificial Intelligence (AI) in Building Smarter Cities: Insights from a Systematic Review of the Literature" (Yigitcanlar et al., 2020), "Can Building 'Artificially Intelligent Cities' Safeguard Humanity from Natural Disasters, Pandemics, and Other Catastrophes? An Urban Scholar's Perspective" (Yigitcanlar et al., 2020), and "The Sustainability of Artificial Intelligence: An Urbanistic Viewpoint from the Lens of Smart and Sustainable Cities" (Yigitcanlar and Cugurullo, 2020). The studies have revealed that AI and AI-based frameworks could potentially improve urban sustainability, particularly in primary focus areas such as education, business efficiency, data analytics, energy, and environmental sustainability. Other notable areas include health, land use, security, transport, and urban management. In addition, AISC can help protect populations from epidemics, natural disasters, and other catastrophes. However, studies on the influences of extensive application of AI in SC remain limited in the literature. Questions about its impact on urban sustainability as well as perceptions of the AI adoption among decision-makers, urban policymakers, planners, and residents remain lingering issues.

Another notable top author of AISC research is Rashid Mehmood who is a resident at King Abdulaziz University in Jeddah, Saudi Arabia, with 9 publications that have gained 600 citations (*h*-index = 7). Mehmood has co-authored some of his top publications with Tan Yigitcanlar, in which they introduced the concept of green AI for SC. In one of their studies, the authors revealed that the green AI approach to SC is underpinned by humanity's capacity to engage, analyse, and transform the environment through making sustainable, efficient, and equitable decisions (Yigitcanlar et al., 2021). The current research findings reveal that collaborations and co-authorships have influenced the productivity of authors in the field. To further investigate this, BA of the co-authorship on AISC research was examined using VOS viewer software.

Figure 4: Top 5 authors of artificial intelligence in sustainable smart cities research (2011-2022)

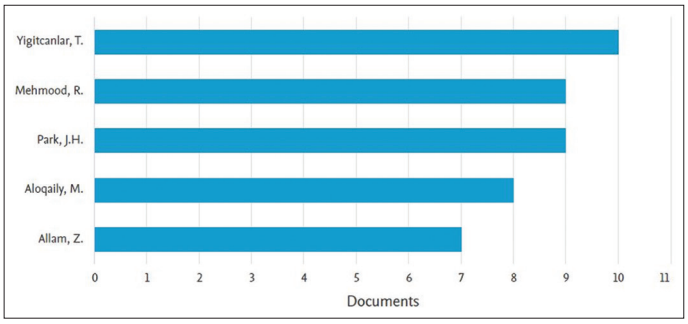


Figure 5 shows the network visualisation of the co-authorships among top AISC researchers worldwide. The visualisation map is based on the authors who have published a minimum of 5 publications with 10 or more citations. The results showed that out of a total of 5,959 authors, 91 fulfilled the set criteria, 68 (or 74.73%) of which had collaborated in the past. A total of 8 clusters were observed each comprising between 3 authors (the smallest cluster has H. Li, Y. Li, and J. Yang) and 19 authors (the largest cluster has J. Chen, X. Chen, J. Zhang, W. Zhang, and X. Zhang). Further analysis showed that while Y. Chen, J. Zhang, and Y. Zhang are the most prolific authors with 21 documents each, the most impactful researchers on the topic are R. Mehmood, Z. Allam, and T. Yigitcanlar with citations ranging from 512 to 592. The highest TLS ranging from 21 to 28 were observed for Y. Liu, Y. Chen, and J. Zhang.

3.5. Affiliations

As a standard practice, researchers are usually based in or associated with institutions, organizations, or companies where they teach or conduct research. Studies have shown that affiliations play a crucial role in the productivity of researchers as well as the growth and development of scientific research in general. Affiliations provide opportunities for funding, collaboration, and access to other non-monetary resources such as equipment and facilities necessary for research particularly in the STEM sectors. Therefore, the top 5 most productive affiliations linked to AISC research were analysed based on Scopus data, as depicted in Figure 6. As observed, the top 5 most active institutions have each produced 15 or more publications on the topic over the years. The list comprises 3 affiliations in the Middle East and North Africa (MENA) region, whereas the remaining 2 are based in China.

The most prolific affiliation is the King Abdulaziz University (KAU) with 23 publications cited 793 times in total. KAU is a public research university located in Jeddah, Saudi Arabia, which specialises in engineering, medicine, business, law, and humanities. The institution has an active AI research program with several research teams involved in designing and developing novel algorithms and computing tools aimed at addressing societal challenges and improving living standards in the Kingdom. The AI groups produced notable works such as "Data Fusion and IoT for Smart Ubiquitous Environments: A Survey" by Alam et al. (2017), "Analysis of Eight Data Mining Algorithms for Smarter Internet of Things (IoT)" by Alam et al. (2016), and "Can Building 'Artificially Intelligent Cities' Safeguard Humanity From Natural Disasters, Pandemics, and Other Catastrophes? An Urban Scholar's Perspective" by Yigitcanlar et al. (2020). Another Saudi-based institution, King

Figure 5: Network visualisation of co-authorships among top artificial intelligence in sustainable smart cities researchers worldwide

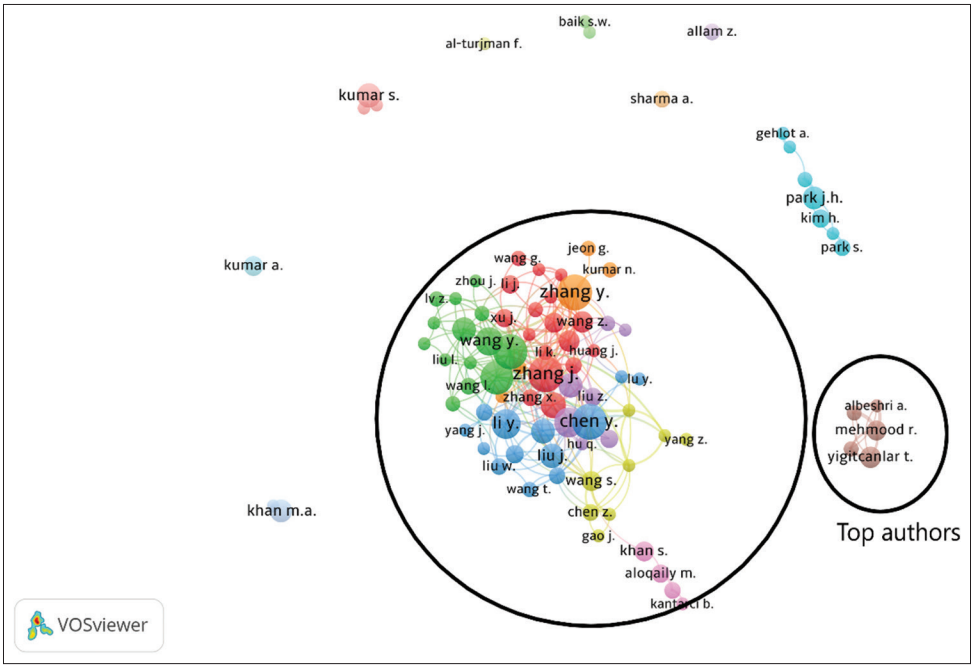
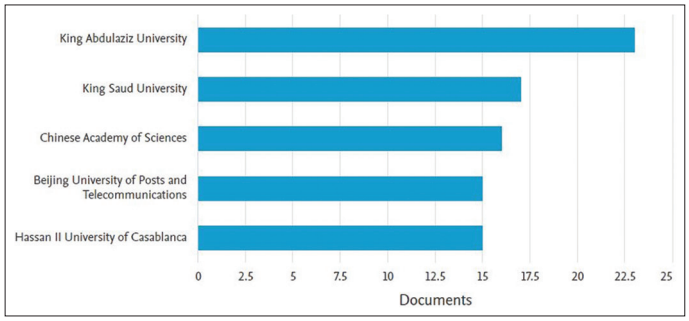


Figure 6: Top 5 affiliations/organisations relating to artificial intelligence in sustainable smart cities research (2011-2022)



Saud University (KSU), has also been active in AISC research over the years with 17 publications cited 443 times. The Riyadh-based institution has an active AI research landscape with several centres of excellence, including the CoE Information Assurance, Complex Engineering Systems, and Intelligent Sensing and Information Processing, dedicated to research spanning the areas of machine learning, robotics, and natural language processing, among others. These efforts have resulted in highly cited works such as "Blockchain and IoT-Based Cognitive Edge Framework for Sharing Economy Services in a Smart City" by Rahman et al. (2019), "Mobile Cloud-Based Big Healthcare Data Processing in Smart Cities" by Islam et al. (2017), and "Privacy-Preserved, Provable Secure, Mutually Authenticated Key Agreement Protocol for Healthcare in a Smart City Environment" by Khatoon et al. (2019). Other remarkably prolific institutions on AISC research are the Chinese Academy of Sciences and Beijing University of Posts and Telecommunications, China, and Hassan II University of Casablanca, Morocco, which have produced 16, 15, and 15 publications, respectively.

The leading position of Saudi-based institutions in AISC research could be ascribed to the nation's intentional policy towards AI-based technologies dubbed the "national AI strategy" and highlighted in Vision 2050. The policy aims to foster AI development and implementation for socio-economic growth and infrastructural development. In furtherance of these objectives, the Kingdom established the Saudi Data and Artificial Intelligence Authority (SDAIA) in 2019 to supervise the development of infrastructure, capacity, and environment for AI as well as collaborations with institutions/organisations within the Kingdom and abroad. Likewise, China has taken strategic steps to become a global leader in AI by 2030 as described in the nation's "New Generation AI Development Plan" established in 2017 by the State Council. China has voted significant finances to AI-based R&D, talent development, and industrialization technologies. Other AI-supporting initiatives include the "Three-Year Action Plan for Promoting the Development of a New Generation of Artificial Intelligence Industry (2018-2020)," proposed by the National Development and Reform Commission of China. The policy aims to support industrial AI development. Another key policy is the "AI Open Source Software Promotion Alliance," which aims to promote the development and sharing of open-source AI software. The outlined submissions indicate that national policies have been crucial to technological growth and scientific development across the world. The impact of nations on the research landscape of AISC is further highlighted below.

3.6. Countries

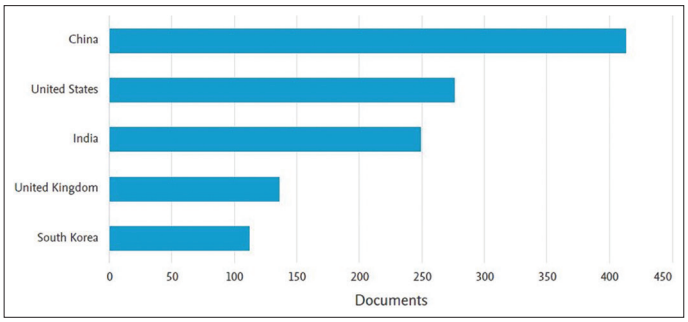
Figure 7 shows the top 5 nations/locations for AISC research from 2011 to 2022 based on data from the Scopus database. The analysis examined the influence of locations on the scientific growth and technological development of AISC research globally. As observed, each of the top 5 nations has published over 100 documents over the time frame of the study. The leading nation in terms of publications output is China with 413, followed by the United States at 276 and India at 249 documents. Saudi Arabia, which has the most prolific institutions when it comes to AISC research, is conspicuously absent from the top

5. This indicates that AISC research in the Kingdom is largely based on national interests with limited collaborations with academics abroad. Since governments significantly influence scientific growth and technological development through funding, policies, and incentives, it can be reasonably surmised that intra-national interests take precedence for AISC research in Saudi Arabia.

To further investigate this, the level or degree of co-authorship among nations was examined through bibliometric analysis. As illustrated in the network visualisation map in Figure 8, the degree of co-authorship among nations actively involved in AISC research is significant with 56 nations out of 138 collaborating on 5 or more publications each. This indicates that 40.58% of the nations actively engaged in AISC research have collaborated, which in turn indicates that the topic has a wide research impact and scientific interest.

In addition, the network visualisation map shows that collaborations have produced 7 clusters comprising 5 to 12 countries. The largest or red cluster consists of Australia, Mexico, Nigeria, Portugal, Sweden, and South Africa, whereas the smallest has Iran, Pakistan, South Korea, the United States, and Turkey. Further analysis shows that China and the United States have the highest number of publications, citations, and total link strength. The findings confirm that the two nations are the most prominent in AISC research despite the several clusters of nations working on various areas of the topic. Thus, it is important to analyse the hotspots or themes currently being examined by various research groups worldwide. Section 3.7 presents the hotspot analysis of AISC research using the keyword co-occurrence analysis feature of VOS viewer software.

Figure 7: Top 5 nations/locations for artificial intelligence in sustainable smart cities research (2011-2022)



3.7. Keyword Co-occurrence

Figure 9 shows the network visualisation map of the co-occurrence of all keywords on AISC research. The map shows the major keywords on AISC research that have occurred 50 or more times in the Scopus database from 2011 to 2022. The findings revealed that 53 major keywords out of a possible 13,439 fulfilled the search criteria, which resulted in 6 clusters (each with 4-19 words). The top 5 occurring keywords are smart city, artificial intelligence, Internet of Things, smart cities, and machine learning. Based on the keyword co-occurrence and cluster analyses, it could be reasonably concluded that there are 6 major hotspots on the topic in the literature.

Cluster 1 (red or largest cluster) consists of keywords such as IoT, network security, cloud computing, object detection, and blockchain, among others. This cluster describes the "digital innovations" and "technologies" typically utilised or associated with AISC research. Various studies have examined the use of IoT and blockchain technologies in the design, operation, and maintenance of sustainable smart cities and related technologies (Li, 2018; Wong et al., 2020). Hence, there is a growing belief that the integrated use of blockchain and IoT could foster the design and development of efficient, transparent, and sustainable smart cities. In particular, the application of IoT-Blockchain could greatly improve areas of society such as energy management (Kiruthika and Ponnuswamy, 2021; Yang and Wang, 2021), transportation (Abbas et al., 2021; Humayun et al., 2020), waste management (Ahmad et al., 2021; Paturi et al., 2021), and public safety (Fernández-Caramés et al., 2020; Xu et al., 2020), among other things. The review of literature has also shown that IoT and

Figure 8: Network visualisation map for co-authorship on artificial intelligence in sustainable smart cities research among nations

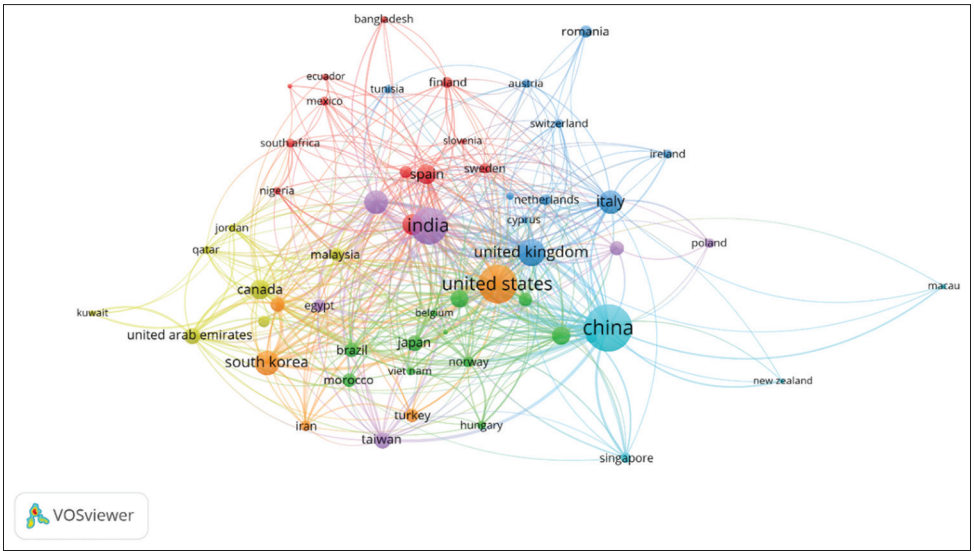
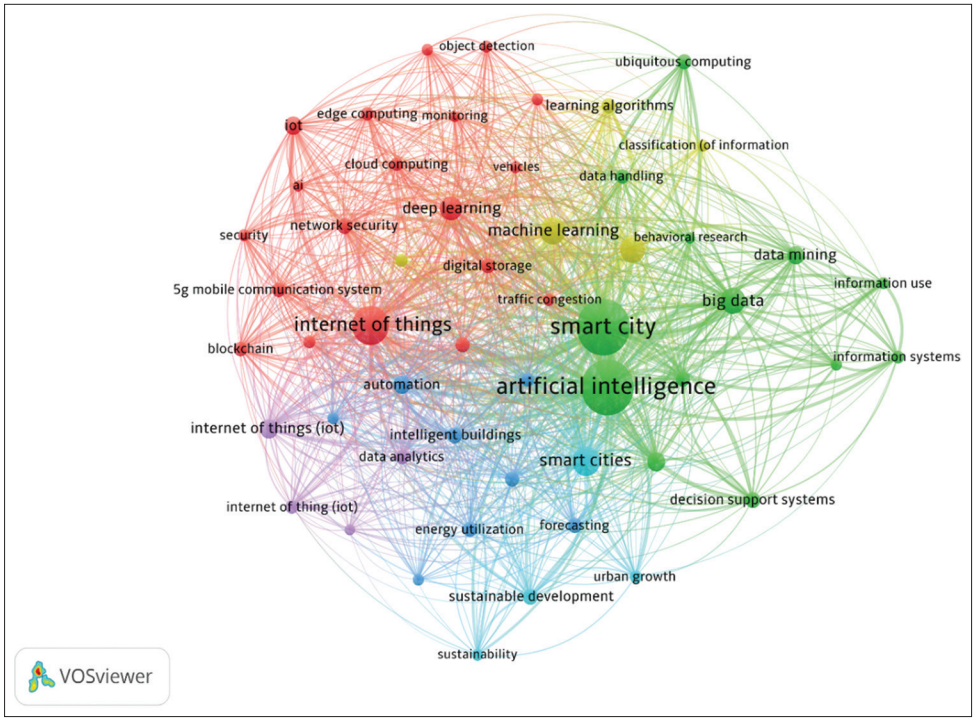


Figure 9: Network visualisation of keywords on artificial intelligence in sustainable smart cities research (2011-2022)



blockchain could be judiciously adopted and effectively utilised in monitoring and optimising energy consumption in buildings using generated, stored, and analysed building energy data (Hakak et al., 2020; Wang et al., 2023). Hakak et al. (2020) described the potential for securing smart cities using blockchain and related IoT technologies. The authors reported that blockchain, IoT, and cloud computing technologies could potentially provide beneficial services for improving the living standards of occupants in sustainable smart cities. Wang et al. (2023) proposed the use of ML-based reduction algorithms to examine energy consumption, patterns, and dimensionality of data on sustainable smart cities. Lastly, the findings revealed that such ML-based algorithms and tools could be used to enhance energy efficiency in smart cities around the world.

Cluster 2 (green) consists of keywords such as smart city, artificial intelligence, big data, data mining, decision support systems, and information systems, among others. In this cluster, the focus of research is "digital infrastructure" or "intelligent data systems" associated with AISC research. Digital infrastructure is a critical component of any smart city as it provides the principal technologies and communication networks required to collect, organise, and analyse the data from various IoT-based components (Ågerfalk, 2020). On the other hand, intelligent data systems refer to analytical tools or algorithms typically utilised to ensure the liveability, efficiency, and sustainability of smart cities (Milovanović et al., 2021). Examples include AI, big data, and data mining algorithms that enable policymakers to make informed decisions about SC. In principle, intelligent data systems require functional digital infrastructure to work effectively. Numerous studies have examined the nexus, impact, potential, and challenges of digital infrastructure or intelligent data systems in AISC research.

Cluster 3 (lime green) consists of keywords such as machine learning, behavioural research, classification of information, and learning algorithms, among others. The cluster describes intelligent or cognitive computing processes associated with AISC research, which introduces and emphasises the human dimension associated with the topic. Hence, it can be inferred that AISC research has also been integrated with augmentation, simulation, and critical understanding of human cognitive abilities (e.g., reasoning, learning, and natural language processing [NLP]). Various studies in the literature have investigated the application of ML, AI, and NLP for the identification and analysis of data patterns. In practice, intelligent tools or cognitive computing systems have been developed over the years to self-learn and self-improve by utilising feedback and experience.

Cluster 4 (turquoise) comprises the keywords smart cities, urban growth, sustainable development, and sustainability. The collection describes the smart sustainability (SS) aspect of AISC research in the literature. The SS concept aims to combine various smart tech and data-based strategies for advancing sustainable development, socio-economic growth, as well as environmental impact reduction and protection. In addition, it is aimed at using ML, data analytics, and policy frameworks to create sustainable urban environments for the betterment of current and upcoming generations.

Cluster 5 (blue) consists of the keywords forecasting, automation, intelligent buildings, neural networks, embedded systems, energy efficiency, and energy utilisation, among others. The keywords aim to describe the "smart energy efficiency" (SEE) aspect of AISC research in the literature. The SEE concept in the context of AISC aims to design and deploy AI technologies for addressing the challenges of energy consumption and carbon emissions reduction. SEE is a key area of research in the development of smart cities,

which aim to use advanced technologies (e.g., building automation, renewable energy, and smart grid technologies) to enhance living standards whilst addressing environmental challenges, reducing energy consumption, and minimizing carbon emissions.

Cluster 6 (purple) includes the keywords data analytics, artificial intelligence, and IoT. The cluster describes the nexus among data analytics, AI, and IoT as fundamental technologies required for designing, developing, and operating smart cities as well as creating sustainable, liveable, and efficient urban environments.

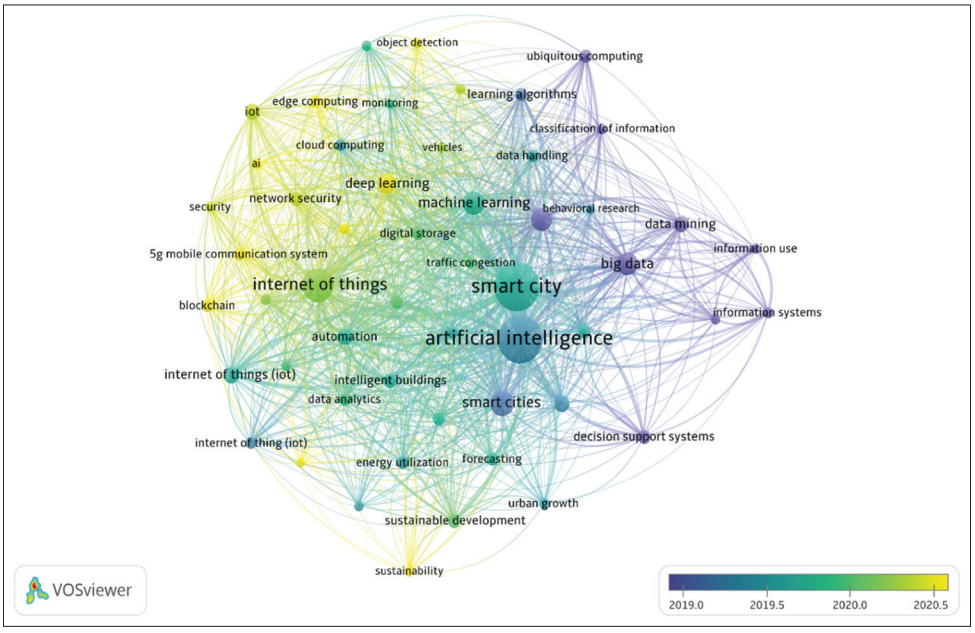
3.8. Future Outlook

Figure 10 presents the overlay visualisation map of AISC research keywords. The map shows that interest in the topic peaked between 2019 and 2020. Researchers' interest in areas such as big data, decision support systems, and data mining for smart cities was significant in 2019, whereas AI, blockchain, and cloud/edge computing became dominant around 2020. Given the evolutionary trajectory of the topic and its current global impact, it is logical to surmise that AISC research will continue to grow and develop worldwide.

With the growing global interest in addressing sustainable development challenges, it is expected that AI will take centre stage in addressing the objectives of SDG 11 described in the United Nations Sustainable Development Goals. According to the policy, the creation of liveable and sustainable cities is necessary to enhance the quality of life, reduce environmental impact, and promote socio-economic development by providing cheap transportation, affordable housing, and sound urban planning for all. However, there are growing concerns about the willingness and capacity of authorities to design, develop, and operate sustainable smart cities. For example, Visvizi and del Hoyo (2021, p. 1) raised concerns about the ability of regional authorities to successfully apply the "four-pronged goal of inclusion, safety, resilience, and sustainability" in smart cities. This view is corroborated by Giuliodori et al. (2023) who affirms that smart governance is critical to attaining urban sustainability, particularly using smart technologies such as AI, ML, and DL. Therefore, Jurado-Zambrano et al. (2023) opined that applying smart governance strategies in achieving SDGs required solid institutions to ensure citizen contribution and transparent government. In addition, such strategies could potentially promote inclusion and stimulate long-term visions that ensure an accelerated drive towards future smart sustainable cities. Lastly, Yigitcanlar (2015) notes that participatory action and engagement are required to encourage sustainable development and high quality of life as envisaged in the master plan of smart cities globally. Thus, future studies on AISC research need not only to focus on city-level data, but also emphasize the multisectoral, multi-scalar, and transboundary social-ecological-infrastructural systems that comprise actors, priorities, and solutions (Ramaswami et al., 2016; Van Aswegen and Retief, 2022).

Based on the above, the future directions of AISC research should focus on the social, ethical, economic, policy, and technical aspects of the topic. For example, future studies could focus on creating AI-based algorithms or frameworks for simultaneous-time monitoring, management, and decision-making in smart cities. AI policies and technologies will also need to be examined to address social and ethical implications that could arise in the future. Likewise, the potential impact and downsides of AI tech and policies on selected demographics (e.g., elderly, disabled, or disadvantaged) will need to be prioritised to eliminate issues of exclusion and lack of participation. On the policy side, government authorities should develop research-based policies, standards, and guidelines for the design, development, and implementation of AI in SC. Such policies must include regulations on confidentiality, data rights, and obligations. On the technical side, future research could focus on investigating novel models for human-AI interaction and collaboration in smart cities, such as the application of AI in human-based loop systems and decision-making. Lastly,

Figure 10: Overlay visualisation map of keywords on artificial intelligence in sustainable smart cities research (2011-2022)



upcoming research should explore compatibility, expandability, and sustainability, as well as safeguarding the long-term capability and flexibility of AI technologies and systems in SC.

4. CONCLUSION

The research landscape and publication trends on artificial intelligence in sustainable smart cities (AISC) between 2011 and 2022 was critically analysed. The PRISMA approach was adopted to identify, select, and analyse publications on the topic indexed in the Scopus database over the selected time frame. The Scopus search returned a total of 1,982 documents comprising various document types and subject areas published by various authors in multiple sources. The publication trends show that the number of publications and citations on the topic has increased exponentially over the 12 years examined in the study. The findings indicate there has been growing interest in AISC research, which is largely attributed to national/international interests, research funding, and the social impact of the topic. The study also finds that with the growing importance of AISC, it is envisaged that global scientific interest in the topic will continue to rise in the coming years. As such, the number of publications, citations, products and services from the academia and industry will soar geometrically. It is also expected that the productivity and collaborations among the top authors (such as Tan Yigitcanlar and Rashid Mehmood), organisations (King Abdulaziz University and King Saud University), and countries (China and the United States) will increase in the coming years. The keyword co-occurrence analysis revealed the existence of 6 clusters, which indicate a similar number of research hotspots on the topic. The cluster analysis shows that the current interest of researchers on the AISC topic is on digital innovation technologies, digital infrastructure, intelligent data systems, intelligent or cognitive computing processes, smart sustainability, and smart energy efficiency.

The authors predict that future AISC research will likely focus on the socio-economic, ethical, policy, and technical aspects of the topic, such as AI-based algorithms for simultaneous monitoring and potential impacts on vulnerable demographics. Governments must create policies and regulations to stimulate the design, development, and implementation of AI in SC, and research should investigate models for human-AI collaboration and safeguard AI technologies.

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