Machine Learning-Driven Framework for Sustainable Water Management in Smart Cities

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Abstract. Sustainable water management in smart cities refers to combined and intelligent management of urban water supply, distribution, wastewater, reuse and stormwater systems to guarantee the security of resources in the long term, protect the environment and resiliency of the city. This paper's purpose is to map and assess the body of international literature about machine learning (ML)-based frameworks in sustainable water management in smart city settings. The study area comprises 2,474 documents that were published in 2020-2025 and are concerned with the intersection of water management, sustainability, and the use of ML. The methodology presupposes scientometric approach based on Scopus indexed publications and bibliometric analysis and visualization by Biblioshiny, VOSviewer and Origin Pro as the tools to evaluate the trends in publications, their thematic development, networks of collaborators, and contributors. The results show that it is a fast-growing area of research with an annual growth rate of 13.48, high citation impact, and a robust cooperation on the global level, mainly driven by China, India, the United Kingdom, and Australia. Significant research areas are wastewater treatment, sustainability, adsorption-based processes, nutrient removal, and increased use of ML in monitoring, forecasting and optimizing the systems. The findings indicate a definite shift in the isolated, technology-focused research, to integrated, system-level, sustainability-focused smart water systems, as well as identify gaps in research on governance, equity and policy integration. Overall, the research highlights the strategic significance of ML-based solutions to the development of sustainable water management of smart cities and provides a general research roadmap of the future interdisciplinary research.

Keywords: Sustainable Water Management, Smart Cities, Machine Learning, Wastewater Treatment, Urban Water Systems, Data-Driven Decision Making

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1 INTRODUCTION

Sustainable water management in smart cities can be defined as the collective management of the whole urban water cycle, the water supply, distribution, use, wastewater treatment, reuse, and stormwater management to guarantee long-term water availability, ecosystem health, and social equity and be resilient to climate and demographic pressures (Mingaleva et al., 2023). It seeks to reconcile human and economic needs with hydrological cycle protection often in the terms of Sustainable Urban Water Management (SUWM), Integrated Urban Water Management, water sensitive cities, and sponge cities (Bhardwaj et al., 2022). This significance has grown with speeding up urbanization, growing standards of living, and industrialization that have augmented water intake and climate change that has shifted rain patterns, heightened drought, severe storms, and diminished reliability of sources (Gacu et al., 2025). Cities have become centers of water consumption and contamination and unless sustainable methods are adopted most of the cities will be confronting an increasing scarcity of water, depletion of aquifers, and water disasters. Such risks have driven planners to reuse, recycle, decentralized and green infrastructure, and climate resilient stormwater approaches to promote infiltration, lessen run-off, and make improvements in terms of resiliency to heavy rain and heatwave (Carrillo-Acosta et al., 2025). Data driven and intelligent solutions are becoming an increasingly popular approach to smart city projects since conventional and static systems are unable to handle the complexity and dynamism of contemporary urban water problems (Leigh & Lee, 2019). Real-time monitoring of consumption, leakage, water quality, and infrastructure condition with the help of ICT, IoT, AI, and big data helps make evidence-based decisions, predictive maintenance, and efficient distribution, decrease losses and power consumption (Koop et al., 2022). High frequency data is generated by Smart metering, remote sensing, and sensor networks, whereas the needs of demand forecasting, prediction of floods and shortage, and the optimization of harvesting, distribution, and reuse schemes are supported by AI and ML (Aivazidou et al., 2021). Data driven tools can be used at the governance level to incorporate water, spatial planning, climate adaptation and more general agendas of smart sustainable cities to enhance transparency, cross-sector coordination, and citizen engagement regarding water conservation and risk management (Fu et al., 2022).

Smart water systems are machine-learned to turn huge streams of IoT data into real-time insights and control optimization of urban networks. RF, SVM, CNN, LSTM, and GNN models process sensor data of pipes, reservoirs, and treatment plants to identify anomalies and forecast system conditions and allow a continuous identification of pressure drops, abnormal flows, and contamination events as opposed to manual inspections (Jayakumar et al., 2024). To predict demand, time-series machine learning models (ANN, LSTM, RNN, ensemble) are used to learn the temporal trends in the water consumption, weather variables, and socio-economic drivers. These models can be used to make accurate predictions of short-term and seasonal water usage, which can be used to support pump scheduling, storage regulation, and tariff design (Karhade, 2025). The detection of leaks depends on the classification and anomaly detection models on the flow, pressure, and smart meter data. Random Forest and the ensemble structure have an extremely high accuracy (AUC ≈ 0.99, F1 ≈ 1.0) and has made 20-25% non-revenue water reductions in pilot smart networks (Cansian et al., 2025). Deep and graph neural networks assistance in predicting water quality using sparse sensor measurements, hydraulic network topology, and multi-source environmental data has been shown to provide an early warning and optimized treatment control at monitored and unmonitored sites through the estimation of water quality parameters including chlorine, BOD, COD, and nutrients using these tools (Al-Qaisi, 2025). On the framework level, the idea of ML-driven decision systems is that forecasting and optimization modules are linked by linking predictive models with constraint-driven allocation and control schemes, including HydroCortex, AquaFlowNet, and AI-IoT optimization schemes (Moghaddam et al., 2025). These combined systems have proven to enhance efficiency of allocation as far as about 30%, lowered energy consumption and operation expenses as far as about 15-25% and decreased total resource use as far as about 18-30% in intelligent communities and arid region water systems (Infant et al., 2025). These ML frameworks will facilitate optimized resource allocation, physical and energy loss reduction, better water quality, and more environmentally friendly urban water management though automated demand-supply matching, high-risk leakage prioritization, predictive maintenance opportunities, and more water quality-focused and environmentally sustainable treatment and irrigation process optimization (Chang & Yang, 2025; Zhao, 2025).

Current research on ML-based water management in smart cities is disjointed by research in diverse fields, planners focusing on resilience and governance, engineers on hydrology and infrastructure, AI researchers on algorithms and learning models, and sustainability scholars on water-energy-food linkage, equity, and regional development (Bibri & Krogstie, 2020; Xiang et al., 2021). It has been repeatedly stated that much research on AI and ML remains small-scale studies, technology-focused with limited exploration of the governance and social implications and pathways to long-term implementation, which further support disciplinary silos (Krishnan, 2022; Vinagre et al., 2023). Such scattered nature of vocabulary, redundancies of work, and lack of credit of cross-domain innovations, such as smart grids, digital twins, and AI-based governance frameworks, can be attributed to this dispersal (De Las Heras et al., 2020). Scientometric and bibliometric analyses provide systematic mapping of disaggregated research through co-citation, co-authorship and keyword network databases, such as Scopus, revealing growth patterns, national and geographical leadership and research, and a distinct move toward integrated and resilience themes and management studies of AI (Coelho et al., 2020). Cluster analysis identifies the major areas of research; leak detection, AI-driven water quality assessment, sponge cities and smart water grids, whilst showing poor cross-disciplinary connection (Sree et al., 2025). Hotspots and underexplored fields of research such as ethics, explainable AI, policy, finance and vulnerable communities are visualized to identify gaps in research and priority interfaces between urban planning, engineering and AI governance (Han et al., 2025). Through this, the scientometric approach as a meta-infrastructure is a means of organizing scattered knowledge and leading a more integrative and cross-disciplinary agenda of intelligent and sustainable urban water management (Quintana et al., 2025).

Scientometric mapping of the machine learning-based smart water management reveals groups of studies, such as IoT-enabled water and wastewater monitoring, leakage detection, smart metering, AI and ML application to integrated water resources, and urban networks, surrogate modelling of distribution and drainage networks, data-driven flood and drainage resilience, smart-city water strategy planning, and machine learning-based water quality measurements (Kovilpillai J et al., 2024). The scientometric research features such powerful organizations as Chinese Academy of Sciences, University of Malaya, Hong Kong Polytechnic University and Northumbira University, significant input of which is made by China, India, USA and European countries (Dai et al., 2025). The technological trends include multi-sensor IoT which are flow, pressure, pH and water quality sensors connected to low power communication technologies such as Sigfox, LoRa and ZigBee to monitor in real-time. The use of advanced ML algorithms, including RF, XGBoost, LSTM, CNN, ANFIS, and reinforcement learning, to predict and control, and growing interest in digital twins and cyber-secure smart infrastructures are emerging trends (Hansen et al., 2025). Scientometric analysis indicates the over-researched domains (leak detection and water quality prediction), and untapped niches (machine learning intersection with governance, equity, decentralized system, and nature-based solution). Scientometric tools, such as the analysis of publications and co-authorship networks, identify mature research fields with leak detection and an emergent field at the interface of machine learning and governance and nature-based solutions (Hurlimann & Wilson, 2018).

2 METHODOLOGY

Figure 1 shows the methodological workflow used in the completion of the bibliometric analysis of wastewater and sustainable water management research. The steps involve specification of a search query, which is used in the Scopus database to access the pertinent publications. The records of choice are then exported as a CSV file which can be processed further. Biblioshiny is used to analyze this file with the purpose of imparting data cleaning, descriptive assessment and bibliometric mapping. Basic bibliometric procedures are conducted to assess the productivity of research, its themes, and patterns of collaboration and the results are presented in the form of graphs and diagrams with the help of VOSviewer and Origin Pro. In general, the results indicate the presence of a systematic and reproducible workflow to map out research trends in wastewater management. **Search Query:** (TITLE-ABS-KEY ("water management") AND TITLE-ABS-KEY ("Sustainable") OR TITLE-ABS-KEY ("Smart cities") OR TITLE-ABS-KEY ("Machine learning")) AND PUBYEAR > 2019 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (EXACTKEYWORD , "Waste Water Management")) AND (LIMIT-TO (SUBJAREA , "ENVI")).

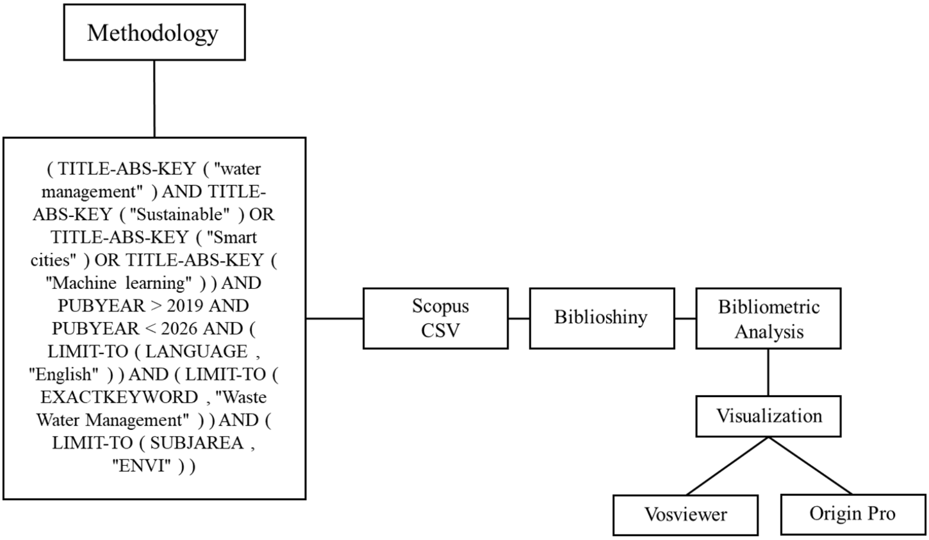

Fig. 1. Methodology Chart

3 RESULTS AND DISCUSSION

Table 1. Bibliometric Overview

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2020:2025
Sources (Journals, Books, etc)	60
Documents	2474
Annual Growth Rate %	13.48
Document Average Age	2.12
Average citations per doc	28.06
References	178683
DOCUMENT CONTENTS	
Keywords Plus (ID)	20900
Author's Keywords (DE)	7076
AUTHORS	
Authors	8784
Authors of single-authored docs	35
AUTHORS COLLABORATION	
Single-authored docs	37
Co-Authors per Doc	5.9
International co-authorships %	39.45
DOCUMENT TYPES	
article	1883
book chapter	1

editorial	23
erratum	3
letter	1
note	8
retracted	3
review	549
short survey	3

Table 1 presents the main bibliometric features of the dataset discussed in the period of 2020-2025. There are 2,474 documents published in 60 sources allowing to state that the base of publications is wide and diverse, and the annual growth rate is 13.48%, which allows stating that the research interest grows. The median age of documents of 2.12 years and the median citations per document of 28.06 evoke high impact and visibility recently. There is thematic diversity based on 20,900 Keywords Plus and 7,076 author keywords. The collaboration intensity is high with 8,784 authors contributing to it with 5.9 co-authors per document and 39.45% international co-authorship. Overall, the field is very rapidly growing, very collaborative, and influential.

Fig. 2. Word Cloud

Figure 2 below represents a word cloud of the most consumed keywords in the wastewater studies with the word size showing relative popularity. Wastewater treatment, wastewater management and wastewater are used to illustrate the significance of research on treatment technologies and management level. Such keywords as adsorption, nitrogen, chemical oxygen demand, phosphorus and sewage can be seen as long-term interest in the removal of contaminants, control of nutrients, and analyzing water quality. The development of such concepts as bioremediation, biomass, water purification, sustainable development shows that people become more interested in the environmentally friendly treatment methods and resources recovery. The findings demonstrate that wastewater research is concentrated on efficient treatment processes, the minimization of pollutants, and sustainable control measures.

Table 2. Annual Scientific Production

Year	Articles
2020	220

2021	326
2022	411
2023	495
2024	608
2025	414

Table 2 represents the annual percentage distribution of the research articles published during 2020-2025 period and the publication output percentage is evidently increasing over the years. It shows a steady rise in the number of articles of 220 in 2020, 326 in 2021, and 411 in 2022 and then further to 495 in 2023. The most recent year, 2024, is associated with the greatest number of publications, 608 articles, which proves the maximum research activity within the period of the study. There is a minor drop in 2025 where 414 articles are found possibly due to partial year coverage of articles. Overall, the results indicate a consistent increase in the volume of research with a significant increase after 2022.

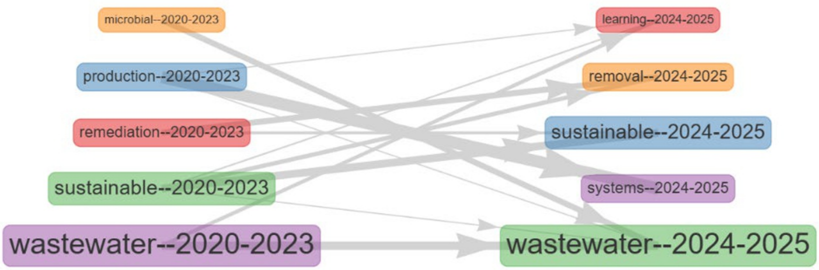

Fig. 3. Thematic Evolution

Figure 3 presents thematic evolution map that shows critical research topics of wastewater 2020-2023 to 2024-2025. The previous discussion on wastewater, sustainability, remediation, production, and microbial trends is dominating on the left, suggesting that the researcher was concerned with the basic concepts of treatment and biological processes. These themes are continuous as they are overlaying directional flows to new recent themes on the right: wastewater, sustainability, systems, removal and learning. The higher level of correspondence of terms such as systems and learning signifies a rise in the move towards approach-based schemes and smart attitudes in wastewater studies. The findings indicate that the vehicle of the treatment research has changed to fundamental themes of treatment towards system-based, sustainable and advanced treatment research.

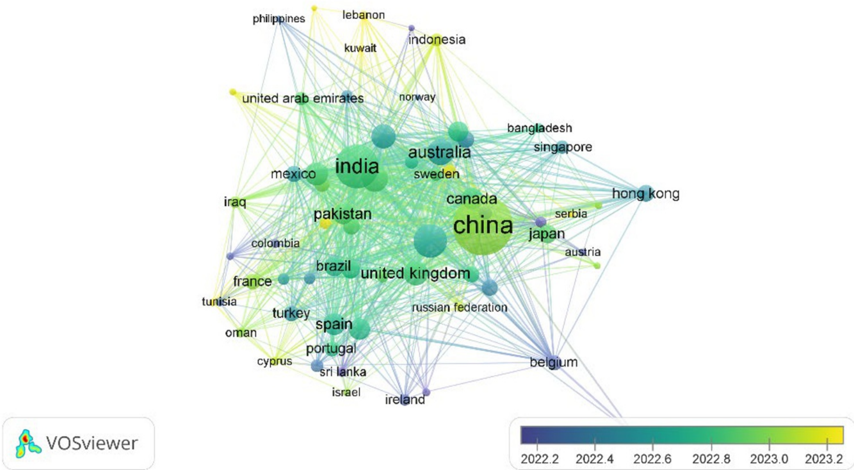

Fig. 4. Co-occurrence of author keywords

Figure 4 presents thematic evolution map that shows critical research topics of wastewater 2020-2023 to 2024-2025. The previous discussion on wastewater, sustainable, remediation, production, and microbial trends are dominating on the left, suggesting that the researcher was concerned with the basic concepts of treatment and biological processes. These themes are continuous as they are overlaying directional flows to new recent themes on the right: wastewater, sustainable, systems, removal and learning. The higher level of correspondence of terms such as systems and learning signifies a rise in the move towards approach-based schemes and smart attitudes in wastewater studies. The findings indicate that the vehicle of the treatment research has changed to fundamental themes of treatment towards system-based, sustainable and advanced treatment research.

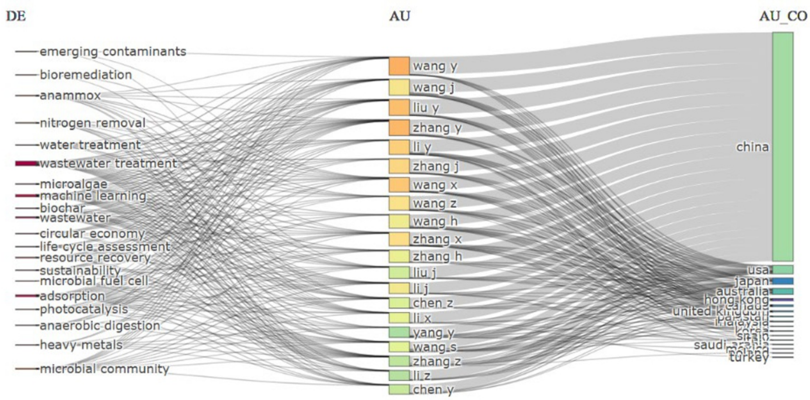

Fig. 5. Three Field Plot

Figure 5 is a three-field Sankey diagram that shows the correlations between the descriptive terms of research dominance (DE), number of authors (AU), and the country of author (AU_CO) in wastewater studies. The thematic breadth of the field is indicated on the left, as wastewater treatment, sustainability, nitrogen removal, bioremediation, adsorption, microalgae, circular economy, and life-cycle assessment are common in the field. These subjects have a co-set of very productive authors of the central panel with concentrated research leadership and collaboration patterns. The right panel has a spotlight on the geographical distribution of contributions with China coming out as the most prominent contributory, closely followed by USA, Japan, Australia, India and the UK. Overall, the results indicate that there has been high thematic focus in terms of wastewater treatment and sustainability; most of the authors have been based in China.

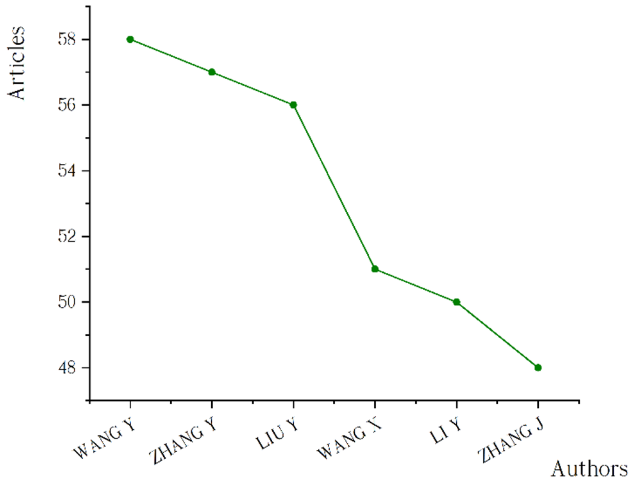

Fig. 6. Most Relevant Authors

Figure 6 shows the publishing record of the most prolific wastewater researchers' scientists where the authors are located on the x-axis and the number of publications located on the y-axis. The most prolific author is Wang Y, then Zhang Y and Liu Y as they have a high output in terms of research. The number of notices performed by Liu Y to Wang X and then the number of notices performed by Li Y and Zhang J gradually decreases. The negative slope is an indication of fluctuation in the productivity of individual research activities among the key contributors but still represents a high level of productivity of all listed authors. Overall, the results indicate that the number of authors contributing a high percentage of publications is low, and Wang Y and Zhang Y are leaders in the field.

4 CONCLUSION

This paper presents a scientometric analysis of machine learning-related sustainable water management studies in smart cities. The analysis of 2,474 publications published between 2020-2025 was conducted to investigate the growth in publications, themes, collaboration trends, and impactful authors. The findings reflect rapid growth of the field, as the annual growth is high, and citation impact is increasing, as the world is becoming more interested in intelligent and sustainable urban water solutions. The research topics boiled down to wastewater treatment, sustainability, the removal of various nutrients, and adsorption-based processes, and machine learning is actively used to monitor, predict, and optimize systems. The global and interdisciplinary nature of this field is reflected in high rates of collaboration, which are driven mostly by China, India, the United Kingdom, and Australia. Thematic evolution starts to show the change in isolated, technology-based research and research, based on integrated, system-oriented and data-driven models, in line with sustainability goals. Although such a development has been achieved, there are still significant gaps in governance integration, equity considerations, policy frameworks, explainable AI and large-scale real-world use. Future studies are needed to match technical innovations with the institutional and regulatory environment and enhance scalability and transparency.

References

1. Aivazidou, E., Banias, G., Lampridi, M., Vasileiadis, G., Anagnostis, A., Papageorgiou, E., & Bochtis, D. (2021). Smart technologies for sustainable water management: An urban analysis. *Sustainability*, *13*(24), 13940. https://doi.org/10.3390/su132413940
2. Al-Qaisi, A. Z. (2025). Smart water systems: The role of technology and engineering in optimizing urban water resources. *J. Inf. Syst. Eng. Manag*, *10*(21s), 833–846.
3. Bhardwaj, A., Dagar, V., Khan, M. O., Aggarwal, A., Alvarado, R., Kumar, M., Irfan, M., & Proshad, R. (2022). Smart IoT and machine learning-based framework for water quality assessment and device component monitoring. *Environmental Science and Pollution Research International*, *29*(30), 46018–46036. https://doi.org/10.1007/s11356-022-19014-3
4. Bibri, S. E., & Krogstie, J. (2020). Environmentally data-driven smart sustainable cities: applied in-novative solutions for energy efficiency, pollution reduction, and urban metabolism. *" Energy Inform*, *3*(1).
5. Cansian, A. R., Guzmán, D. A., Rosa, A., & de Toledo Machado, J. (2025). Nature-Based Solutions for urban drainage: A systematic review of sizing and monitoring methods. *Water*, *17*(17), 2524. https://doi.org/10.3390/w17172524
6. Carrillo-Acosta, N., Santos-Rocha, A. C., Bautista, M. C., & Low, M. O. (2025). Unveil-ing the nexus of scientific production, water resource management, and global water challenges. *Earth Sci. Res. J*, *28*(4), 379–386.
7. Chang, Y., & Yang, J. (2025). Artificial intelligence applications in river management: Challenges and insights from a bibliometric review. *Ecohydrology: Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology*, *18*(4). https://doi.org/10.1002/eco.70057
8. Coelho, J. A., Glória, A., & Sebastião, P. (2020). Precise water leak detection using machine learn-ing and real-time sensor data. *IoT*, *1*(2), 474–493.
9. Dai, Y., Huang, Z., Khan, N., & Labbo, M. S. (2025). Smart water management: Governance innovation, technological integration, and policy pathways toward economic and ecological sustainability. *Water*, *17*(13), 1932. https://doi.org/10.3390/w17131932
10. De Las Heras, A., Luque-Sendra, A., & Zamora-Polo, F. (2020). Machine Learning technologies for sustainability in Smart Cities in the post-COVID era. *Sustainability*, *12*(22), 9320. https://doi.org/10.3390/su12229320

11. Fu, G., Jin, Y., Sun, S., Yuan, Z., & Butler, D. (2022). The role of deep learning in urban water man-agement: A critical review. *Water Res*, *223*(118973).
12. Gacu, J., Monjardin, C., Mangulabnan, R., Pugat, G., & Solmerin, J. (2025). Artificial Intelligence (AI) in surface water management: A comprehensive review of methods, applications, and challeng-es. *Water (Basel)*, *17*(11).
13. Han, Z., Zhang, S., He, L., & Zhu, B. (2025). Predicting and investigating water quality index by robust machine learning methods. *Journal of Environmental Management*, *381*(125156), 125156. https://doi.org/10.1016/j.jenvman.2025.125156
14. Hansen, M. M., Koonsanit, K., & Kulmala, V. (2025). How can data contribute to Smart City inno-vation: a study from Thailand's Smart City initiatives. *Front. Sustain. Cities*, *6*(1473123).
15. Hurlimann, A., & Wilson, E. (2018). Sustainable urban water management under a changing cli-mate: The role of spatial planning. *Water (Basel)*, *10*(5).
16. Infant, S. S., Vickram, S., Saravanan, A., Mathan Muthu, C. M., & Yuarajan, D. (2025). Explainable artificial intelligence for sustainable urban water systems engineering. *Results in Engineering*, *25*(104349), 104349. https://doi.org/10.1016/j.rineng.2025.104349
17. Jayakumar, D., Bouhoula, A., & Al-Zubari, W. K. (2024). Unlocking the potential of artificial intelli-gence for sustainable water management focusing operational applications. *Water (Basel)*, *16*(22).
18. Karhade, P. (2025). Sustainable urban water management: A review of innovative technologies and strategies for smart cities. *International Journal for Research in Applied Science and Engineering Technology*, *13*(5), 5298–5301. https://doi.org/10.22214/ijraset.2025.71449
19. Koop, S. H. A., Grison, C., Eisenreich, S. J., Hofman, J., & van Leeuwen, K. (2022). Integrated water resources management in cities in the world: Global solutions. *Sustainable Cities and Society*, *86*(104137), 104137. https://doi.org/10.1016/j.scs.2022.104137
20. Kovilpillai J, J. A., S, S., Mir, M. H., Jayanthy, Pragya, P., & Rajkumar. (2024). Advancing Water Quality Monitoring in Smart Cities using Machine learning Techniques. *2024 Asia Pacific Conference on Innovation in Technology (APCIT)*, 1–7.
21. Krishnan, S. R. (2022). Smart water resource management using Artificial Intelligence-A re-view. *Sustainability*, *14*(20).
22. Leigh, N. G., & Lee, H. (2019). Sustainable and resilient urban water systems: The role of decentralization and planning. *Sustainability*, *11*(3), 918. https://doi.org/10.3390/su11030918
23. Mingaleva, Z., Chernova, O., & Mitrofanova, I. V. (2023). Bibliometric analysis of research trends in water management aimed at increasing the sustainability of the Socio-economic development of a region. *Water*, *15*(20), 3688. https://doi.org/10.3390/w15203688
24. Moghaddam, H. K., Rahimzadeh Kivi, Z., Abtahizadeh, E., & Abolfathi, S. (2025). Sustainable water allocation under climate change: Deep learning approaches to predict drinking water shortages. *Journal of Environmental Management*, *385*(125600), 125600. https://doi.org/10.1016/j.jenvman.2025.125600
25. Quintana, D., Felix-Herran, L. C., Tudon-Martinez, J. C., & Lozoya-Santos, J. de J. (2025). On smart water system developments: A systematic review. *Water*, *17*(17), 2571. https://doi.org/10.3390/w17172571
26. Sree, M., Rao, G., Prasanna, E. L., & Kalyani, B. (2025). Smart industrial re-al-time water quality monitoring and prediction using machine learning. *INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS*, *13*(4).

27. Vinagre, V., Fidélis, T., & Luís, A. (2023). How can we adapt together? Bridging water management and city planning approaches to climate change. *Water*, *15*(4), 715. https://doi.org/10.3390/w15040715
28. Xiang, X., Li, Q., Khan, S., & Khalaf, O. I. (2021). Urban water resource management for sustainable environment planning using artificial intelligence techniques. *Environmental Impact Assessment Review*, *86*(106515), 106515. https://doi.org/10.1016/j.eiar.2020.106515
29. Zhao, Y. (2025). Advancing smart communities with a deep learning framework for sustainable resource management. *PloS One*, *20*(8), e0329492. https://doi.org/10.1371/journal.pone.0329492