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Knowledge-Based and Intelligent Engineering Trends in Smart Cities: A Bibliometric Analysis of Machine Learning Applications

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Abstract

Background: Artificial intelligence (AI) and machine learning (ML) have become a revolutionary force in the development of smart cities and are changing the way cities are built, run and managed. With the rapid acceleration of the degree of urbanization and technological convergence, the state of research in this interdisciplinary area is a question that is very important for both researchers and policy makers.

Objective: This study aims to present an all-round analysis of the smart city applications of ML, in terms of both bibliometric and thematic analysis. The focus is on identifying trends in publication, major contributors, emerging topics of research and methodological trends that define advances in this area.

Methods: A total of 1960 peer-reviewed journal articles indexed in Scopus (excluding MDPI and Frontiers) from 2015 to April 2025 were analysed according to the PRISMA protocol in order to guarantee data accuracy and transparency. Python and VOSviewer tools were used to summarize and map the publication trends, institutional productivity, thematic clusters and the development of different levels of paradigms. To improve reliability, the same search criteria were used to extract a parallel dataset of 720 records from the Web of Science (WoS) Core Collection (excluding ESCI, MDPI and Frontiers). A cross-validation of publication patterns, thematic and disciplinary representation was conducted separately on the WoS dataset.

Results: The analysis reveals a significant rise in research output after 2020, with China, India and Saudi Arabia leading the research output, which is consistent with national AI and urban digitization initiatives. The most-cited articles show a thematic shift from infrastructure-focused works such as IoT, smart grids and mobility systems towards more specifically ethically oriented works such as federated learning, climate resilience and algorithmic governance. A number of different methodologies such as deep learning, reinforcement learning and privacy-preserving AI models have been developed. Two of the four areas studies show a high level of agreement between Scopus and WoS but WoS is more prevalent in urban studies and planning and Scopus additionally encompasses engineering and computer science.

Conclusion: In this regard, our findings demonstrate a clear convergence of ML with the domains of urban policy, sustainability and sociotechnical governance and a paradigm shift from technology-led to value-led innovation. This development corresponds to the increased transparency, inclusiveness and responsible use of AI in the field. The paper offers a validated and data-driven point of reference to researchers, practitioners and policy-makers so as to guide and affect the emerging frontiers of AI-enabled smart city transformation.

Index Terms

Artificial intelligence; Bibliometric analysis; Machine learning; ML; Smart cities; Sustainability; Urban intelligence.

1 INTRODUCTION

Due to rapid urbanization, cities are in need of intelligent systems to increase operational efficiency, sustainability and quality of life of citizens. Therefore, data-driven technologies such as machine learning (ML) and artificial intelligence (AI) have paved the way for smart cities. Today, these technologies play an important role in the urban management areas related to traffic optimization, predictive energy consumption, real-time surveillance, local waste management and public policies (Nitin and Vijay, 2024; Rosario and Boechat, 2024).

As the ML applications in smart cities grow across various fields, including engineering, computer science, urban planning and environmental studies, it becomes imperative to review the status of academic research, trace its progress and recognize thematic and technological trends (Gupta et al., 2022; Karger et al., 2024; Kousis and Tjortjis, 2021). While individual studies discuss individual applications or technologies, a systematic bibliometric review is needed to synthesize the fragmented landscape, quantify academic contributions and extract trends in research productivity, thematic focus and new trends (Poleto et al., 2023; Santoso et al., 2024).

In this study, a systematic bibliometric analysis is conducted using information extracted from the Scopus database, which includes the literature period from 2015 to 2025. It integrates quantitative indicators, such as growth of publications and citation analysis and yields of institutional productivity with qualitative appraisals of keyword evolution and research themes, challenges and funding evolution. This study also addresses cross-cutting issues with ML as related to other disciplines including governance, ethics, social sciences and urban policy, including the growing need for interdisciplinary approaches in the deployment of AI in smart city ecosystems. To guide this analysis, the research questions shown in Table 1 are addressed in this review. To provide methodological soundness, the present study conducts an independent verification using the Web of Science database, which is a complementary resource to Scopus as it provides wider disciplinary coverage across social sciences and urban planning. The interpretative power is enhanced and the problem of single-database bias in the bibliometric mapping is reduced by this comparison validation.

Table 1. *Research questions guiding the bibliometric review of ML applications in smart cities.*

No.	Research question
RQ1	How has research into machine learning in smart cities evolved in terms of publication and citation trends over time?
RQ2	Which papers, countries and institutions have made the most influential contributions to this field?
RQ3	What are the major research themes and methodological paradigms that characterize ML applications in smart cities?
RQ4	What are the key application domains where ML has been deployed in smart city research?
RQ5	How have keywords and topics evolved over time and what emerging interdisciplinary trends can be identified?

1.1 Background

AI and ML systems have been incorporated quickly into smart city urban management systems that can produce increased operational efficiency and better quality of life in urban areas. This literature review presents a knowledge synthesis of recent studies by summarizing a considerable proportion of literature collected to date about ML innovations in smart cities and it uncovers trends in themes and notable gaps in the research within the smart city literature. In the last couple of years, the concept of smart cities has been growing, getting more knowledge on modern digital technologies, where AI and ML are critically involved. As mentioned in El-Agamy et al. (2024), digital twin (DT) technology (Ebrahiem et al., 2024; Khavarian-Garmsir, 2023), which is a virtual replica of the real-world urban systems, is a critical platform for smart city management that can facilitate data-driven decision-making and prediction in real-time. A bibliometric analysis of 4220 articles on DT (El-Agamy et al., 2024) revealed thematic clusters of DT research literature as the primary origin of new benchmarks for the comprehension of AI-based urban systems.

ML applications have been considered in various areas such as transportation, energy management and smart services in smart cities. A bibliometric analysis of 197 publications from 2013 to 2021 (Gupta et al., 2022) pointed to the fast-paced development of the integration of AI and internet of things (IoT) in smart city projects. The results indicate that ML can be applied to various levels of smart cities in terms of infrastructure to service-oriented applications and demonstrate flexibility for complex problems in such cities. AI has played a huge part in resource management by making the distribution of resources more efficient and improving the system efficiency. Grid stability, predictive maintenance and optimization of renewable energy are among the major innovations in smart city energy planning with AI (Camacho et al., 2024).

ML has also disrupted the transportation industry. Mitieka et al. (2023) conducted a bibliometric review of 3223 documents on smart mobility and found four different phases of research related to different topics such as big data, deep learning (DL) and real-time analytics. However, the review also identified gaps in multidisciplinary approaches and research into smart mobility in developing regions to be targeted in future studies. A new topic is the combination between blockchain and artificial intelligence, which has gained a lot of attention because of its application to data security, decentralized governance and natural aesthetics of urban planning. Based on the bibliometric study of 505 articles published between 2017 and 2023, Alaeddini et al. (2023) indicated the main trends in blockchain-powered smart cities in terms of integration of smart devices into smart city governance.

Despite the rapid development, some challenges and knowledge gaps are still apparent in AI-based smart cities. An analysis of 1982 publications identified six major hotspots of research in AI for sustainable smart cities: digital innovation, intelligent data systems and AI-IoT integration (Zaidi et al., 2023). However, socioeconomic, ethical and policy-related issues are under-researched. Another extensive study of 9320 papers published between 1992 and 2023 (Esfandi et al., 2024) identified five main ML applications in smart cities, namely energy efficiency in buildings, transportation and mobility, smart grids, urban planning and AI-enabled policy frameworks. Although the first four dimensions have received significant research attention, policy frameworks are an emerging category, which indicates a gap in the research into AI-driven urban governance.

Increasingly, the involvement of various disciplines in the development of ML-smart city studies can be seen from the increasing number of publications in this field. A research study of 197 publications from 2013 to 2021 (Gupta et al., 2022) proved that the application of AI and IoT in smart cities is a growing research area. Another extensive bibliometric study on 4220 articles (El-Agamy et al., 2024) highlighted the emergence of DT integration with ML for urban analytics that witnessed a move towards predictive and simulation-based governance models. The technological developments made in the field of smart urban infrastructure are evident, the AI-enabled decision-making systems, smart grids and energy-efficient, intelligent transportation networks being the main areas of focus (Matei and Cocosatu, 2024).

ML is becoming a key element of optimizing and managing traffic in autonomous vehicles, electric vehicles and unmanned aerial vehicles (UAVs) within our cities. However, security risk and data privacy issues are still difficult (Szpilko et al., 2023). As is usually mentioned, AI is regarded as an important tool to smart transportation through traffic congestion forecasting, real-time traffic monitoring and adaptive traffic signal control (Bharadiya, 2023; Liang et al., 2024; Soomro et al., 2019; Szpilko et al., 2023). Urban governance and policy analytics are among the topics important and use AI to increase the data-driven decision-making process as well as the smart governance models (De Albuquerque Jacques et al., 2024; Matei and Cocoșatu, 2024; Soomro et al., 2019).

AI can be used for remote patient monitoring as well as for predictive diagnostics and smart wearable technologies in healthcare to provide medical services in urban environments (Nabi et al., 2023). Nevertheless, security and privacy issues of healthcare AI applications are still open topics for further investigation (Nabi et al., 2023; Szpilko et al., 2023). Apart from air quality analysis, prediction of weather patterns and designing for disaster resilience are areas of research for AI-based smart cities (Soomro et al., 2019; Szpilko et al., 2023; Venigandla et al., 2024).

Throughout the evolution of research themes over time, there has been a move from a techno-centric approach to a more holistic, multidisciplinary one. The introduction of the IoT, big data and AI applications has started in smart cities (Gupta et al., 2022; Kousis and Tjortjis, 2021). In recent studies, various attention has been drawn to interlinking socio-technical dimensions, AI-based urban policies and ethical governance (El-Agamy et al., 2024; Esfandi et al., 2024). Emergent trends have seen the application of ML in the area of energy efficiency, urban planning and smart governance (Purna Prakash et al., 2024). However, alternative research frameworks have brought up the questions of fragmented and technology-based approaches (Mora et al., 2017) and collaborative and interdisciplinary models (Gupta et al., 2022).

This review focuses on the multiple and richly changing uses of ML in smart city ecosystems. This study involves many fields such as transportation, energy management, urban governance, healthcare and environment monitoring. Although these advancements showcase the transformative potential of ML, there are still considerable challenges, especially concerning matters such as data privacy, cybersecurity and the integration of AI into regulatory/policy frameworks. In so doing, this study uses a bibliometric approach to systematically investigate ML innovations in smart cities through analysis of publication trends, thematic focus areas and emerging technological advances. The methodology used for this holistic analysis is explained in detail in the next section.

2 METHODOLOGY

2.1 Data collection

This research uses a structured bibliometric approach to analyse the global research into application of ML and AI in smart city development. Data were obtained from two major academic databases, Scopus and the Web of Science (WoS) Core Collection, to guarantee the comprehensiveness, cross validation and robustness of the results on disciplines such as computer science, engineering, environmental studies and urban analytics.

The first identification process was a consolidated Boolean query: T1 = ("Machine Learning" OR "Artificial Intelligence") AND ("Smart City" OR "Urban Development”). This search resulted in 9484 records from Scopus and 2897 records from WoS. To guarantee the reliability and relevance of the datasets, a number of refinement criteria were used. The following inclusion and exclusion criteria were used in the filtering process: peer-reviewed journal articles published between 2015 and April 2025 for Scopus and between 2015 and October 2025 for WoS, written in the English language and indexed under the related field (computer science and engineering and technology). Publications from non-academic sources, conference proceedings, short notes and non-English publications were excluded. Additionally, records from ESCI as well as publications from MDPI and Frontiers were removed from both Scopus and WoS to ensure quality and consistency.

After this screening step, a total of 1960 documents from Scopus and 720 records from WoS were kept for bibliometric analysis. These records were downloaded in plain text format to allow standardized processing and analysis of the data and reproducibility of the results.

The analysis process was carried out using two different but complementary tools, namely VOSviewer and Python, each of which has different but interconnected analytical purposes. VOSviewer was used for network-based visualizations, which included keyword co-occurrence mapping, thematic cluster identification (e.g., IoT, smart city, AI, governance), and co-authorship network analysis, which made it possible to identify collaborative structures and thematic clusters within the literature. In parallel, Python scripts were used for the quantitative and temporal analysis, which included publication growth trends, distribution of number of citations and identification of the most cited papers, temporal drift of keywords as a heatmap to track the changes in research topic, paradigm frequency mapping (ML, DL, reinforcement learning (RL)), keyword growth analysis (early years versus recent years) and thematic domain classification (e.g., environment, energy, traffic or governance).

This two-framework approach complemented both relational and statistical components of bibliometric analysis providing a multidimensional perception of the scholarly development of ML in the context of smart cities. In addition, the WoS dataset played a significant role in the cross validation of Scopus insights. Comparative analyses of publication trends, evolution of keywords and clustering them thematically also confirmed consistent global trends across the sources and thus added to methodological rigour and reduced database-specific bias.

To increase methodological transparency, a flow diagram based on the PRISMA was used to describe the data screening and analysis process (Figure 1). It specifies each stage of the procedure, from the initial retrieval of data to the data refinement and finally to the analytical processing, which provides an overview of how the final count of 1960 Scopus and 720 WoS publications were systematically derived and analysed. This structured and replicable design is a comprehensive foundation for the following bibliometric, thematic and interdisciplinary analyses presented in the subsequent sections.

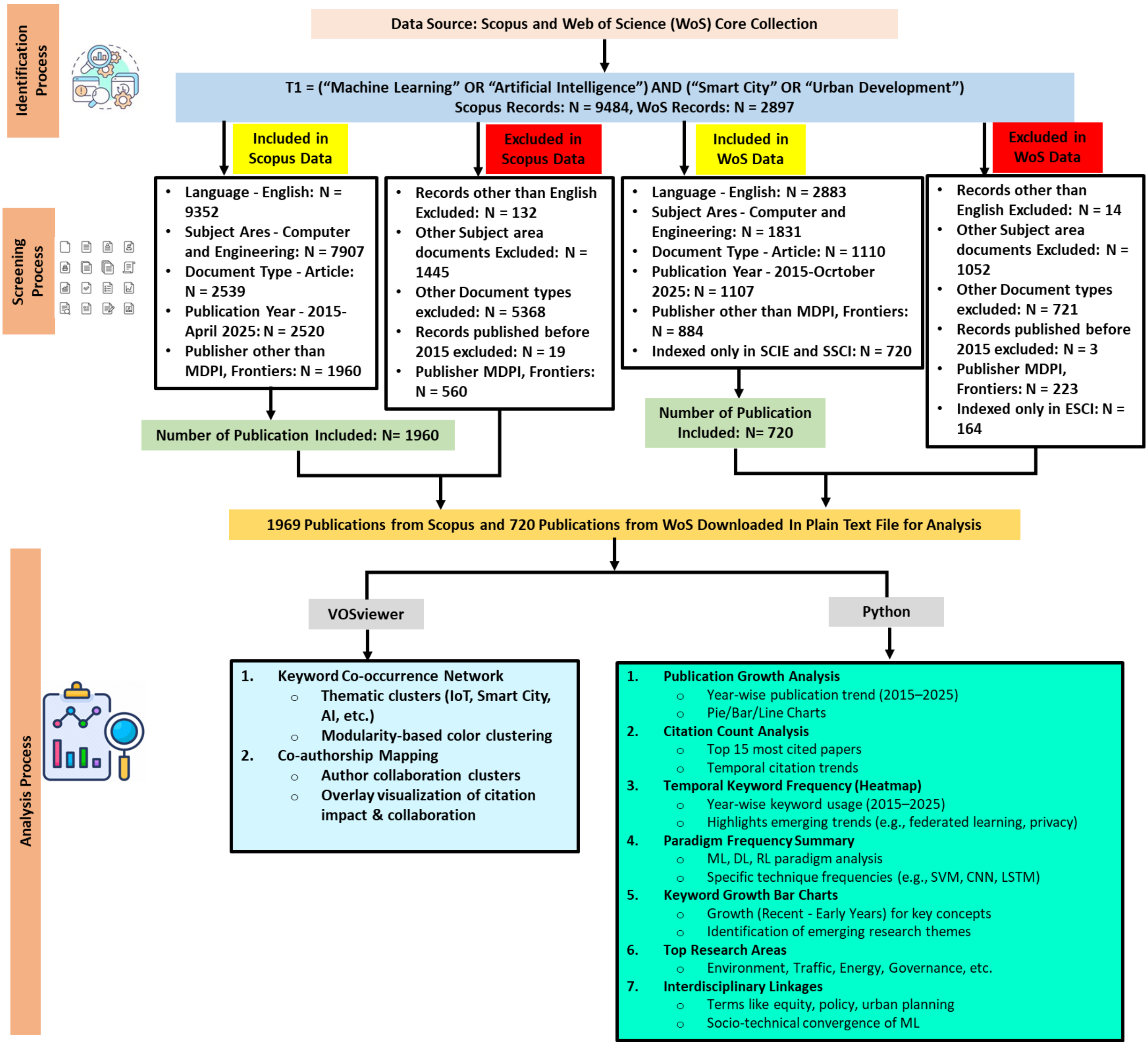


Figure 1. *Overview of data selection and analysis pipeline using Scopus, WoS, VOSviewer and Python.*

2.2 Data cleaning and preparation

Once the raw data were collected from Scopus, a structured data cleaning and normalization process was applied to increase the analytical reliability of the data. Duplicate records were detected and removed on the basis of DOI and title match. For the co-authorship analysis and institutional productivity analysis, the names of authors and institutions were standardized to prevent fragmentation. Incomplete entries as missing key metadata (keywords, author names, publication years, etc.) were removed from the dataset.

Besides structural cleaning, a full keyword normalization was performed. A total of 15,241 different keywords were extracted from fields that were author-defined and indexed. However, many keywords had been duplicated in different forms, including singular/plural form, hyphenation and formatting. Specifically, 2,173 keywords were found as duplicates and were made up of 246 keywords with hyphen or spacing variations and 987 singular/plural duplicates. In keeping with analytical accuracy and thematic integrity, a final consolidated keyword table was created combining all of the variations and consolidating their frequencies. The result of this consolidation was a refined set of 14,260 unique normalized keywords, which were used as the basis for keyword co-occurrence mapping, frequency distribution analysis and thematic clustering.

The cleaned dataset contained full bibliographic information such as article title, author(s), institution(s), keywords, source journal, publication year and citations. These metadata were exported as comma-separated values (CSV) files and were processed by using two major tools: Python (pandas library and matplotlib library) for statistical and temporal visualizations and VOSviewer for bibliometric mapping based on networks. In the Methodology section, these tools are described, and the actual results and visual figures obtained by the application of these tools are shown and interpreted in the Results section.

Normalization and keyword consolidation were performed for the Scopus dataset as well as for the WoS records. Duplicate DOIs were removed, author affiliation was normalized and keyword co-occurrences were normalized. Comparative visualization, as well as comparison and inter-database consistency check, were carried out with the refined WoS dataset. Table 2 displays the most frequent keywords taken from this last set that further substantiate the convergence between this set of literature to the research goals of this bibliometric study.

2.3 Bibliometric analysis techniques

In this paper a multi-layered bibliometric approach using descriptive, relational and temporal analyses was used to analyse the intellectual structure and thematic development of ML research in smart cities. The analysis was performed by means of two key tools, Python and VOSviewer which offer complementary functionalities (Ebrahiem et al., 2024; Khavarian-Garmsir, 2023). Python was used for data preprocessing, normalization, statistics and visualizations (temporal heatmaps and frequency graphs). VOSviewer allows building network-based visualizations, such as co-occurrence and co-authorship maps based on bibliographic metadata (Bukar et al., 2023; Guo et al., 2023; Muktiarni et al., 2023).

2.3.1 Publication and citation trends

An analysis using Python was carried out to understand publication trends and the annual distribution of research output from 2015 to April 2025 for Scopus data and from 2015 to October 2025 for WoS data and to represent these by means of visualizations. Thus, it was possible to identify the growth patterns and peak publication years. The top 15 most-cited papers were also extracted and ranked as horizontal bar charts to indicate the foundational studies. In addition, aggregated metadata were created for institutional and geographic information to further determine the top ten contributing institutions to provide insight into global leadership and collaborative hotspots in the field.

2.3.2 Thematic mapping and research focus analysis

To analyse the thematic structure of the research domain, VOSviewer was used to make a co-occurrence analysis of the keywords. Normalized author-defined and indexed keywords were both reduced to low values and a minimum frequency of five was applied to ensure that noise was reduced and insignificant keywords were filtered. VOSviewer is a modularity-based clustering algorithm based on keywords for nodes and a co-occurrence frequency index as edges for forming a visual network. Three prominent research themes were present in the clusters: "smart city", "machine learning" and "deep learning" connected with associated subdomains: IoT, transportation, energy management, cyber security and governance. The analysis identified the relationship of the lines of research in the broader context of urban innovation through artificial intelligence (Dritsas and Trigka, 2024; Fadhel et al., 2024; Moumen et al., 2023; Nabi et al., 2023; Necula, 2023; Rane et al., 2024; Szpilko et al., 2023; Ullah et al., 2024).

2.3.3 Topic evolution and emerging research areas

Python was applied to a temporal keyword frequency analysis in order to examine the development of the topics of research over time. The variants were merged (e.g., "AI" with "artificial intelligence") and subsequently 20 most frequent keywords were chosen. An annual usage trend was shown in a temporal heatmap, which showed emergent topics such as "federated learning (FL)", "edge computing", "privacy" as well as "smart governance". These findings point to a wider outlook from the initial infrastructure focus to an emphasis on ethics in the use of alternative AI systems (Li et al., 2024; Stoykova and Shakev, 2023). This time-based mapping also indicated the growing interdisciplinary overlap between ML and other disciplines (e.g., urban policy, sustainability and citizen-centric governance). As explained in the following Results section, these results show the shifting of the smart city research agenda towards both technological development and socio-political demands (Almeida et al., 2024; Dritsas and Trigka, 2024; Li et al., 2024).

Table 2. *Most frequent keywords (after consolidation result) from Scopus dataset.*

	Normalized keyword	Variants	Total frequency in Scopus data		Normalized keyword	Variants	Total frequency in WoS data
Analysis of Scopus data	smart city	smart cities, smart city, smart-cities, smart-city	1552	**Analysis of WoS data**	smart city	smart city, Smart Cities, Smart-City, smart-city, smart-cities	358
	machine learning	machine learning, machine learning algorithms, machine learning method, machine learning model, multimodal machine learning, ML, machine-learning	1445		machine learning	machine learning, machine learning algorithms, machine learning method, machine learning model, multimodal machine learning, ML, machine-learning	231
	internet of thing	internet of thing, internet of things, internet-of-thing, internet-of-things, iot, iots, internet of things (iot), internet-of-things (iot)	995		internet of thing	internet of thing, internet of things, internet-of-thing, internet-of-things, iot, iots, internet of things (iot), internet-of-things (iot)	218
	artificial intelligence	artificial intelligence, AI, artificial-intelligence	768		artificial intelligence	artificial intelligence, AI, artificial-intelligence	156
	deep learning	deep learning, deep-learning, DL, deep learning models, deep learning model, deep learning algorithms, deep learning techniques	602		deep learning	deep learning, deep-learning, DL, deep learning models, deep learning model, deep learning algorithms, deep learning techniques	83
	learning systems	learning systems	350		blockchain	blockchain, blockchains	38
	learning algorithm	learning algorithm, learning algorithms	212		security	security	37
	big data	big data, big-data	205		cloud computing	cloud computing	32
	edge computing	edge computing, edge-computing	195		sensor	sensor, sensors	31
	network security	network security	186		edge computing	edge computing	30
	decision making	decision making, decision-making	177		predictive model	predictive model, predictive models	30
	Blockchain	blockchain, blockchains	165		real-time system	real-time systems	29
	neural network	neural network, neural networks, neural-networks	152		big data	Big data; big data; Big Data	29

2.4 Qualitative frame and contextual analysis

Frame-based qualitative coding: A customized lexicon was generated for operationalizing seven sociotechnical and interdisciplinary frames of interest: governance/policy, privacy/surveillance, equity/inclusion, sustainability/resilience, deployment/implementation, techno-optimism and techno-scepticism. In order to go beyond frequency counts and thus to capture discursive orientation and interpretive context, each abstract was programmatically screened for the presence and intensity of these frames by matching relevant terms and phrases. Frame scores were computed for each document and were accumulated on an annual basis.

Temporal and comparative analysis: Aggregated frame scores were normalized by year, in order to allow the longitudinal analysis of trends in discourse within and between the Scopus and WoS corpora. Comparative visualizations and statistics allowed us to spot priorities and emerging thematic focuses at both the annual and cumulative levels.

Stance and contextual signals: To complement the qualitative analysis, the abstracts were all parsed for linguistic markers of stance (i.e., hedges, e.g., "may", "might", "could" and modals, e.g., "must", "required", "can", "cannot") in order to quantify the expression of uncertainty, obligation or assertion by authors. This approach allowed discussion of the qualification of research findings and recommendations, therefore illuminating narrative strategies and the changing epistemic tenor of the field.

Exemplar extraction and keyword in context (KWIC) analysis: Representative sentences (exemplars) for each frame were taken for qualitative review. KWIC analyses were also implemented for terms of high thematic importance which provide windows of surrounding text in order to elucidate the contextual deployment of terms in the narrative. This strategy helped identify not only what terms are employed, but how they are located in arguments and discussions.

2.5 Python-based analytical workflow

Python was used extensively for the bibliometric and temporal analyses in this study through different preprocessing methods: normalization of keywords, frequency analysis and data visualization. Several well-established libraries were used for improving the scalability and reproducibility. Data handling operations using the Scopus-exported CSV dataset have been performed with the help of the pandas and NumPy libraries, reading and transforming the dataset, filtering by yearly publication and document type and removing duplicates (Ding et al., 2023; Fazil et al., 2023). All the entries were standardized by being converted to lowercase, removing extraneous whitespace and normalizing formatting (e.g., hyphens and plurals). The keywords were defined and indexed by the author and standardized.

For keyword normalization and frequency analysis, regular expressions and collections were identified. The keywords were tokenized with the help of a counter and the frequencies were calculated for the same. The subsequent thematic clustering analysis supported the distribution of high frequency keywords on the list. Matplotlib and Seaborn were employed to visualize publication trends, frequency of keywords, frequencies by paradigms, etc. Line and bar charts, pie charts, polar plots and evolution heatmaps of keywords were included in the visualization of trends. Keywords were grouped by year and by usage across time for insights into elevation of "federated learning", "privacy" and "governance".

2.6 Cross-validation with WoS data

A further WoS-based bibliometric analysis was performed in order to provide cross-validation of results. Publication trends, distribution at country level, journal source and thematic co-occurrence networks were compared to Scopus outputs. This relative approach allows methodological transparency and contributes to the generalizability of the results. The resulting VOSviewer visualizations including the co-authorship and keyword co-occurrence networks are shown in the Results section.

3 RESULTS

This bibliometric review comprehensively synthesizes the intellectual landscape, thematic evolution and emerging frontiers of ML application in smart city development. This section uses a combination of quantitative metrics and visual analytic techniques to synthesize the principal findings that emerged from the study of a curated set of 1960 Scopus indexed journal publications from 2015 to April 2025 as well as 720 WoS indexed journal publications from 2015 to October 2025. A number of dimensions were analysed, covering the dates and titles of publications and citations, contributions from institutions and countries, research focus areas, evolution of keywords, popular emerging technologies, interdisciplinary linkages and funding landscapes. To construct the co-occurrence network, keyword heatmap and publication trend graph, co-occurrence networks and citation clusters were built on the basis of visual tools, VOSviewer and Python. Publications between the cited works and the authors were identified on the basis of analysis of the cited works and the authors, which helped identify seminal works and thematic concentration. Collectively, these findings offer deeper insights into the research maturity of the field, key contributors, the most popular ML methodologies and the changing priorities of the smart city domain.

3.1 Publication and citation trends

This sub-section studies the trend of publications and citations in the past ten years. It has an interest in the geographical and institutional distribution of contributions as well as the role played by flagship publications in defining the field.

> **RQ1. How has research into machine learning in smart cities evolved in terms of publication and citation trends over time?**

Figure 2 shows the longitudinal development of studies on ML in smart cities in the Scopus and WoS databases from 2015 to October 2025. The data show a strong and steady upward trend in publication volume and scholarly impact, confirming the rapid growth of maturity of this interdisciplinary field. Within Scopus, the number of papers published annually has risen from 65 papers in 2018 to 439 papers in 2024, while WoS has shown a similar but more selective growth, up to 132 papers in the same year. Both datasets indicate that the most productive period was 2020-2024, signifying the shift from conceptual studies to implementation-oriented studies on a large scale.

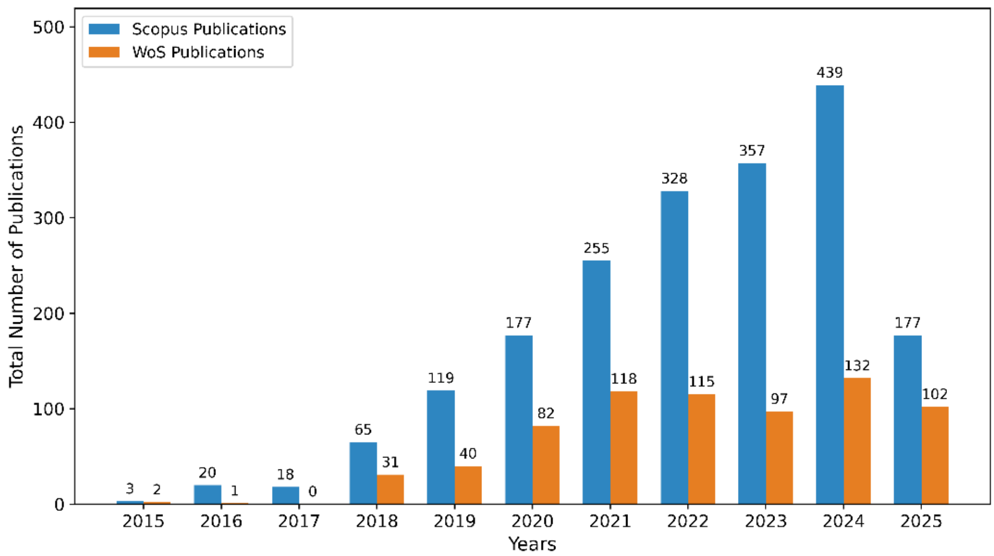


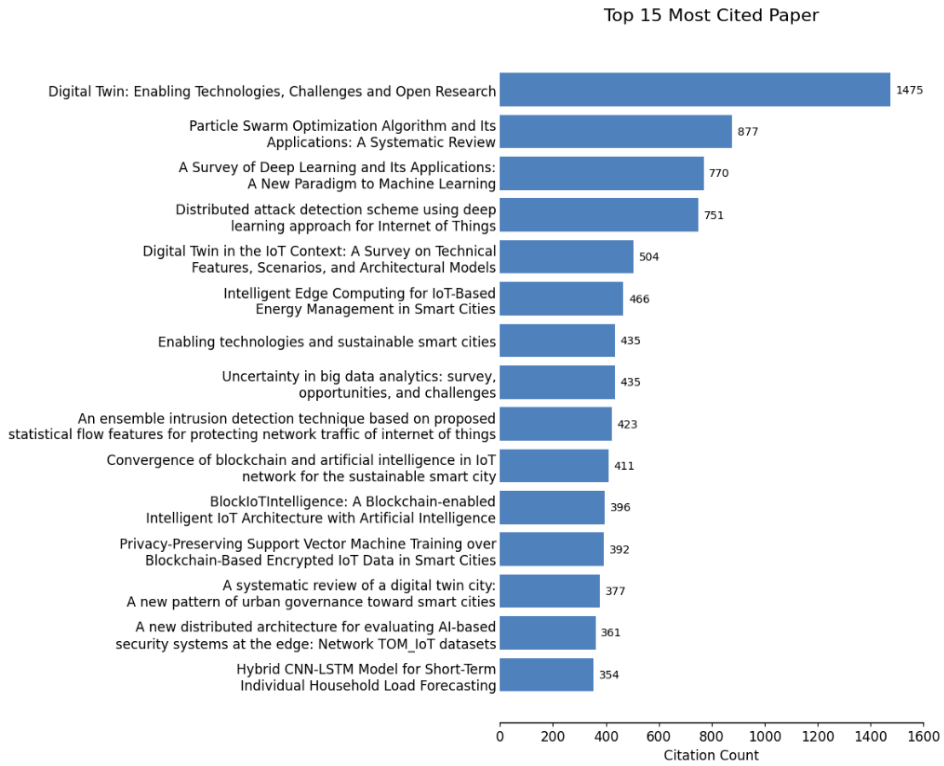
Figure 2. *Publication growth trends of ML-smart city research in Scopus (2015–April 2025) and WoS datasets (2015–October 2025).*

Citation patterns reflect this growth with the most influential contributions between 2019 and 2022 with the most citation counts. In fact, 2020 alone recorded 13,790 citations, closely followed by 2021 (13,066) and 2022 (12,356) – emphasizing their pivotal role in guiding future AI-driven urban management advancements. In recent papers (2023-2025), the citation activity has only started to grow, as they are still very young papers and so are in the early stages of accruing influence, as compared to earlier papers (2015-2018), where the citation activity was much more modest, since the field was in its early stages of development.

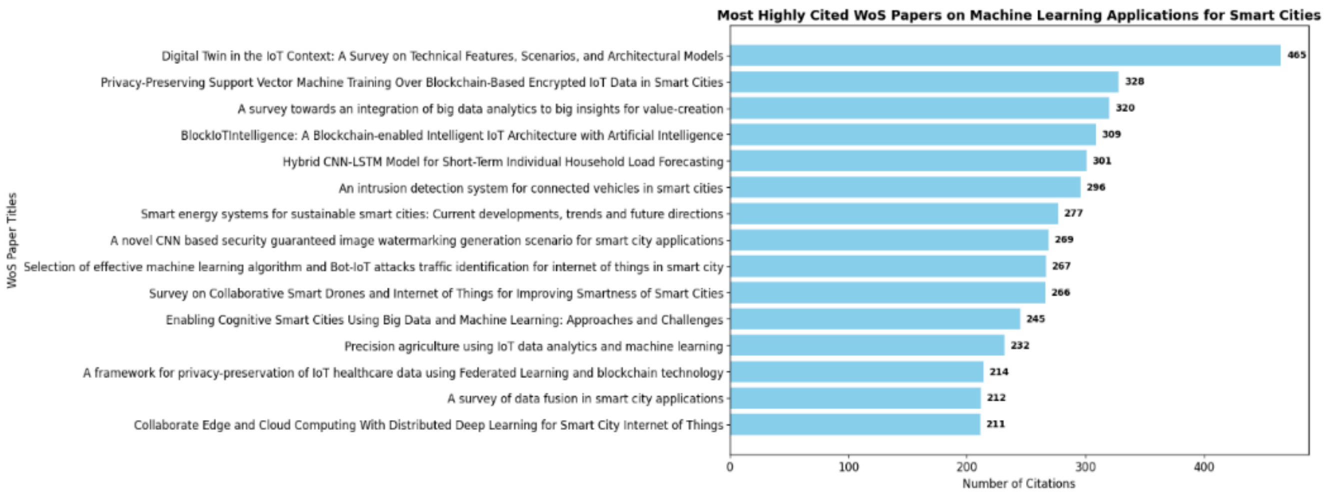
Collectively, this trajectory points to the global growth of ML-enabled smart city research due to the development of deep learning, IoT integration and intelligent infrastructure. While Scopus encompasses a wider quantitative scope, WoS focuses more on influential studies with a cross-disciplinary approach taking computer science, environmental systems and urban governance into account. All of this indicates a distinct transition of the initial experimental designs into mature, data-driven, ethically oriented solutions in smart cities: this represents the scientific and policy establishment of ML as an innovation in cities.

RQ2. Which papers, countries and institutions have made the most influential contributions to this field?

Figures 3 and 4 are both useful for identifying the most influential contributions that have shaped the field of ML research in smart cities. A review of both the Scopus and WoS datasets shows the scientific contributions, countries and institutions that have contributed most to the advancement of this field.



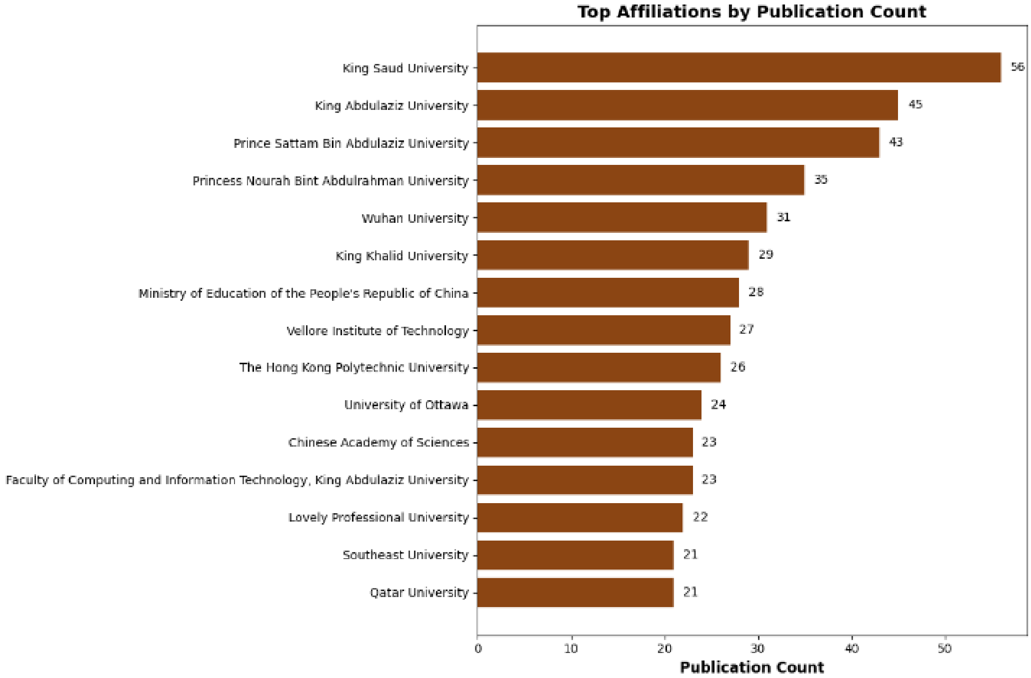
(a)



(b)

Figure 3. *Top 15 most cited papers on ML applications for smart cities from (a) Scopus (2015–April 2025) and (b) WoS datasets (2015–October 2025).*

The most-cited papers are the intellectual pillars of the field. In the overall ranking of Scopus, the top three articles are Digital Twin: Enabling Technologies, Challenges and Open Research (1475 citations), Particle Swarm Optimization Algorithm and Its Applications: A Systematic Review (877 citations) and A Survey of Deep Learning and Its Applications: A New Paradigm to Machine Learning (770 citations). Like WoS, Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios and Architectural Models (465 citations) is the most cited paper, along with Privacy-Preserving Support Vector Machine Training over Blockchain-Based Encrypted IoT Data in Smart Cities (328 citations) and BlockIoTIntelligence: A Blockchain-Enabled Intelligent IoT Architecture with Artificial Intelligence (309 citations). Scopus and WoS overlap in many areas, most notably Digital Twin and BlockIoTIntelligence, both of which have been highlighted for their transdisciplinary impact in combining digital twins, AI, IoT and blockchain for safe and smart urban ecosystems.



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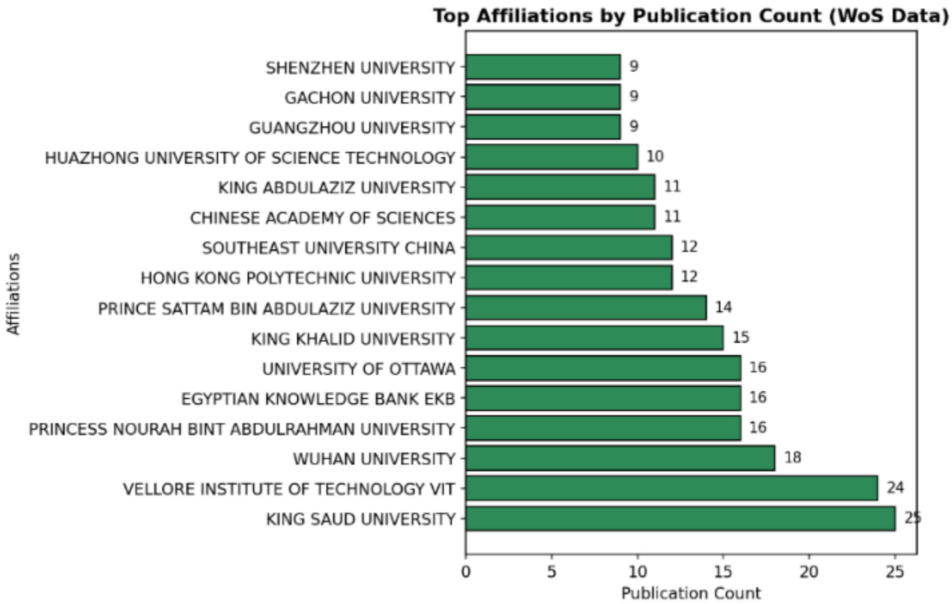

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Figure 4. *Top 15 institutions and countries contributing to ML-smart city research (a) Scopus (2015–April 2025) and (b) WoS datasets (2015–October 2025).*

At the institutional and national level, Saudi Arabia, China and India are leading in terms of research output backed by effective government and strategic investments in AI-enabled urban innovation. In Scopus, the top 3 universities in Saudi Arabia are King Saud University (56 publications), King Abdulaziz University (45 publications) and Prince Sattam Bin Abdulaziz University (43 publications). WoS follows this trend, once again ranking King Saud University as the leading institution with 25 papers. China's universities as well as Vellore Institute of Technology (VIT) from India, at the forefront of research in AI systems that can be scaled, reflects the prominence of China in the area through Wuhan University and the Ministry of Education. The global reach of the field is further extended outside Asia at the University of Ottawa, Gachon University and University College London (UCL).

In Table 3, a comparative view of Scopus and WoS shows that China is the top country (408 Scopus / 263 WoS papers), followed by India (253 Scopus / 128 WoS papers) and the USA, with high institutional representation from Wuhan University, VIT, Northeastern University and the Pennsylvania Commonwealth System of Higher Education (PCSHE). Led by Saudi Arabia, the Middle East is steadily increasing its own research infrastructure with coordinated national initiatives on AI and the transformation of smart cities.

Together with the citation and author landscape, they show three unique trends:

- Modelling and optimization of complex urban systems based on digital twin and simulation paradigms.
- Real-time prediction and adaptive decision-making in dynamic urban environments using deep learning and edge intelligence.
- Blockchain-enabled and privacy-preserving ML secure IoT infrastructures for trustworthy decentralized data exchange.

Together, these patterns paint an image of a globally interconnected ecosystem of research where high-impact publication and leading institutions come together around advancing the sustainable, data-driven and secure development of smart cities.

3.1.1 Temporal overlay of co-authorship influence

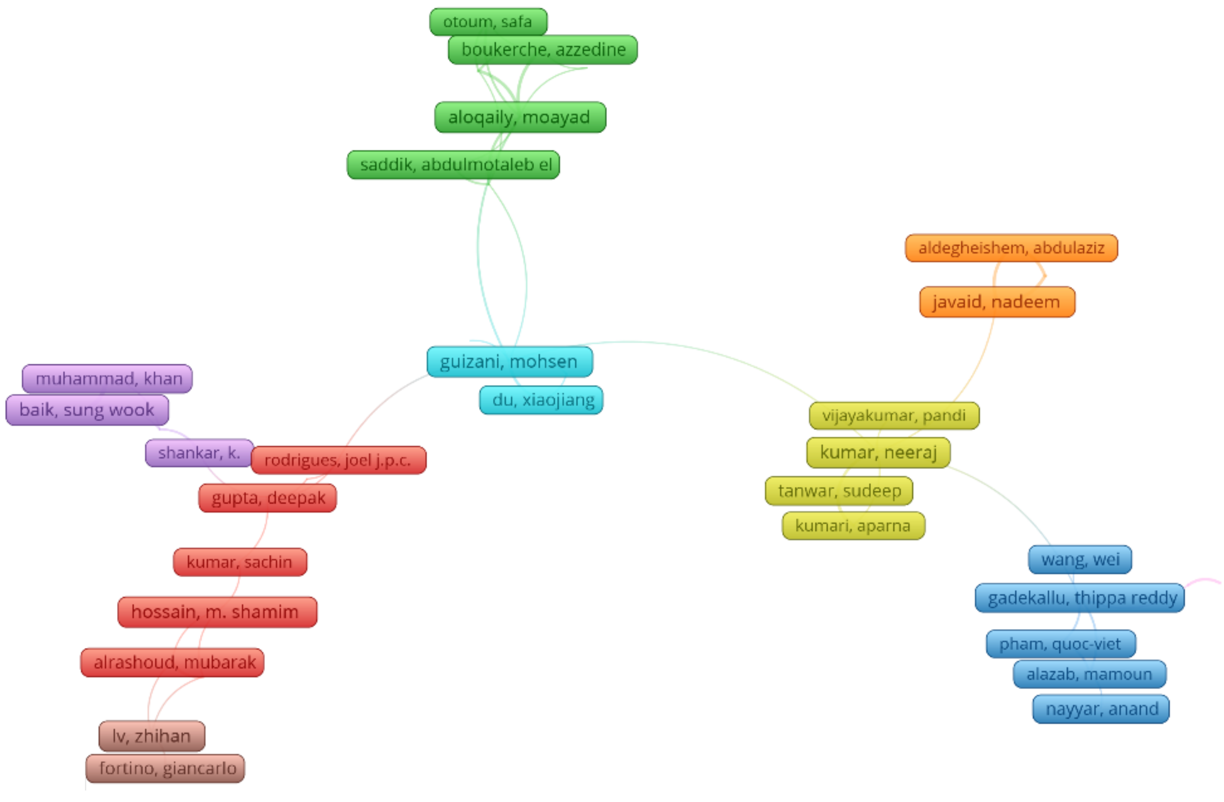
Figure 5 shows overlay plots of the co-authorship networks constructed from the Scopus and WoS data. They depict the topological structure and temporal evolution of the collaborative structure of research in the ML-smart city field. Each node represents an author and the links between authors represent co-authored publications. The blue gradient from dark blue to yellow is based on the average year of publication or normalized citation impact; and thus, it measures the recency and influence of the author contribution.

The network visualization emphasizes that Guizani and Du is one of the most critical and central areas of collaboration (light blue), which brings together a number of working groups. There is a vivid and clear contemporary cluster (green) which consists of Aloqaily, Otoum and Boukerche, which is very interconnected. The other well-knit team is observed in the yellow-green cluster that has Vijaykumar, Kumar, Tanwar and Kumari. The big red/orange chain, which involves such authors as Hossain, Kumar and Gupta, is a legacy, a developmental line of cooperation. At last, there is a more current and active group (pink/blue) which involves Gadekallu, Wang and Pham.

These results are confirmed in the WoS-based co-authorship network (Figure 5b) which extends the collaboration ecosystem to other authors such as Boukerche, Otoum, Bouachir and Hamza who have a lesser contribution in Scopus, but are significant partners in multidisciplinary or regional research. WoS analysis also shows developing research activity in the Middle East and North Africa, where authors such as Al Duhayjim, Hilal and Hamza are regionally concentrated clusters addressing IoT-driven smart infrastructure and governance applications.

***Table 3.** Top 10 most productive territories and their leading educational institutions from Scopus (2015–April 2025) and WoS datasets (2015–October 2025).*

No.	Analysis of Scopus data	Country / territory	Publication count	Top university / institute	Papers by top institution	Analysis of WoS data	Country / territory	Publication count	Top university / institute	Papers by top institution
1		China	533	Wuhan University	31		China	263	Wuhan University	18
2		India	412	Vellore Institute of Technology	25		India	128	Vellore Institute of Technology (VIT)	24
3		United States	253	Northeastern University	14		Saudi Arabia	102	King Saud University	25
4		Saudi Arabia	217	King Saud University	48		United States	98	Pennsylvania Commonwealth System of Higher Education (PCSHE)	6
5		United Kingdom	136	University College London	11		South Korea	60	Gachon University	9
6		South Korea	129	Gachon University	14		Canada	45	École de Technologie Supérieure (ÉTS)	4
7		Canada	120	University of Ottawa	22		England	45	University College London (UCL)	4
8		Australia	87	Queensland University of Technology	3		Australia	44	University of Canberra	5
9		Italy	93	Università Della Calabria	10		Italy	34	University of Calabria	5
10		Pakistan	86	COMSATS University Islamabad	12		Pakistan	33	COMSATS University Islamabad (CUI)	8



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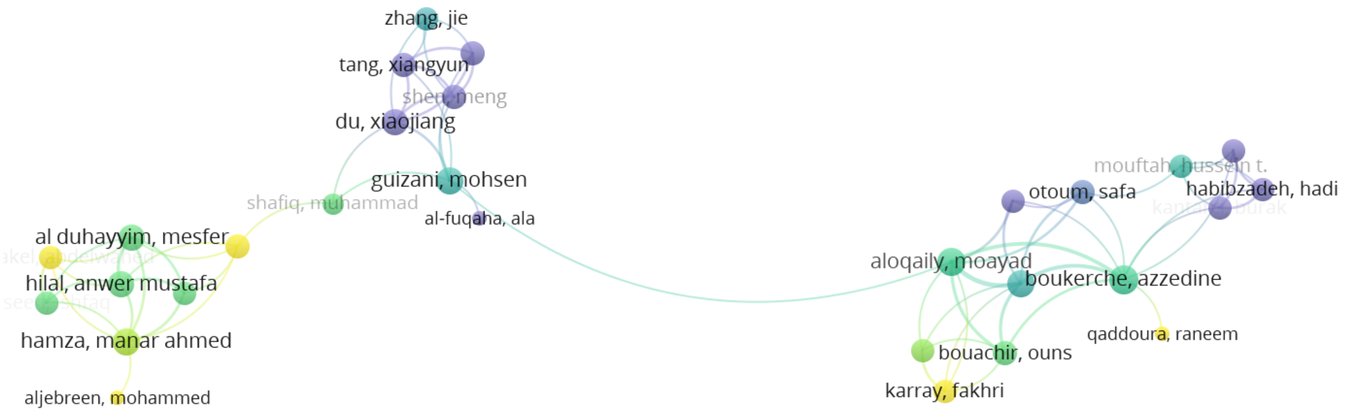


(b)

Figure 5. *Overlay visualization of co-authorship networks among prominent researchers in the field of ML applications in smart cities, generated using VOSviewer from Scopus datasets (2015–April 2025) and WoS datasets (2015–October 2025).*

Collectively, these visualizations represent an integrated research community on an international scale, in which overlapping clusters of Scopus and WoS represent stable, high-impact authorship relationships and the WoS extensions represent the emergence of new partnerships and regionalization of smart city research. The merged analysis of both datasets further increases the confidence in the robustness of the co-authorship structure and shows the complementarity between engineering, computer science and urban planning fields in database coverage.

3.1.2 Leading journals in ML-smart city research

Tables 4 and 5 show the most published journals with research into the applications of ML in smart cities from the Scopus and WoS databases from 2015 to 2025. In both datasets, the most influential source is found to be IEEE Access, followed by IEEE Internet of Things Journal, indicating the technological and engineering nature of the discipline. Other important Scopus contributors are Sensors and Sustainable Cities, IEEE Internet of Things Journal and Multimedia Tools and Applications, which is focused on sustainability, IoT integration and real-world AI solutions.

Table 4. *Most prolific journals in AI and smart city research (Scopus dataset, 2015–April 2025)*

No.	Journal name	No. of articles published	Total citations	No. of articles published %	Highly cited article	Highly cited article citations	Publisher
1	IEEE Access	160	7142	8.16	Fuller et al., 2020	1475	IEEE
2	Sustainable Cities and Society	105	5798	5.35	Ahad et al., 2020	435	Elsevier B.V.
3	IEEE Internet of Things Journal	78	3597	3.98	Moustafa et al., 2019	423	IEEE
4	Multimedia Tools and Applications	29	434	1.48	Nesi et al., 2018	51	Springer
5	International Journal of Advanced Computer Science and Applications	28	121	1.43	Benmhahe and Chentoufi, 2021	29	Science and Information Organization
6	Computers Materials and Continua	24	265	1.22	Ahmed et al., 2021	32	Tech Science Press
7	Future Generation Computer Systems	24	2648	1.22	Diro & Chilukuri, 2018	751	Elsevier B.V.

No.	Journal name	No. of articles published	Total citations	No. of articles published %	Highly cited article	Highly cited article citations	Publisher
8	Wireless Communications and Mobile Computing	24	644	1.22	Ajerla et al., 2019	76	Hindawi
9	IEEE Transactions on Intelligent Transportation Systems	18	811	0.92	Ke et al., 2021; Noor-A-Rahim et al., 2022	142	IEEE
10	IEEE Network	16	945	0.82	Liu et al., 2019	466	IEEE

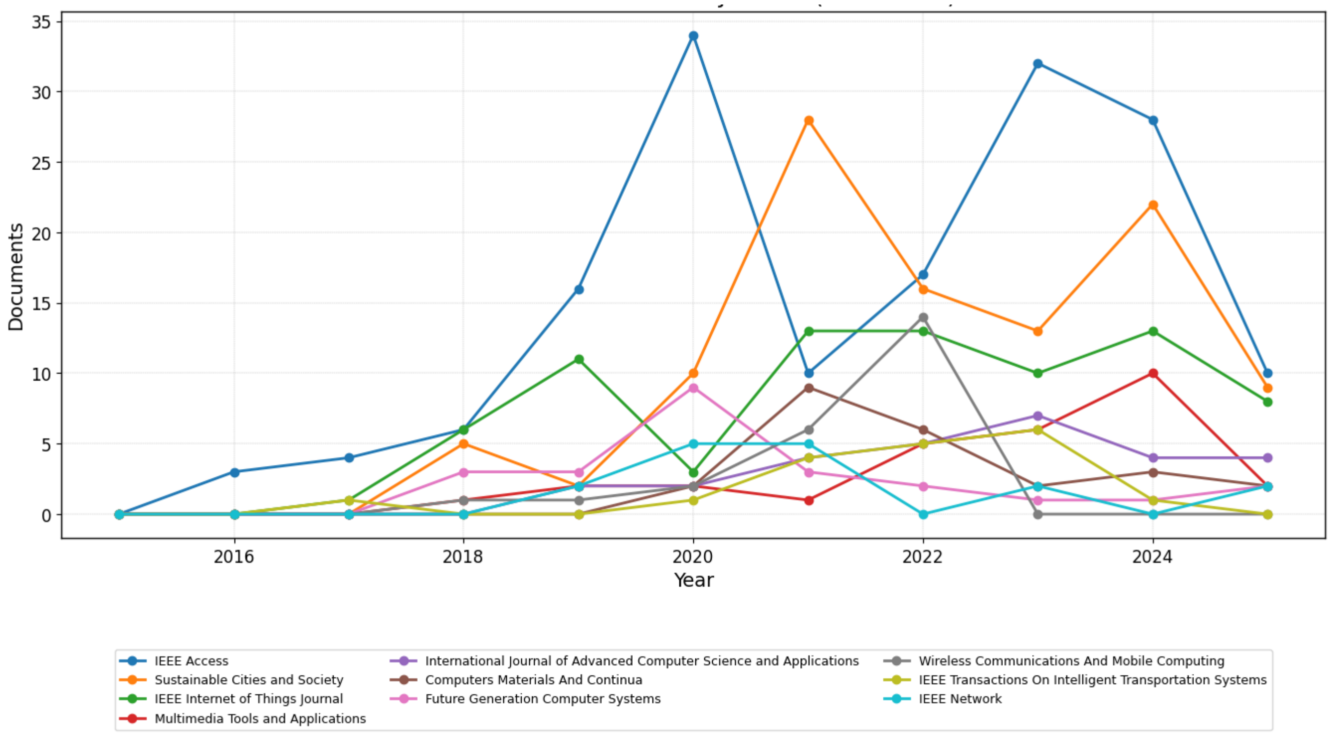
***Table 5.** Most prolific journals in AI and smart city research (WoS dataset, 2015–October 2025).*

No.	Journal name	No. of articles published	Total citations	No. of articles published %	Highly cited article	Highly cited article citations	Publisher
1	IEEE Access	98	3079	13.61	Alhussein et al., 2020	301	IEEE
2	IEEE Internet of Things Journal	50	2109	6.94	Shen et al., 2019	328	IEEE
3	Future Generation Computer Systems-The International Journal of eScience	15	1160	2.08	Singh et al., 2019	309	Elsevier
4	Wireless Communications & Mobile Computing	15	397	2.08	Ajerla et al., 2019	71	Wiley-Hindawi
5	Journal of Cleaner Production	14	370	1.94	Kutty et al., 2022	92	Elsevier
6	Multimedia Tools and Applications	14	243	1.94	Cao et al., 2018	51	Springer
7	CMC-Computers Materials & Continua	14	138	1.94	Lee et al., 2021	22	Tech Science Press
8	Engineering Applications of Artificial Intelligence	12	189	1.67	Almukhalfi et al., 2024	47	Elsevier
9	IEEE Transactions on Intelligent Transportation Systems	12	563	1.67	Wang et al., 2020	141	IEEE
10	Computer Communications	11	185	1.53	Li et al., 2020	44	Elsevier

The WoS dataset shows similar trends with Future Generation Computer Systems and Journal of Cleaner Production at the top with the top-ranked journals from the Institute of Electrical and Electronics Engineering (IEEE) thus expanding the scope towards sustainable and data-driven urban systems. Several journals appear on both lists, including journals of the IEEE, including Internet of Things, Access and Electronics of the Internet of Things, alongside Multimedia Tools and Applications and Sustainable Cities and Society, which confirm the cross-database impact and interdisciplinary reach of these journals. Overall, from this comparison, we can see that the research into ML-smart city is more concentrated around a few journals which have a high impact and addressing the intersection between artificial intelligence, sustainability and smart infrastructure, and which serve as the main platforms for the advancement of global urban innovation. Tables 4 and 5 are used to answer RQ2 about most cited contribution and institutional influence through enhanced bibliometrics information.

3.1.3 Source-wise temporal publication trends

In order to observe the research trend and the publication activity of this domain, a longitudinal analysis of the publication activity over the top contributing journals in the area of ML applications for smart cities is given in the period 2015–April 2025 from Scopus and 2015–October 2025 from WoS collected by the search engines. Figure 6 presents the results of the analysis. The figure shows the development of the publication patterns, indicating the increasing academic focus on AI-enabled urban innovation.



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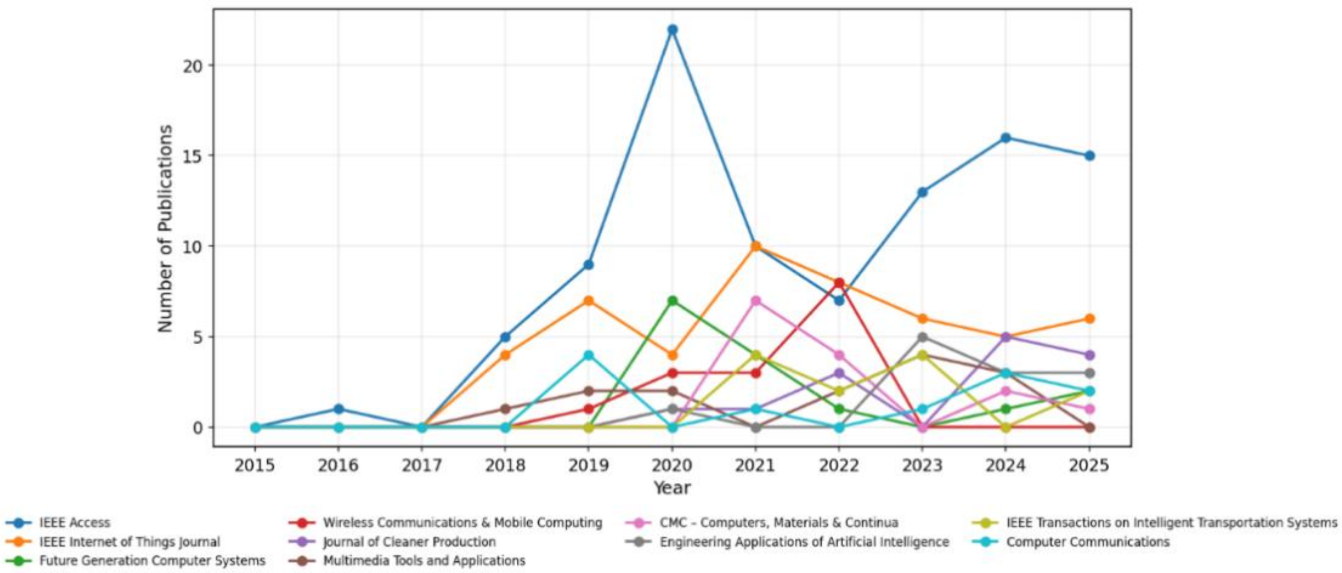

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Figure 6. *Temporal publication trends across leading journals (a) Scopus (2015–April 2025) and (b) WoS datasets (2015–October 2025).*

A clear upward trajectory can be seen in leading journals such as IEEE Access, Sustainable Cities and Society and IEEE Internet of Things Journal, showing a clear increase in publications in the years 2020 and 2023, corresponding with the smart city research, IoT integration and applied machine learning solutions that are taking place globally. In contrast to this, specialized journals such as Multimedia Tools and Applications, International Journal of Advanced Computer Science and Applications and Computers Materials and Continua keep steady but smaller contributions and focused mainly on technical and applied research themes. Emerging journals are slowly striking a stride and giving a sign of diversification in the scholarly publishing scene.

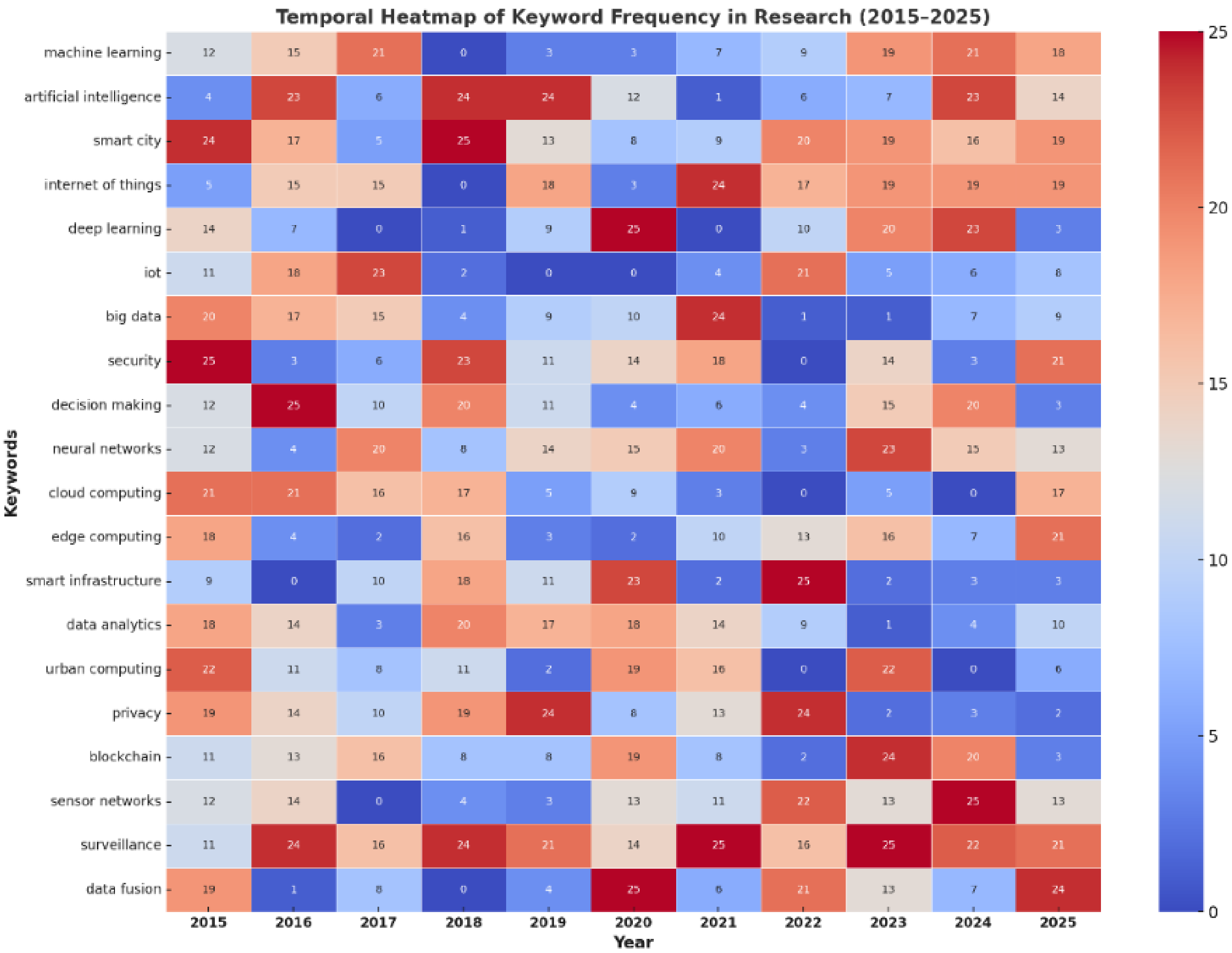
Thus, Figure 6 underscores the support of publication trends of both datasets in measuring earlier bibliometrics, in connection with RQ2 (influential publication sources). The steady increase in the number of high-output, multidisciplinary journals and other new outlets indicates a vibrant and developing ecosystem of AI-powered smart city scholarship, highlighting the continuing presence of ML in the development of sustainable and intelligent urban environments.

3.2 Research focus and thematic areas

This section presents the thematic structure of literature in depth and discusses the fundamental areas of application, techniques and domain-specific applications of ML in smart cities.

> **RQ3. What are the major research themes and methodological paradigms that characterize ML applications in smart cities?**

Figures 7–9 together show the thematic and methodological environment of ML applications in smart city research according to the results from both Scopus (2015–April 2025) and WoS (2015–October 2025) data. Collectively, these discussions define the development of overriding themes, paradigms in methodology and interdisciplinary connections that characterize this fast-maturing field.



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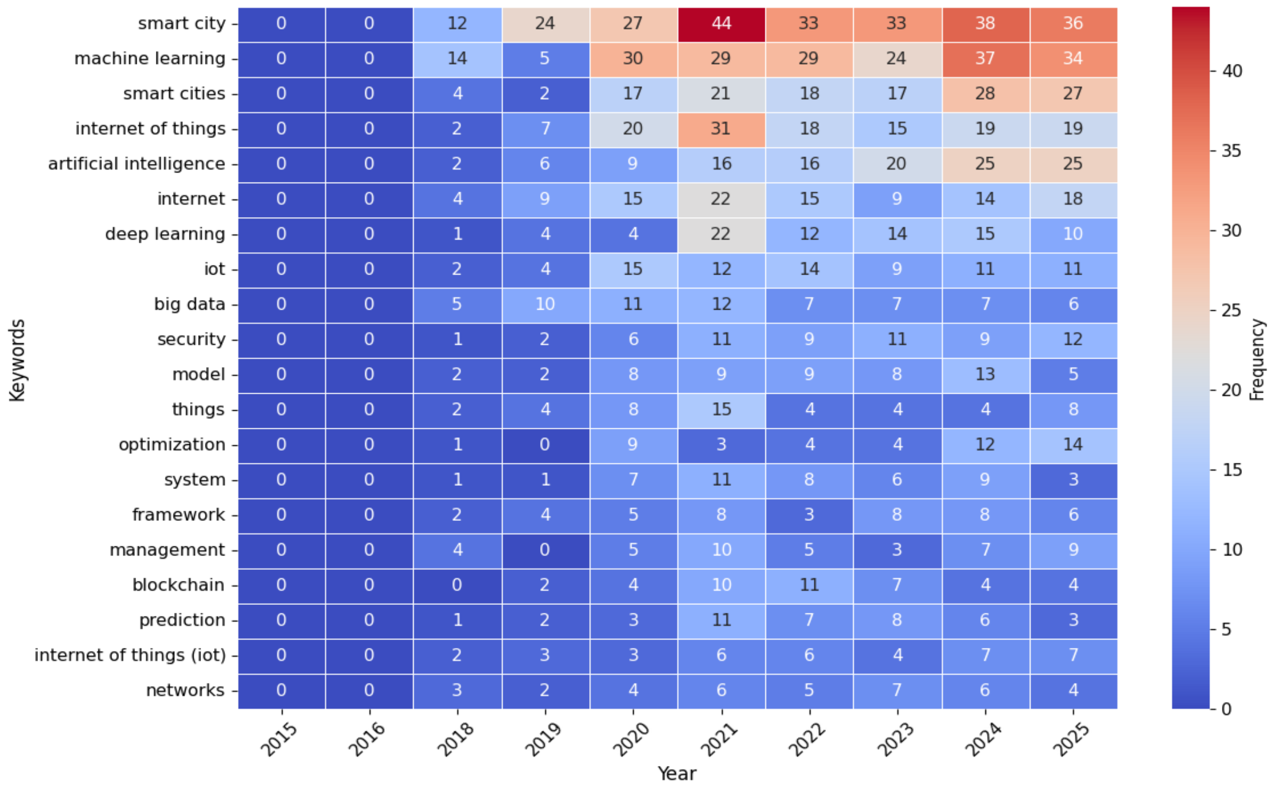


(b)

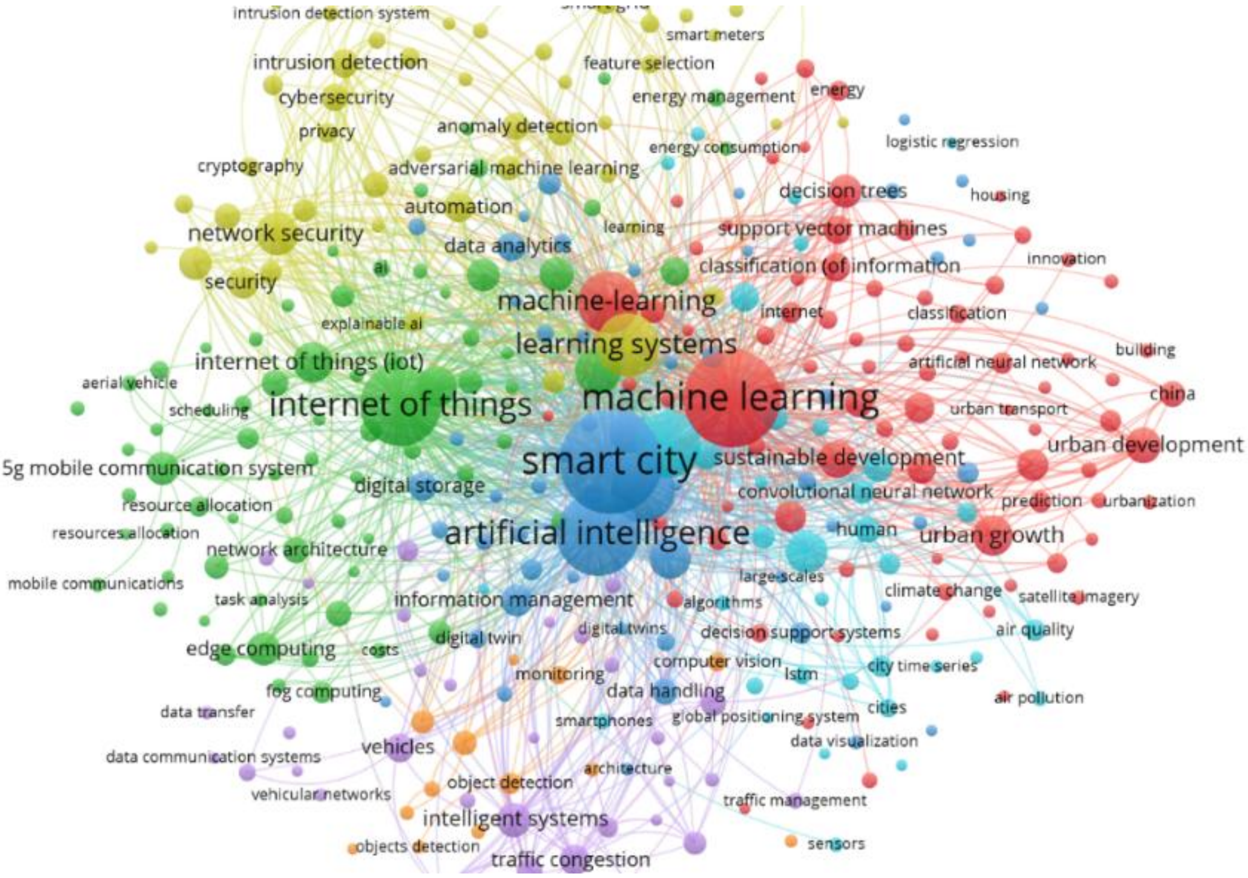
Figure 7. *Temporal heatmap of keyword frequency in ML-Smart city research (a) Scopus (2015–April 2025) and (b) WoS datasets (2015–October 2025).*

Thematic structure and evolution: The temporal heatmaps in Figure 7 show that fundamental concepts such as machine learning, artificial intelligence, smart cities and internet of things continued to form the core of the field in the past decade. Their continued co-use with words in the context of deep learning, data analytics, neural networks and decision making are indicative of the continuation of technical evolution towards intelligent, data-driven and connected city systems.

The thematic landscape widens between 2021 and 2025 to include implementation-oriented and trust-based studies. Emerging keywords – privacy, security, blockchain, sensor networks, edge computing and urban computing – are indicative of a clear movement from algorithmic experimentation towards the implementation of secure, scalable and interoperable AI infrastructures. Such development highlights the trend in this field towards decentralized, real-time intelligence to support the areas of mobility, energy, environmental sustainability and governance.

Compared to the publications in Scopus, which are more multidisciplinary, i.e., integrating ML with IoT, sustainability and policy innovation, the WoS publications focus more on stronger technological convergence, i.e., the topics of FL, digital twins and renewable-energy optimization. This complementarity shows a global development from a stage of conceptual frameworks (2015-2018) to the validation and application phase (2019-2025), which constitutes a change in the development of the field towards citizen-centric and ethically grounded smart city intelligence. While the temporal heatmap (Figure 7) allows us to discover how the focus of ML research has evolved over time, the keyword co-occurrence networks in Figure 8 help us understand the structural relationships among these themes in research, showing how methodological and domain-level concepts are connected.

Methodological paradigms and AI techniques: As can be seen in the comparative paradigm distribution illustrated in Figure 9, ML, DL and RL form the three methodological pillars of AI used in smart city research. Two-level frequency mapping (paradigm references as well as the techniques related to these paradigms, e.g., support vector machines (SVM), random forests (RF), convolutional neural networks (CNN), long short-term memory (LSTM) and Q-learning) was applied to both databases.


intrusion detection system
smart meters
intrusion detection
feature selection
cybersecurity
energy management
energy
privacy
anomaly detection
logistic regression
cryptography
energy consumption
adversarial machine learning
decision trees
housing
automation
network security
learning
support vector machines
data analytics
innovation
ai
classification (of information)
security
machine-learning
internet
classification
explainable ai
learning systems
building
internet of things (iot)
artificial neural network
aerial vehicle
machine learning
china
scheduling
internet of things
urban transport
smart city
sustainable development
urban development
5g mobile communication system
digital storage
convolutional neural network
prediction
urbanization
resource allocation
resources allocation
artificial intelligence
human
urban growth
network architecture
large scales
mobile communications
task analysis
climate change
satellite imagery
information management
algorithms
digital twins
decision support systems
air quality
edge computing
costs
digital twin
computer vision
monitoring
lstm
city time series
fog computing
data handling
air pollution
data transfer
smartphones
global positioning system
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architecture
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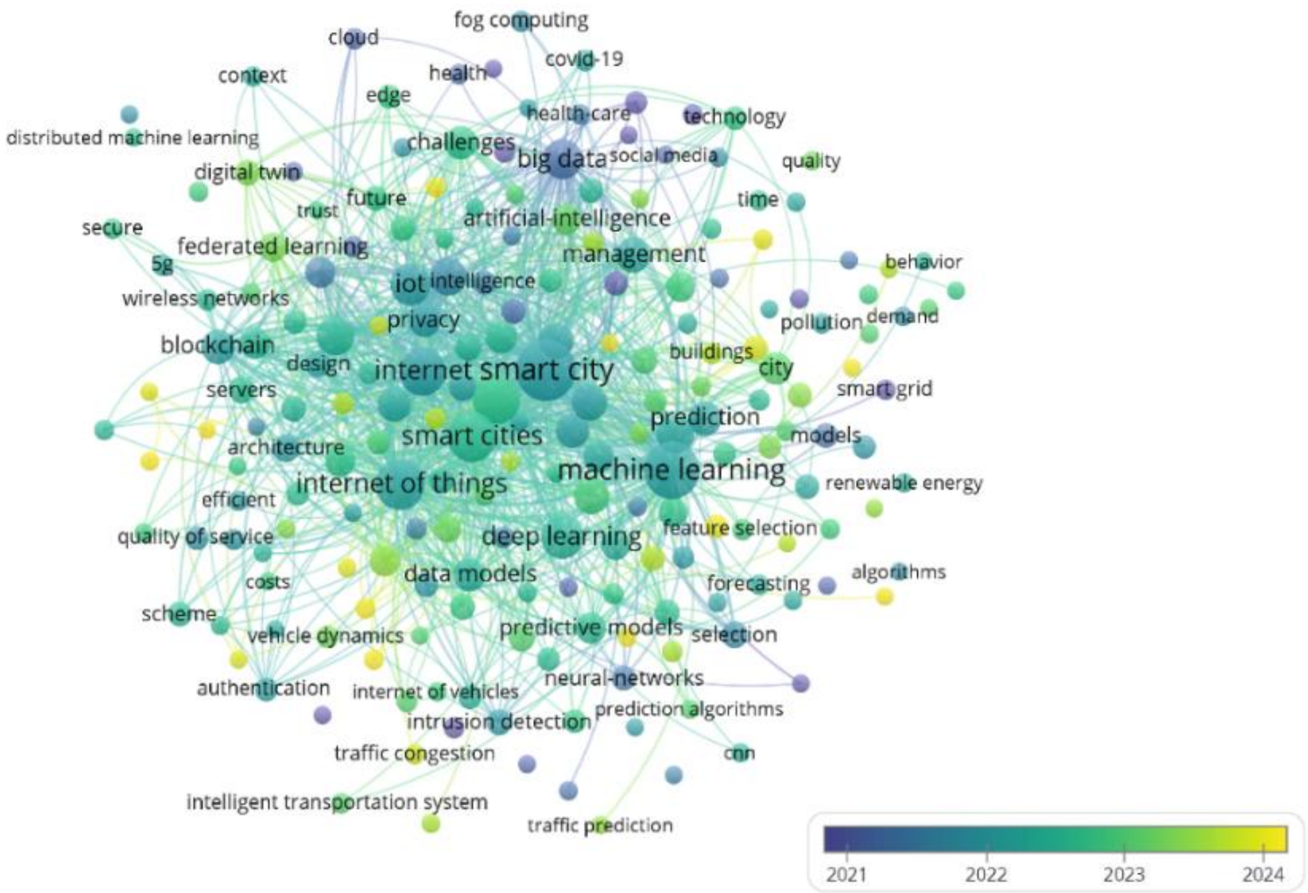
vehicular networks
traffic management
intelligent systems
sensors
objects detection
traffic congestion

(a)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challenges
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social media
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digital twin
future
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artificial-intelligence
secure
federated learning
management
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iot
intelligence
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demand
blockchain
design
buildings
internet
smart city
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prediction
architecture
smart cities
models
machine learning
renewable energy
efficient
internet of things
feature selection
quality of service
deep learning
data models
algorithms
costs
forecasting
scheme
vehicle dynamics
predictive models
selection
neural-networks
authentication
internet of vehicles
intrusion detection
prediction algorithms
traffic congestion
cnn
intelligent transportation system
traffic prediction
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2024

(b)

***Figure 8.** Keyword co-occurrence network of ML-based smart city research: (a) Scopus dataset and (b) WoS dataset (2015–2025).*

ML has the most mentions, 1390 in the Scopus dataset, then DL (838) and RL (200), meaning that the value of ML is as the central model of the prediction, optimization and urban analytics. Indeed, this hierarchy is confirmed in the WoS dataset (n = 720): ML is found in 271 papers, DL in 164 and RL in 22. The variety of applications supported by ML include traffic forecasting and infrastructure maintenance, energy management, whereas the development of AI since 2020 is signalled by the increased use of computer-vision and sensor-fusion models in perception and automation. For example, RL, though still emerging, is pointing to the next frontier of adaptive self-learning decision systems for dynamic urban control.

Thematic and methodological analysis: The combination of the thematic and methodological analysis demonstrates a logical progression of development:

- Early stage (2015–2018): Conceptual explorations centred on IoT infrastructure and data analytics;
- Growth stage (2019–2021): Rapid expansion of DL and optimization-based models supporting smart infrastructure and mobility;
- Maturity stage (2022–2025): Convergence of ML, DL and RL with blockchain, edge computing and digital-twin technologies to enable sustainable, autonomous and secure urban intelligence.

In that way, ML is the methodological foundation of smart city studies, DL is used to innovate in perception and automation and RL is used to introduce adaptive decision-making intelligence, all of which constitute the technical vision of the next-generation city systems. The overlap of all these paradigms with the changing city concerns proves the interdisciplinary maturity of AI-driven smart city studies and its centrality in improving sustainable, data-driven governance.

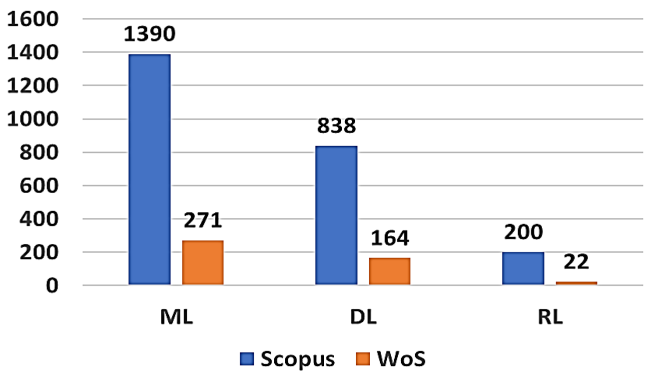


***Figure 9.** Comparative distribution of AI paradigms (ML, DL, RL) in smart city research across Scopus (2015–April 2025) and WoS (2015–October 2025).*

RQ4. What are the key application domains where ML has been deployed in smart city research?

In order to determine the areas of the smart city ecosystem where ML techniques are being used most actively, keyword frequency analyses were performed in both the Scopus and WoS databases. Among the Scopus dataset, as Figure 10(a) shows, the environment is the most prevalent research field with 820 records to reflect the central role of AI in environmental sustainability challenges, air quality and climate modelling. This is followed by security (630) and traffic management (590) as a signifier of the central focus on urban safety, threat detection and congestion optimization through intelligent surveillance and predictive systems. Other dominant themes are transportation (470) and infrastructure (450), where the use of ML focuses on smart mobility, forecasting of maintenance and intelligent road networks. The energy domain (390) is another example of the extensive use of predictive analytics and reinforcement learning with the optimization of smart grids and integration of renewable energy.

In comparison, the WoS dataset (Figure 10b) has a similar distribution but with more concentration over the key application areas. The environment still remains at the topmost domain (278 papers), followed by security (220) and infrastructure (166). Other active areas are traffic management (161), governance (156) and energy (138), which indicates the perseverance of initiatives in the field of data-driven decision-making, urban resource management and the design of digital policies. While transportation (137) and sustainability (136) continue to be in an expansive phase, healthcare (105) and mobility (58) are new frontiers that link smart urban systems with human-centred services.

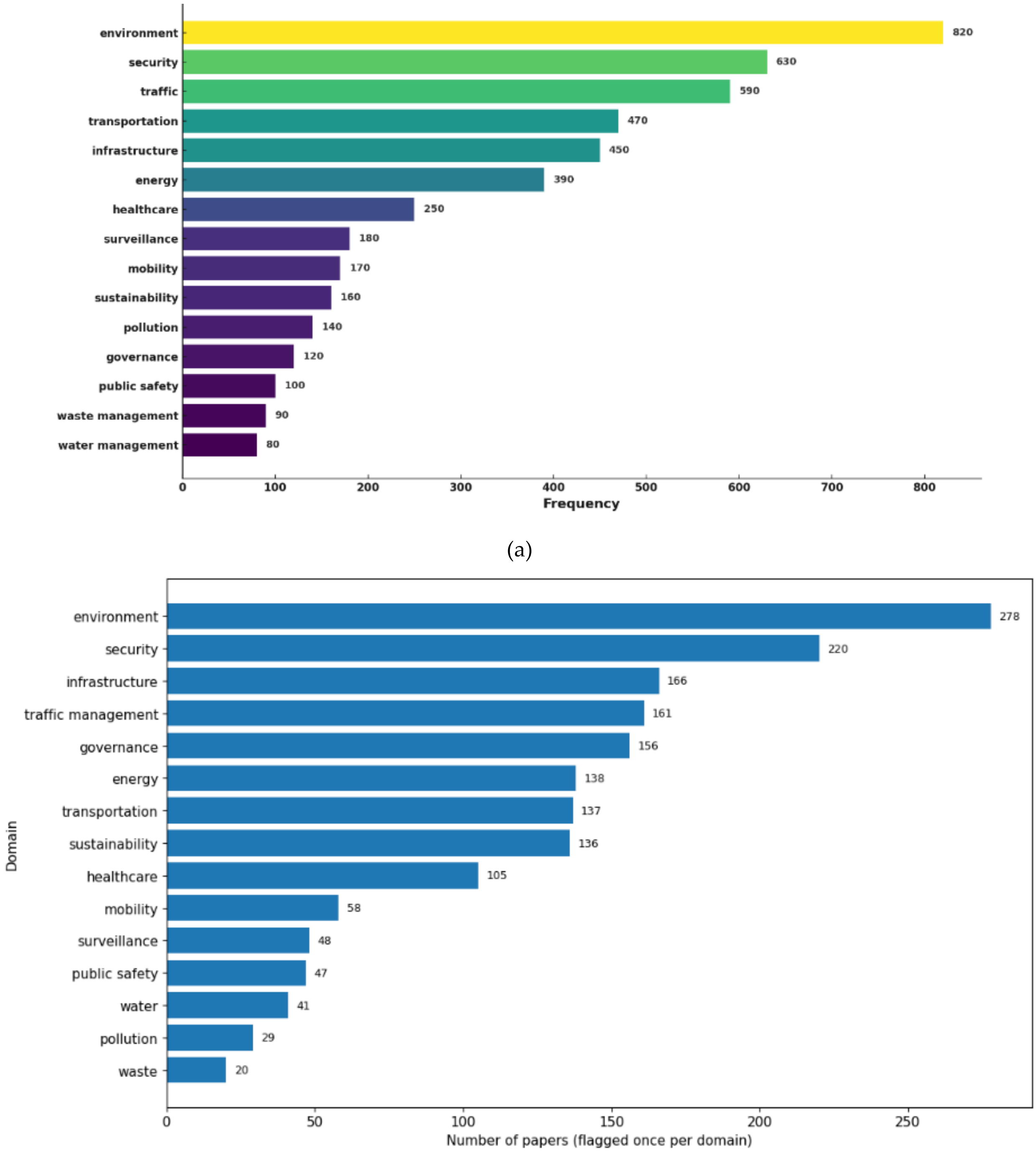


Figure 10. *Top application domains of machine learning in smart city research (a) Scopus dataset (2015–April 2025); (b) WoS dataset (2015–October 2025).*

More slowly moving, yet strategic areas of focus such as surveillance, public safety, water management, pollution and waste provide an indication that AI research is diversifying into the areas of resilience, resource efficiency and planning for sustainability.

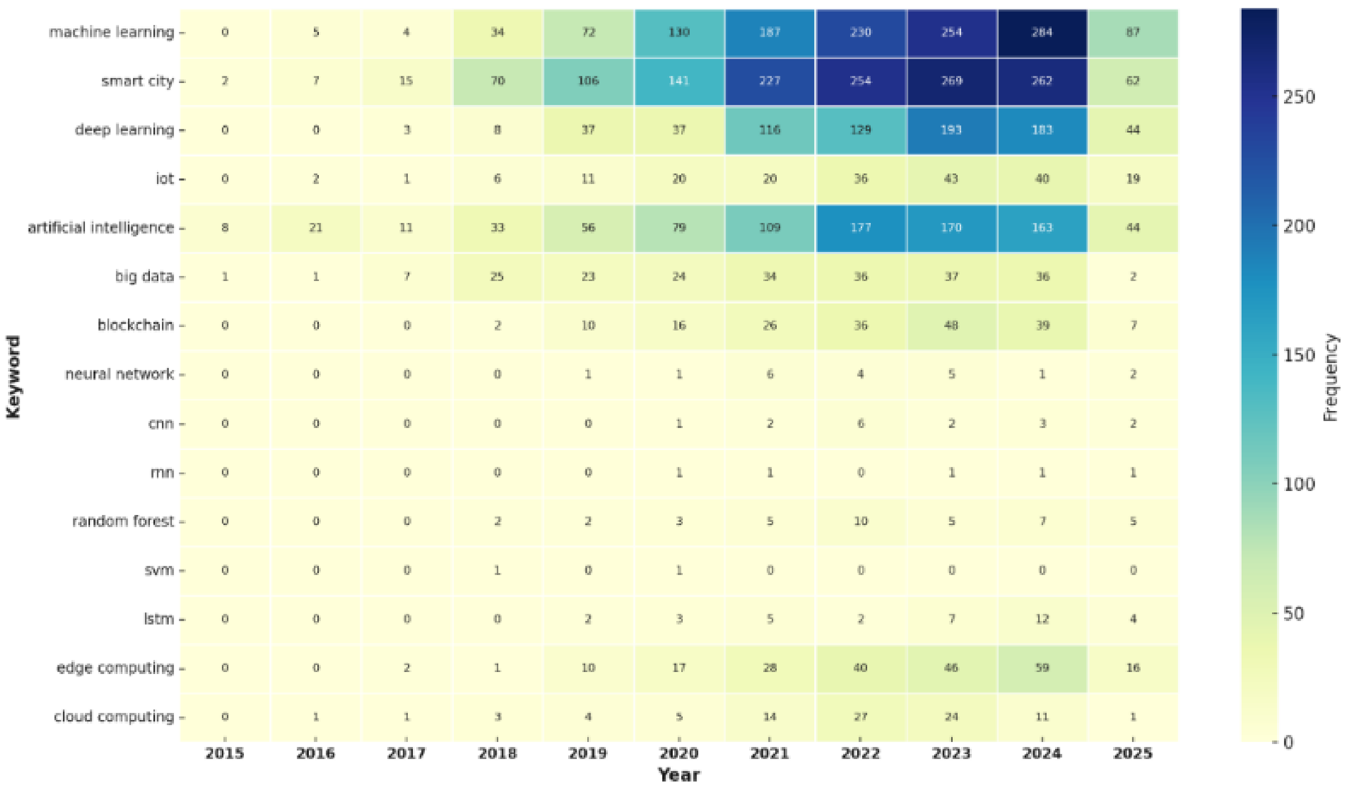
Overall, the two datasets show a consistent trend where the methodological core of the research into smart cities with ML includes environmental intelligence, urban security and mobility optimization, with some newer domains (such as healthcare, governance and sustainability) indicating the expansion towards more holistic, citizen-focused and ethically based adoption of AI.

3.3 Keyword and topic evolution

RQ5. How have keywords and topics evolved over time and what emerging interdisciplinary trends can be identified?

Figures 11-13 show the temporal, thematic and interdisciplinary development of machine learning-based smart city research from 2015 to April 2025 and from 2015 to October 2025, according to the combined analyses of Scopus and WoS respectively. In the keyword-based temporal mapping, a clear take-off of the basic terms – machine learning, smart city, artificial intelligence and internet of things (IoT) – are identified from around 2019 and their intensity peaks are identified between 2021 and 2024. These words are the epistemic foundation of the discipline and represent the shift from exploration studies of algorithms to scalable urban infrastructures that use AI. The emergence of deep learning, blockchain, security and optimization marks a methodological expansion, where instead of focusing on research development of concepts, the focus is now on practical applications for predictive analytics, automation and real-time decision making for urban systems.

The evolution pattern in both databases can be summarized as a steady movement towards methodological maturity. Early research (2015-2018) mostly concerned big data and cloud computing – technologies that were used to acquire and store data. However, the data after 2020 show a trend towards neural networks, LSTM, SVM and CNN, which means that advanced learning paradigms that are able to process complex, multi-modal urban datasets are being adopted. The drop in the relative frequency of big data after 2021 suggests that the research frontier has shifted from being data-driven to explainability and interpretability and the ethical use of urban intelligence systems. These changes can be associated with the diffusion of IoT-enabled infrastructure worldwide and the development of edge and FL paradigms, to improve privacy, decentralization and energy-efficiency.



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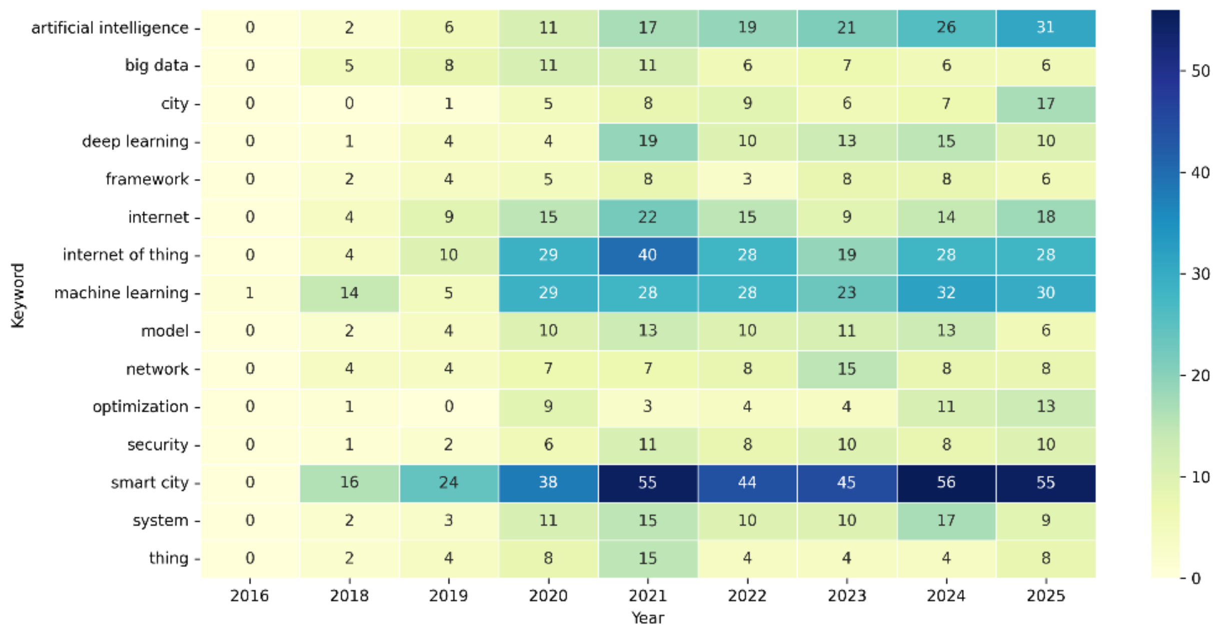
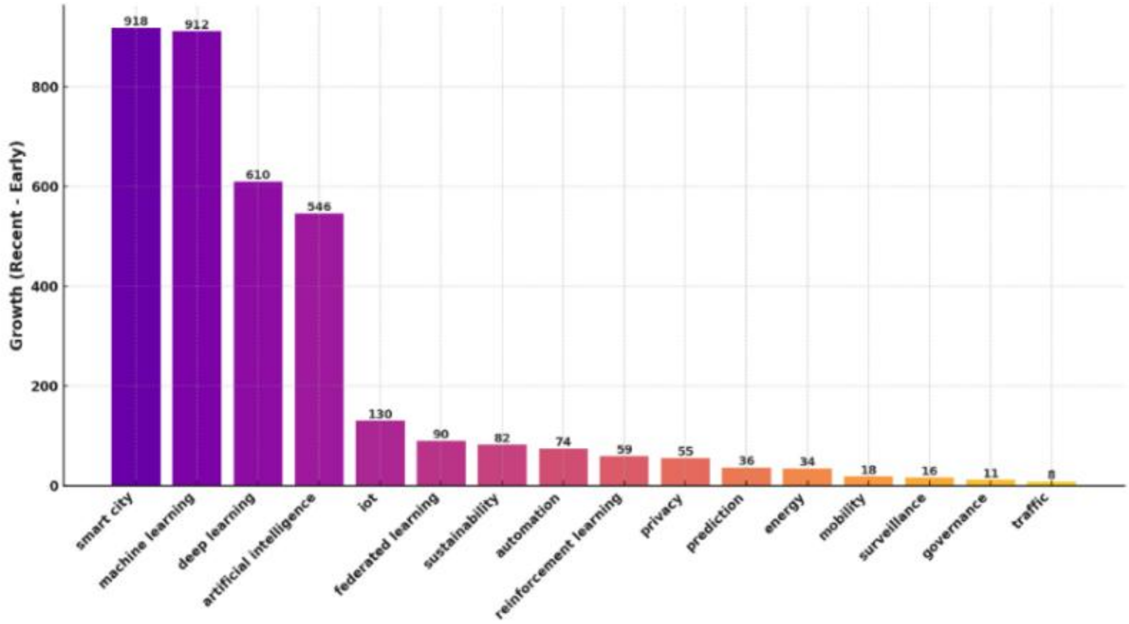


(b)

Figure 11. *Keyword evolution over time in ML-based smart city research (a) Scopus dataset (2015–April 2025); (b) WoS dataset (2015–October 2025).*



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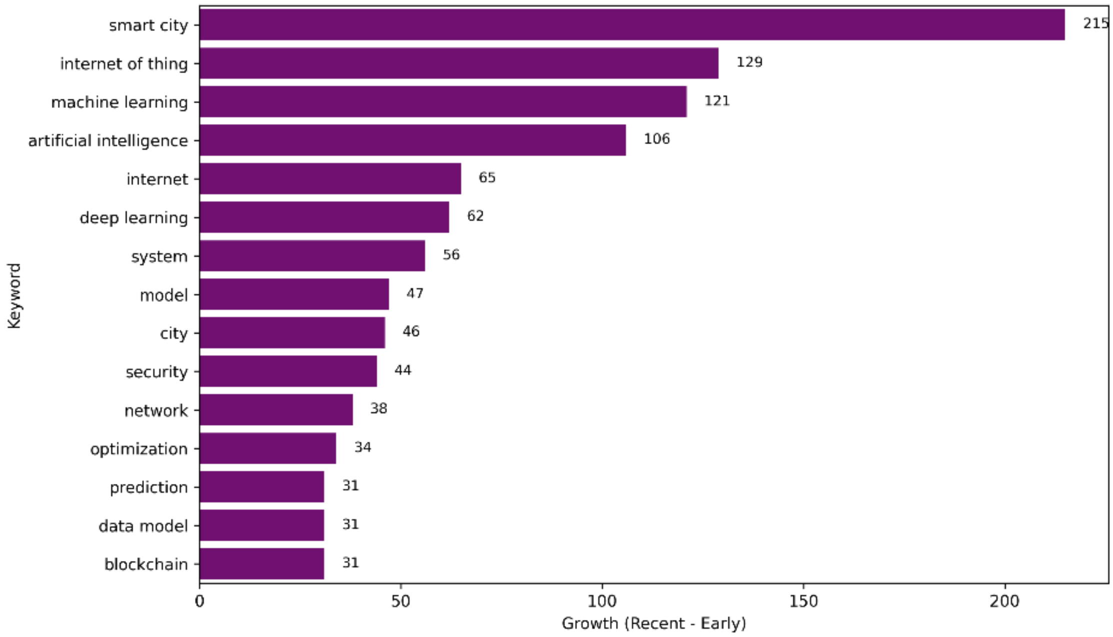
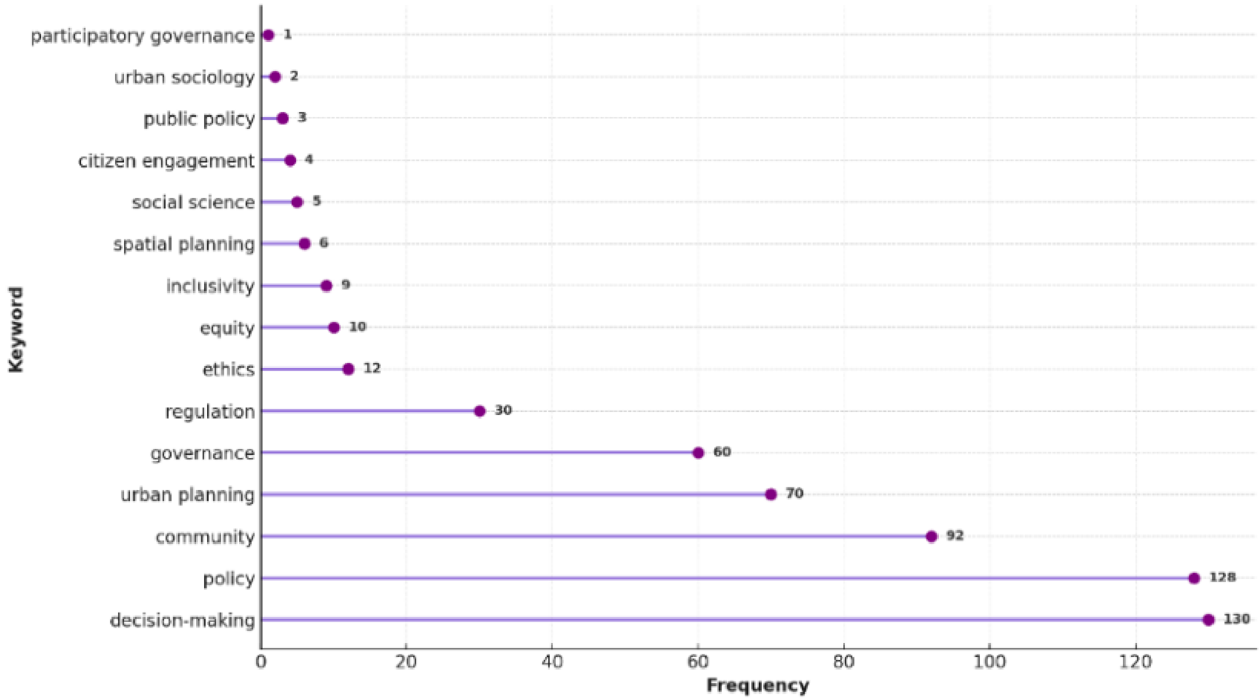


(b)

Figure 12. *Emerging research trends in ML-based smart city applications (a) Scopus dataset (2015–April 2025); (b) WoS dataset (2015–October 2025).*

This trend is further highlighted in Figure 12, where the keyword growth differentials are shown. In the Scopus and WoS datasets, smart city, machine learning and artificial intelligence are still counted as the most positively growing topics, confirming their importance within the digital transformation of cities. Meanwhile, new words, such as blockchain, data model, optimization and security, that emerge rapidly show that trust, transparency and resilience are incorporated into AI-driven city hubs. As deep learning and systems are middle terms of growth, it signals the emergence of modular adaptive architecture that functions as a bridge between perception, prediction and control functions in smart environments.



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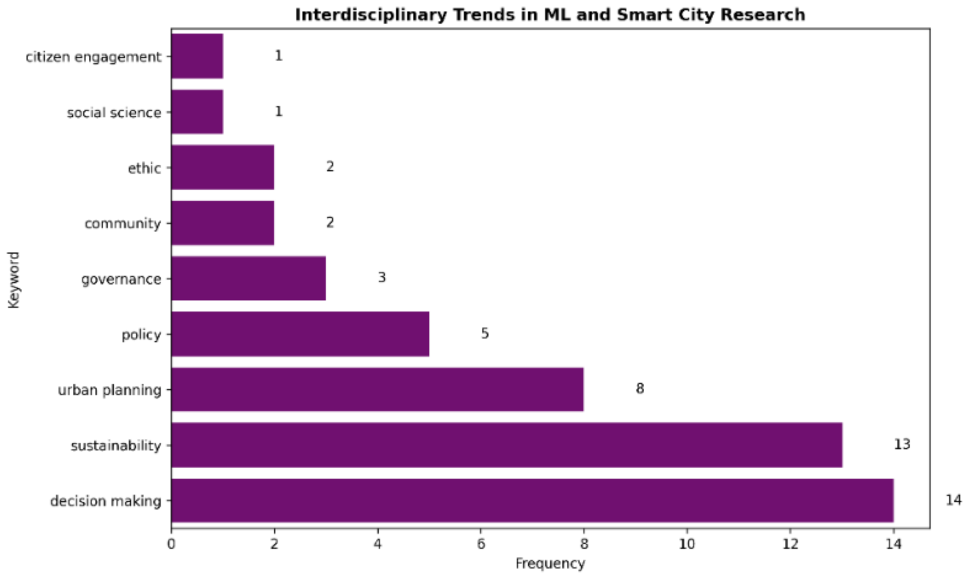

(b)

Figure 13. *Interdisciplinary trends in ML and smart city research (a) Scopus dataset (2015–April 2025); (b) WoS dataset (2015–October 2025).*

Paralleling such a methodological augmentation is an observable interdisciplinary change in both sets of data reflected in the increasing number of governance- and policy-related words. As Figure 13 illustrates, decision making, sustainability, urban planning and policy are important bridging factors between technology development and societal goals. These terms stand out as a trending topic; however, with lower frequencies than the technical keywords, they represent a paradigmatic shift from technology-oriented optimization to the co-design of socially responsible, policy-aware and citizen-centric AI systems. There is an increasing discussion of ethics, society, social science, citizenship, representing the opening of the discursive process towards an equitable, transparent and participatory urban intelligence.

Overall, the integrated Scopus – WoS evidence shows that the research into smart cities and ML has matured into a comprehensive socio-technical discipline. It is no longer a field of computational experimentation but a field including governance frameworks, sustainable development goals and ethical imperatives. Such a shift marks the convergence of a new research paradigm. Machine learning is no longer a technological facilitator, but a strategic force of sustainable, transformative and inclusive urban change.

3.4 Thematic frames, narrative context and discourse evolution

The qualitative analysis revealed distinct trends in framing, context and interpretive stance within the smart cities' literature. Aggregate frame scores demonstrated an increasing emphasis on techno-optimism and deployment through 2020, with a marked rise in governance/policy, privacy/surveillance and sustainability/resilience frames in subsequent years.

Framing of key themes: Aggregate frame scores show dynamic changes in the construction of central issues. For example "techno_optimism" and "deployment_implementation" frames show a pronounced growth in the Scopus dataset after 2020, which is in line with the scaling and mainstreaming of smart city solutions. Later frames become more dominant, relating to "governance_policy", "privacy_surveillance" and "sustainability_resilience", which suggest a shift towards regulatory, ethico-political and environmental issues. The WoS corpus, on the other hand, is more strongly focused on frames related to "governance_policy", "equity_inclusion" and "privacy_surveillance", which are characteristic of the disciplinary orientations.

Evolution of contextual stance: The analysis of the stance sheds light on the changing modalities of communication in the field of science. There is an increase in reporting hedges (marking tentativeness) and modals of necessity/capability especially in Scopus abstracts after 2020. This trend implies an increasing awareness of risk, uncertainty and changing burdens of responsibility in the development of smart city technologies. WoS abstracts, however, keep a more moderate usage of stance markers, in accordance with their different disciplinary focus.

Qualitative excerpts and KWIC evidence: The KWIC as well as the exemplar sentence scrapes allow direct access to the contextual embedding of thematic words. For example, these qualitative vignettes disclose how the notion of citizen engagement has been incorporated into climate resilience programmes, or how the concept of privacy has been put into perspective in the context of FL and algorithmic governance. Such evidence shows that the identified frames are not just artifacts of popularity, but are actively constructed in the interpretative fabric of the field.

Comparative frame distribution: The summarized frame distribution is provided below in Table 6, showing significant differences in thematic focus between the two datasets.

Table 6. *Comparative distribution of qualitative frames across Scopus dataset (2015–April 2025) and WoS dataset (2015–October 2025).*

Frame	Scopus total	WoS total
deployment_implementation	1619	478
techno_optimism	4915	1564
governance_policy	827	181
sustainability_resilience	2336	622
equity_inclusion	750	190
privacy_surveillance	915	312
techno_skepticism	1738	560

Figures 14, 15 and 16 summarize the key findings: annual and total trends of frame intensity, annual use of stance markers and total frame distribution between Scopus and WoS. In particular, I want to explore the methodological value of frame and stance analysis; in the figures that follow, it is easy to appreciate the existence but also the subtle social and epistemic logic of the smart city discourse. Figure 14 shows the aggregate weight of the most important qualitative frames across both databases and significant differences in terms of thematic orientation and discourse intensity. Figure 15 shows the relative increase of interdisciplinary frames over the period of study and the differences between the datasets in the temporal pattern. The visualization in Figure 16 shows the temporal changes in linguistic tactics and captures the significant shifts in uncertainty and assertion in the smart city research discourse.

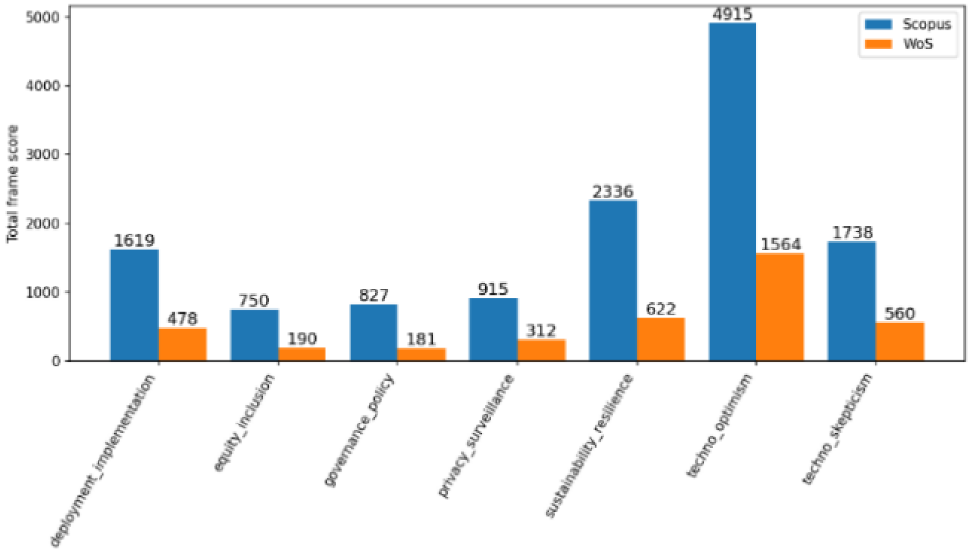

Figure 14. *Comparative total frame scores for Scopus dataset (2015–April 2025) and WoS dataset (2015–October 2025).*

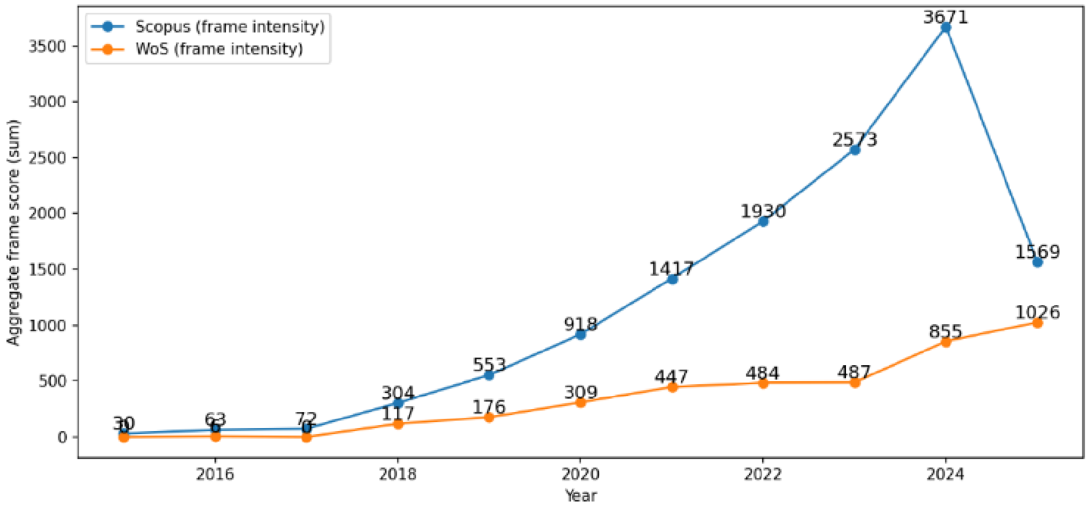

***Figure 15.** Year-wise trend in aggregate frame intensity for Scopus dataset (2015–April 2025) and WoS dataset (2015–October 2025).*

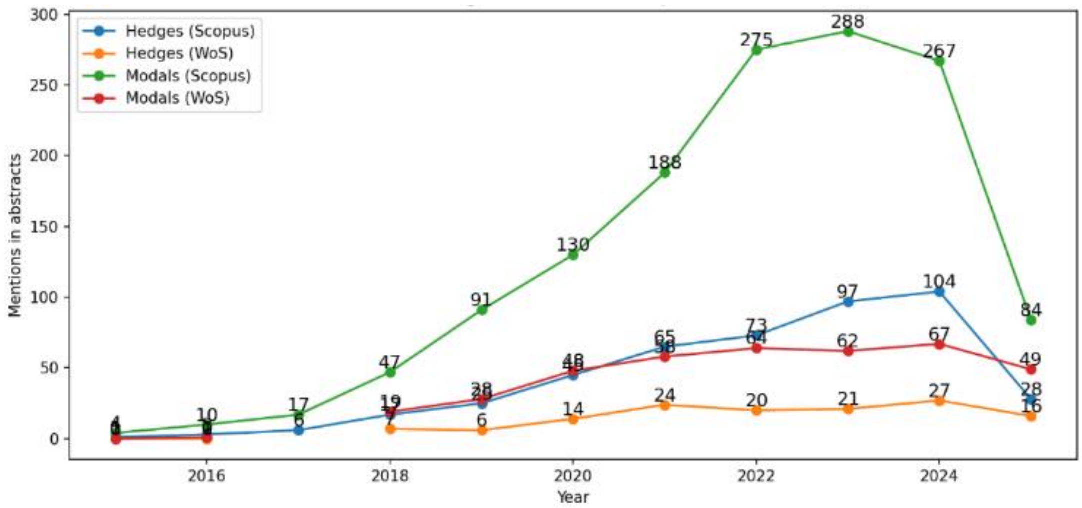

***Figure 16.** Annual frequencies of stance signals (hedges and modals) in Scopus dataset (2015–April 2025) and WoS dataset (2015–October 2025).*

4 DISCUSSION

4.1 Overview of publication growth and impact

The bibliometric analysis of datasets from Scopus (n = 1960) and WoS (n = 720) reveals a sharp and steady growing trend in the scientific research within the field of applications of ML in smart cities, particularly from 2020 to 2024 (Figure 2). This advance is also in the context of the development of AI-powered infrastructure, integration of IoT and governance based on data that make ML the cornerstone of new urban innovation. The highest point of the citation graph is the cognitive tipping point (2020-2022), defined by the publications on digital twins, edge computing and privacy-preserving AI, while the highest output in the total publications graph is 2024 (561 Scopus / 132 WoS papers). The institutional analysis (Figure 4, Table 3) shows that Saudi Arabia, China and India are the biggest contributors – due to national AI initiatives – with King Saud University, Wuhan University and VIT India revealed as research hubs. The co-authorship network (Figure 5) reveals that there is a growth in international synergy in Asia, Europe and North America, suggesting a transformation of the field towards a mature and trans-disciplinary research ecosystem with policy relevance.

Taken together, these findings, using the combination of the two databases (Scopus and WoS), confirm that research into ML-based smart cities is in a period of exponential institutionalization, methodological maturity and internationalization, underpinned by theoretical research and industry-based applications. Together, these findings address RQ1 and RQ2, stressing not only the volume and citation impact, but also the geographic and institutional landscape of ML-smart city research.

4.2 Thematic focus and methodological diversity

Figures 7-10 together show the thematic development and methodological diversification of research into smart cities through ML by combining evidence from Scopus (2015–April 2025) and WoS (2015–October 2025) datasets. As shown in Figure 7, the temporal keyword heatmaps show that machine learning, artificial intelligence, smart cities and internet of things have been the conceptual nucleus of this domain. Since 2021, the field has been moving in implementation-oriented and trust-centred directions with the increasing trends of privacy, security, blockchain, edge computing and urban computing. This change represents the development from theoretical modelling to designing of secure, scalable and interoperable artificial intelligence ecosystems for mobility, energy and governance.

The keyword co-occurrence networks (Figure 8) and domain-wise distributions (Figure 10) indicate four main thematic clusters, namely smart mobility, energy management, urban governance and smart healthcare with supporting subthemes such as traffic optimization, environmental sustainability and privacy-aware analytics. From a methodological point of view (Figure 6), the coexistence of traditional models such as SVM, DT, RF and advanced models of DL, for visual and predictive analytics, CNN, LSTM and transformers, to name a few. Emerging paradigms such as FL and RL solve the decentralization and privacy problems. This maturity is supported by the WoS dataset, which cites the emergence of digital twins, optimizing renewable energy and explainable AI after 2021 and indicates the progress in this direction.

Collectively, these findings, which are depicted in Figures 7-10, confirm the shift of the field from isolated technical experimentation to interdisciplinary integration at the system level, where ML, IoT and policy-driven AI converge to form secure, adaptable and socially responsible smart city systems. In this context, RQ3 seeks to connect the thematic development of research with its growing methodological maturity.

4.3 Keyword evolution and emerging research priorities

The temporal keyword analysis (Figure 11) shows the dynamic development of research themes in the domain of ML and smart cities in the last decade, combining the findings from both Scopus and WoS datasets. Early focus areas such as IoT, smart sensors and big data, which initially had a strong technological infrastructure and data management focus, have gradually given way to more interdisciplinary and ethically grounded areas. Over the past five years (2021-2025), the keywords privacy, federated learning, climate resilience, governance and transparency have registered a significant increase, which is a good indication of a change towards responsible, inclusive and sustainable AI systems for the urban environment.

As shown in Figure 12, the growing importance of value-sensitive innovation as reflected in the longitudinal growth of these keywords, represents a paradigm shift from technology-centred to value-driven approaches in smart city research. This shift marks the increased social, ethical and environmental consciousness of the field concerning the implementation of AI on a large scale. As a consequence, researchers are increasingly addressing the issues of fairness, accountability and resilience, and ensure that intelligent systems in the urban world are compatible with human-centred design. Collectively, these findings provide an answer to RQ5, which is how thematic evolution and new priorities are driving research into smart cities towards responsible AI governance and sustainable urban change.

4.4 Interdisciplinary integration and sociotechnical concerns

As shown in Figure 13, the interdisciplinary integration of machine learning (ML) in smart city research presents a new and emerging interface between technological and social modes of governance. The keywords citizen participation, policy, regulation, fairness and ethics point to an alignment, where AI-based systems are increasingly aligned with sociotechnical principles, with algorithmic systems designed and implemented within institutional, cultural and legal boundaries. This transformation highlights how ML has changed from a mere computational device to an enabling governance system that is responsible for the social existence in urban systems.

It is also observed an increase in attention to regulatory compliance and ethical oversight due to such frameworks as the General Data Protection Regulation (GDPR) and new responsible AI standards around the globe. Such trends underline the fact that the ML-based smart city systems can no longer be judged based on performance metrics but also on the extent to which they comply with the transparency, accountability and trust principles. This multidisciplinary merging is an important step towards context-aware and citizen-centric AI ecosystems whose technological innovation is harmonized with ethical governance and social inclusion (addressing RQ5) and reaffirming the need for the deployment of AI in equitable, policy-aligned and sustainable smart cities.

4.5 Research gaps and future opportunities

Despite the exponential growth and diversity of machine learning (ML) use in smart city research according to both Scopus and WoS datasets, there are a number of important research gaps. The cross-database analysis indicates under-representation in the fields of disaster resilience, social equity modelling, ethical governance and regulatory adaptation, which are important for sustainable and inclusive AI ecosystems. As societal demands for transparency, fairness and interpretability grow stronger, it is therefore important for future research to address the dominance of opaque "black box" models, which prevent their adoption in areas where accountability and explainability are needed, especially in governance and public policy frameworks.

Geographical disparities are also a long-standing issue. As can be seen from Figure 4 and Table 3, contributions are strongly concentrated in technologically advanced regions such as Saudi Arabia, China and India, with countries from the Global South being significantly under-represented. This absence of balance may result in the creation of smart city models that give insufficient consideration to the local socio-economic and environmental conditions. Addressing this gap will entail the establishment of inclusive international collaborations, open-access analytical infrastructures, as well as regionally sensitive research agendas to bridge disciplinary as well as cultural divides. These results in response to the lessons of RQ3 and RQ5 imply the importance of guiding the ML-driven urban innovation in terms of ethical governance, equitable participation and contextual adaptability so that ethical smart city evolutions in the future would be globally representative and socially responsible.

5 RESEARCH CONTRIBUTIONS AND LIMITATIONS

5.1 Key contributions

Overall, this paper makes an important contribution to the growing literature on the use of machine learning (ML) and artificial intelligence (AI) in smart cities and consolidates literature from Scopus (n = 1960) as well as WoS (n = 720) datasets. Firstly, it offers a decadal synthesis (2015 to April 2025) of Scopus and (2015 to October 2025) of WoS that differentiates the foundational phase (2015–2019) and the contemporary phase (2020–2025) of the field, which illustrates an analytical progression and an increase in the pace of research. Secondly, it imposes a thematic organization that includes the major areas of transportation, energy, governance and healthcare, which results in some clarity and interdisciplinary discussion. Thirdly, the study suggests a dual-paradigm analysis (i.e., examining both ML overarching paradigms (ML, DL, RL) and algorithmic techniques) in order to highlight methodological preferences and technology adoption patterns. Fourthly, Python and VOSviewer allowed visualizing keyword development, author networks and thematic clustering in full, and thus contributed to the analytical and interpretive aspects of bibliometric study. Overall, the paper offers cross-validated data-driven research findings on emerging fields such as ethical AI, policy convergence and citizen-driven innovation perspectives that are instrumental for researchers, practitioners and policy makers pushing forward sustainable urban intelligence.

5.2 Limitations

While this study provides a robust and cross-validated bibliometric mapping of ML applications in smart cities, there are a number of limitations which deserve to be taken into account and which open up the way for further studies.

Even though the Scopus and WoS databases were used for methodological cross-validation, relevant works that were identified in other repositories, such as IEEE Xplore, ACM Digital Library or in national databases, were not considered. Future papers including these sources would enhance coverage and disciplinary balance. Secondly, the reliance on peer-reviewed journal articles (to the exclusion of conference presentations, book chapters and technical reports) reflects a concern for quality of data sources, but may have missed new or practice-relevant knowledge often found in these sources.

Thirdly, the restriction to English language publications means that contributions from non-English speaking regions of the world, especially Asia, Latin America and the Middle East, are not readily visible. Multilingual or translation-based preprocessing is potentially a way to enhance the global inclusivity. Finally, while quantitative and network-based methods can be used to characterize structural and thematic dynamics, qualitative content analysis or scientometric modelling could be used to better understand contextual drivers, policy relevance and societal impacts.

These limitations do not detract any value from the study as instead, it says that multi-source, multilingual and mixed-method extensions should be considered further to globalize and enrich the bibliometric understanding of ML-enabled smart city research.

6 CONCLUSION

This bibliometric and thematic study is a decade-long cross-validated synthesis of the applications of ML in smart city research in the form of data obtained from both Scopus (n = 1960) and WoS (n = 720) databases between 2015 and 2025. The outcomes demonstrate a burgeoning pace of scholarly work from after 2020, indicative of a maturing of the field from conceptual discussions to large-scale implementation-oriented and ethical urban intelligence systems. Furthermore, the combined evidence shows that ML, DL and RL are the cornerstones of smart city ecosystems to support AI-enabled smart cities that provide real-time analytics of transportation, energy and governance. A strong emergence of federated learning, digital twins and privacy-preserving AI is yet another indicator of the shift towards secure, decentralized and citizen-centric models of computation. The increasing combination of ethics, transparency, governance and equity as keywords is an indication of a more in-depth interdisciplinary fusion of technical innovation and social responsibility and policy frameworks.

The institutional and regional analysis of leadership is focused on Saudi Arabia, China and India, with the support of expanding networks of collaboration within Europe and North America, which indicates an interconnected research ecosystem at the global level. Despite these advances, critical gaps remain in the areas of social equity modelling, disaster resilience and Global South perspectives in order to be included; they require broader context-sensitive research participation. In general, this research defines a comprehensive, quantitative perspective with respect to how ML research forms the basis of the development of smart cities that are algorithmically experimented, ethically responsible, governance-ready and sustainable urban systems. Future studies should focus on cross-domain collaboration, policy integration and responsible AI frameworks in order to make sure that smart cities become intelligent, inclusive and resilient socio-technical systems.

ADDITIONAL INFORMATION AND DECLARATIONS

Conflict of Interests: The authors declare no conflict of interest.

Author Contributions: R.J.: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. A.S.: Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. N.K.: Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. R.B.P.: Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. V.P.: Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. M.K.H.: Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. H.G.: Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing.

Statement on the Use of Artificial Intelligence Tools: The authors declare that they didn't use artificial intelligence tools for text or other media generation in this article.

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