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SURVEY

IoT Innovations in Sustainable Water and Wastewater Management and Water Quality Monitoring: A Comprehensive Review of Advancements, Implications, and Future Directions

AHMAD ALSHAMI[1], ESLAM ALI[2,3], MOUSTAFA ELSAYED[4], ABDELRAHMAN E. E. ELTOUKHY[5], AND TAREK ZAYED[2]
[1]Department of Civil and Environmental Engineering, FAMU-FSU College of Engineering, Florida State University, Tallahassee, FL 32310, USA
[2]Department of Building and Real Estate (BRE), The Hong Kong Polytechnic University, Hong Kong
[3]School of Geomatics, Civil Engineering Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt
[4]Department of Civil and Environmental Engineering, FAMU-FSU College of Engineering, Florida A&M University, Tallahassee, FL 32399, USA
[5]Management Science and Engineering Department, Khalifa University, Abu Dhabi, United Arab Emirates

Corresponding author: Eslam Ali (eslam.a.saleh@connect.polyu.hk)

ABSTRACT This comprehensive review explores IoT innovations in water, wastewater management, and water quality monitoring, emphasizing the transformative potential of these technologies. Combining socio-metric and systematic review (SR) techniques, the study analyzes scientometric trends and co-occurrence networks linked to review topics. Research primarily centers on these aspects, averaging 15 articles annually since 2017, peaking at 24 in 2021. The SR unveils the widespread use of multiple sensors in monitoring, particularly water level, flow, and pH sensors. Common wireless technologies are emphasized for their role in advancing real-time monitoring. Innovative protocols such as Sigfox and Zigbee enhance sensor-IoT connectivity, improving communication in infrastructure management. Common challenges hindering system efficiency and data flow include sensor accuracy, energy optimization, communication reliability, interdisciplinary collaboration, and sensor coverage. Addressing these gaps is crucial for advancing IoT-driven water systems and enhancing decision-making. This study guides IoT practitioners in integrating automation and sustainability in water and wastewater management.

INDEX TERMS IoT, Internet of Things, monitoring systems, water management, wastewater management, water quality, real-time, flow sensors, level sensors, wireless sensors.

I. INTRODUCTION

Water is essential for human survival and various activities such as industry, agriculture, and household usage [1]. Efficient water and wastewater infrastructure, including dams, reservoirs, pipelines, and treatment facilities, is essential to ensure adequate and reliable water supply while minimizing wastage, especially in regions with water scarcity [2], [3], [4], [5], [6], [7], [8]. The increasing demand for water resources due to economic development and population growth, coupled with the negative impact of human activities on the environment, has heightened the importance of sustainable water management practices [4], [9], [10], [11]. These practices aim to balance the competing economic development needs and environmental conservation while ensuring access to clean and safe water resources for future generations.

As part of the Sustainable Development Goals (SDGs) related to water and sanitation, a paradigm shift is needed in managing water and wastewater infrastructure [12], [13], [14]. Sustainable water management practices, such as smart

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metering, water loss management, and demand-side management, can significantly contribute to reducing water wastage and promoting sustainability in the management and monitoring of water distribution networks [15], [16], [17], [18]. On the other hand, sustainable wastewater treatment, such as nutrient removal, resource recovery, and advanced treatment technologies, can reduce pollution and promote sustainability in smart cities [19], [20], [21]. Additionally, efficient drainage network management practices, supported by smart technologies and innovative approaches, can optimize the performance of the network, reduce energy consumption, minimize environmental impacts, and enhance overall sustainability [22], [23], [24], [25]. Therefore, adopting sustainable water and wastewater management practices is critical to ensure water resources' long-term availability and quality and achieve the SDGs related to water and sanitation.

Recently, the integration of Internet of Things (IoT) technologies in WWM-WQM has revolutionized infrastructure management and has the potential to improve the effectiveness, efficiency, and sustainability of water and wastewater systems. IoT-enabled sensors and data analytics play a vital role in smart water management, allowing real-time monitoring of water quality, quantity, distribution, and data-driven decision-making [26], [27], [28]. With the help of IoT sensors, monitoring of real-time water consumption and usage can be afforded, detecting leaks or inefficiencies in the water supply system, and providing valuable insights into consumption patterns for water conservation efforts [29]. IoT sensors can also be utilized to monitor water quality parameters in real-time, including pH, temperature, and turbidity, enabling prompt detection of abnormalities or contamination, and facilitating timely corrective action [30]. In wastewater management, IoT technologies can provide real-time monitoring of effluent quality and treatment efficiency in wastewater treatment plants, allowing for early detection of inefficiencies or malfunctions and helping to prevent potential health and environmental risks. Moreover, IoT technologies enable remote and autonomous operations, allowing for remote monitoring and control of water and wastewater infrastructure components, such as pipes, pumps, manholes, and valves, leading to improved system efficiency and reduced human intervention [31]. Advances in IoT technologies, including edge computing, machine learning (ML), and artificial intelligence (AI), have further enhanced the collection and analysis of data from infrastructure systems, leading to improved management and decision-making in water and wastewater management [32], [33].

Despite the growing importance and progress of IoT technologies and the high demand for smart cities that require IoT applications in managing infrastructure, systematic reviews (SR) about using IoT applications in infrastructure management are few and far between [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46]. While existing reviews have concentrated on specific dimensions of IoT applications in water management, such as IoT's role in stormwater management [45], leakage monitoring [36], and the implementation of intelligent utilities in urban contexts [41], [42], [43], [44], the demand for a more all-encompassing review is discernible. Such a comprehensive examination should encompass a broader spectrum of IoT applications, spanning water conservation, wastewater infrastructure supervision, water quality monitoring, and the broader scope of environmental sustainability. It is also imperative to intricately explore the harmonization of emergent technologies, such as AI and robust big data analytics, with IoT methodologies in the scope of water and wastewater management. Through a comprehensive review, the gaps in the literature can be effectively addressed, thereby highlighting the transformative potential of IoT in water and wastewater infrastructure while simultaneously promoting sustainable practices for smart cities and beyond.

Therefore, the primary goal of this research is to provide a comprehensive understanding of the latest developments within IoT technologies, concentrating specifically on their applications within three distinct dimensions: water infrastructure management, wastewater infrastructure management, and water quality monitoring. Beyond a mere literature survey, this research holds two fundamental goals: firstly, to bridge existing knowledge gaps through an all-encompassing review, exploring the multifaceted applications of IoT in these areas. Secondly, the study aims to distill prevailing trends, identify research gaps, and chart future directions for leveraging IoT technologies in effective water and wastewater management practices. The specific objectives of this study are as follows: 1) to explore the diverse sensing technologies and communication mechanisms that are employed and developed within these three dimensions; 2) to emphasize the diverse applications where IoT sensors, data collection systems, and real-time monitoring add value; 3) to review various real-world case studies and identify obstacles hindering the rapid advancement of these technologies; and 4) to discuss research gaps and limitations introduced by previous studies and outline proposed solutions and future research directions, considering all limitations that may hinder practical implementation.

To comprehensively synthesize existing research, this study adopts a mixed-method approach that combines quantitative scientometric analysis (SA) with qualitative systematic review (SR)techniques. In utilizing the scientometric review, we employ conventional software tools, namely Vosviewer and Citespace. Our analytical focus encompasses exploring annual publication trends, co-occurrence keyword networks, and citation burst maps. Concurrently, our SR methodology builds upon the approach introduced by Alshami et al. [47], extending and enhancing their work. It is worth mentioning that the study by Alshami et al. [47] mainly sought to streamline the conventional SR process by leveraging ChatGPT. For an intricate understanding of their methodological implementation, readers are encouraged to refer to Alshami et al. [47].

The subsequent sections are structured as follows: Section II outlines a concise overview of the methodological framework encompassing systematic and scientometric techniques. In Section III, we present the results of the scientometric review, followed by the related discussions. Section IV encompasses the findings of the SR, structured under three main headings. Finally, the conclusion is drawn, synthesizing insights from systematic and scientometric reviews.

II. MATERIALS AND METHODS

This study employs a hybrid methodology that combines the utilization of ChatGPT, an AI language model, with manual processes, particularly in the systematic analysis component. By adopting this hybrid approach, we aim to harness the complementary strengths of human expertise and AI capabilities, thereby optimizing the systematic review process, enhancing efficiency, and ensuring the precision of our findings. The methodology employed in this study has been previously developed and evaluated in a comprehensive work by Alshami et al. [47]. We direct readers to the aforementioned study for a thorough explanation and evaluation of this methodology. This paper focuses on spotlighting the methodology and presenting the detailed outcomes of implementing this hybrid approach. The hybrid methodology encompasses three pivotal phases, as depicted in Fig.1. The following subsections provide concise descriptions of the flowchart's primary components.

A. ARTICLE SELECTION AND IN-DEPTH DATA EXTRACTION

This phase encompasses several processes, the first involving searching the databases. To ensure comprehensive coverage of scientific publications, Scopus and Google Scholar databases are chosen as the primary sources of information. To generate a thorough list of appropriate keywords pertaining to the utilization of IoT in water and wastewater management, a systematic approach was employed, utilizing a gradual strategy of input questions on ChatGPT, as detailed in Alshami et al. [47]. The keyword set utilized in our search query is as follows: "TITLE-ABS-KEY ((""internet of things" or "IoT") AND ("water" OR "wastewater" OR "sewer" OR "sewage" OR "sanitation") AND ("infrastructure" OR "infrastructures"))". Furthermore, the search process was restricted to peer-reviewed journal and conference papers published between 2010 and 2023. Consequently, technical reports, lecture notes, review articles, and any papers published before 2010 were excluded from consideration.

Subsequently, as illustrated in Fig.1, the aforementioned search strategy yielded 496 records from Scopus, which were further refined to 145 records after thoroughly examining the titles and abstracts using the methodology established by Alshami et al. [47]. This methodology encompasses the screening process and categorizes the identified papers into three main areas of interest: IoT-based wastewater infrastructure management, IoT-based water infrastructure management, and IoT-based water quality monitoring. The selection of these dimensions was a deliberate decision aimed at encompassing the main areas of emphasis in our research. This approach was intended to effectively narrow the filtration process to articles most pertinent to these particular domains. Thus, papers that align with one or more of these categories are included and classified accordingly, while those that do not pertain to any of these categories are excluded [47].

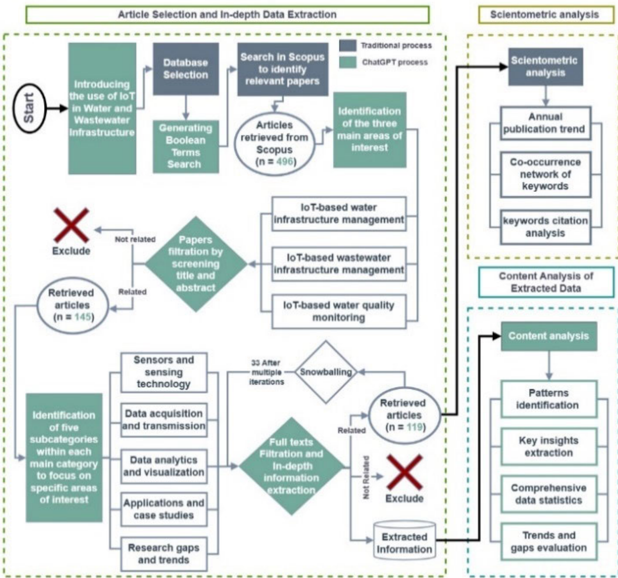

FIGURE 1. The workflow methodology for the scientometric and systematic review approaches.

Following the identification of 145 relevant articles within the aforementioned categories, the subsequent step involves conducting a comprehensive assessment of the full texts and extracting in-depth information. The primary objective of this phase is to assess the appropriateness of the remaining articles concerning their inclusion in the study. Additionally, the phase involves extracting insightful and valuable information from these articles. To make the most of ChatGPT in this regard, as detailed in Alshami et al. [47], five subcategories were initially identified under each main category. This allowed us to concentrate on specific areas of interest and thoroughly explore various topics that are pertinent to our review. These subcategories were carefully chosen to cover different aspects of implementing IoT in managing water and wastewater infrastructure, such as sensors and sensing technology, data acquisition and transmission, data analytics and visualization, applications and case studies, and research gaps and limitations.

To facilitate the full-text evaluation and information extraction process, a set of 14 carefully crafted questions was fully automated using ChatGPT [47]. These questions covered and assessed all aspects of the studies, as depicted in Fig. 2. Consequently, papers that did not address these aspects were excluded from further consideration, while all pertinent information pertaining to these aspects was extracted from the included articles. As a result of this rigorous process, the number of included articles was decreased to 86, from which all relevant information was extracted.

To ensure comprehensive coverage and minimize the possibility of missing relevant articles, a two-way snowballing search was executed on the references and citations of the chosen articles [48]. The backward snowballing approach encompassed examining the references in the included articles, aiming to uncover additional relevant papers. On the other hand, the forward snowballing approach encompassed examining the articles that have cited the included ones [48]. Through this iterative snowballing technique, we identified and collected 52 additional articles. These newly identified articles underwent the same full-text filtration and information extraction process described earlier. As a result, 19 articles were deemed irrelevant and subsequently excluded, while the remaining 33 were found to meet the predetermined inclusion criteria, ultimately increasing the number of relevant articles to 119.

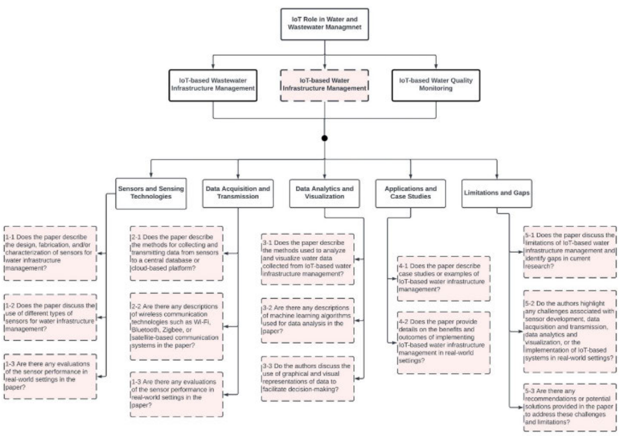

FIGURE 2. **The taxonomy structure of the systematic review dimensions, presenting the first level of categorization. Within each dimension, subcategories are detailed in the second level, representing the specific areas to be covered. The black dot denotes that the five subcategorizes in the second level are applied to the three dimensions. Additionally, the figure showcases the questions utilized for automated full-text evaluation and information extraction, constituting the third level of the content analysis process.**

B. SCIENTOMETRIC EXAMINATION OF PUBLICATION PATTERNS AND CITATION ANALYSIS

After obtaining studies that fulfilled the established criteria for inclusion and exclusion, a scientometric analysis is conducted to delve deeper into the publication patterns and interrelationships among keywords in IoT advancements in wastewater and water infrastructure management (Fig.1). This analysis aimed to discern the annual publication trends and explore the interconnectedness of keywords within the targeted categories: wastewater infrastructure management, water infrastructure management, and water quality monitoring.

To achieve this objective, we utilize VOSviewer and CiteSpace, widely employed scientometric software [49], [50], to analyze the 119 studies obtained during the data article selection phase. By leveraging these tools, we analyze and visually represent the interrelationships among keywords in a general context and across different categories. This analysis provides valuable insights into the associations and connections between research themes and areas within IoT advancements in water and wastewater infrastructure management. Additionally, these network visualizations facilitate the identification of clusters and subclusters of related keywords, shedding light on key research themes and the strength of keyword co-occurrence.

C. CONTENT ANALYSIS OF EXTRACTED DATA

The content analysis phase thoroughly examines the extracted data from the reviewed articles, specifically emphasizing the subcategories outlined in Fig. 2. The primary objective is to uncover and extract meaningful insights from the collected information. For instance, insights related to the use of various sensor types and their benefits are derived from the results of questions 1-1 and 1-2 (Fig. 2). Similarly, an examination of trends in data transmission technologies is conducted based on the answers to question 2-1.

Furthermore, the analysis stage encompasses a comprehensive examination of the research gaps and limitations addressed in prior research works, in addition to the recommendations put forth by researchers. To achieve this, a systematic approach using ChatGPT, as elucidated in the work of [47], is adopted to identify and classify challenges and limitations explored by various authors. This categorization is facilitated by utilizing the outcomes derived from questions 5-1 and 5-2 as depicted in Fig. 2. Subsequently, a comparative analysis using ChatGPT is employed to assess the degree to which the identified limitations and challenges are addressed through suggested recommendations and solutions. This comparative examination offers valuable perspectives on the current gaps in research and underscores the domains that merit deeper research and investigation.

III. SCIENTOMETRIC ANALYSIS RESULTS AND DISCUSSION

In this section, we delve into the findings of our scientometric analysis, which encompasses an exploration of the annual publication trends and a meticulous examination of the analysis rooted in keywords.

A. ANNUAL PUBLICATIONS TREND

In Fig. 3 depicts the annual publication count for different categories: IoT-based wastewater infrastructure management, IoT-based water infrastructure management, IoT-based water quality monitoring, and the combined count for all three categories spanning the period from 2012 to 2023. Notably, we have aggregated the statistics for all these categories based on individual categorization, considering that some articles cover more than one aspect. It is evident that articles emphasizing IoT applications in these domains began to emerge in 2017. Interestingly, except for a solitary article in 2012 and two articles in 2016 focusing on IoT's role in water infrastructure management and water quality monitoring, no substantial literature was available before 2017. Additionally, the trend line indicates a rapid growth in the development and accumulation of knowledge concerning IoT applications in wastewater and water management and water quality monitoring. This trend signifies a recent surge in research attention dedicated to IoT's role in water and wastewater management, especially since 2017.

FIGURE 3. Annual trend line of publication in IoT-based applications in wastewater and water infrastructure management and water quality monitoring from 2012 to 2023.

Notably, the majority of research efforts have been directed towards the study of IoT applications in these three aspects, with an average of 15 articles per year since 2017 and a peak of 24 articles in 2021. Further scrutiny reveals that the average number of articles per year for IoT-based monitoring in water infrastructure, wastewater infrastructure, and quality monitoring were 6, 5, and 4 articles, respectively. The highest counts were recorded in 2019, 2021, and 2022 for IoT-based monitoring in water infrastructure (9 articles), wastewater infrastructure (10 articles), and quality monitoring (10 articles), respectively. The rising trajectory in the annual article count since 2017 underscores the paramount significance of utilizing IoT-based sensors in diverse infrastructure management schemes.

B. CO-OCCURRENCE NETWORK OF KEYWORDS

Keyword co-occurrence analysis is an effective bibliometric approach that provides insights into the body of knowledge of a designated research domain, uncovering trends, frontiers, and hotspots. Fig. 4 presents the keywords' co-occurrence network for all articles belonging to three categories, illustrating the relationships between the defined author keywords and the frequency of their appearance together. Every node depicted in the diagram symbolizes a specific keyword, its magnitude denoting the frequency of its appearance across studies. The thickness of the lines connecting two keywords mirrors the rate at which they tend to appear together. A minimum of two occurrences were specified for a keyword to be included in the analysis, resulting in the retrieval of 232 keywords and the identification of 7 colored clusters.

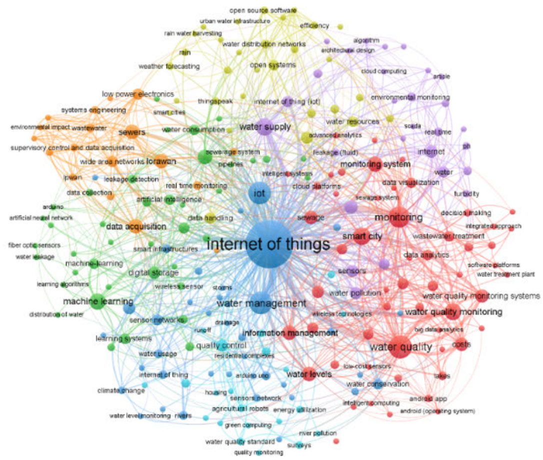

FIGURE 4. Co-occurrence network of keywords in IoT applications in WWM-WQM research.

The blue cluster predominantly focuses on IoT applications in water management and conservation. Leading keywords within this cluster include "Internet of Things", "IoT", "water management", "sensor network", "water level monitoring", and "climate change". The primary emphasis of this category revolves around utilizing IoT with various sensor networks for enhanced water management and infrastructure optimization. The red cluster encompasses 27 author keywords, concentrating on research related to IoT in water quality monitoring and IoT-based monitoring systems in water and wastewater treatment plants. Noteworthy keywords within this cluster include "water quality monitoring systems", "water quality," and "monitoring systems".

The green cluster centers around machine learning, artificial neural networks, optical fiber, and wireless sensors for predicting water leakage and achieving smart infrastructures. To further elaborate on the author's keywords used in IoT-based wastewater and water management and quality monitoring research, separate co-occurrence networks were generated for each category, as depicted in Fig. 5-7. These individual networks reveal 4, 4, and 5 clusters for articles related to IoT-based wastewater management, IoT-based water management, and IoT-based water quality monitoring, respectively.

C. CITATION BURST ANALYSIS OF KEYWORDS

Citation burst analysis, as proposed by Chen et al. [51], offers valuable insights into keywords that undergo sudden spikes in citations within a specific timeframe, making it a powerful tool for identifying trending research topics over time. Fig. 8 displays the top 28 keywords with the most significant citation bursts, arranged by the initial year of each burst. The analysis was conducted using CiteSpace 5.7.R1. Each red line corresponds to a keyword and represents the magnitude of its citation burst, superimposed on the entire time span covered by articles from 2010 to 2023 (Fig. 8). Additionally, the figure

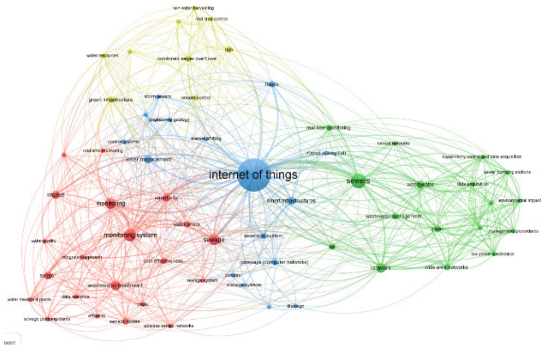

FIGURE 5. Co-occurrence network of keywords of IoT applications in wastewater infrastructure management.

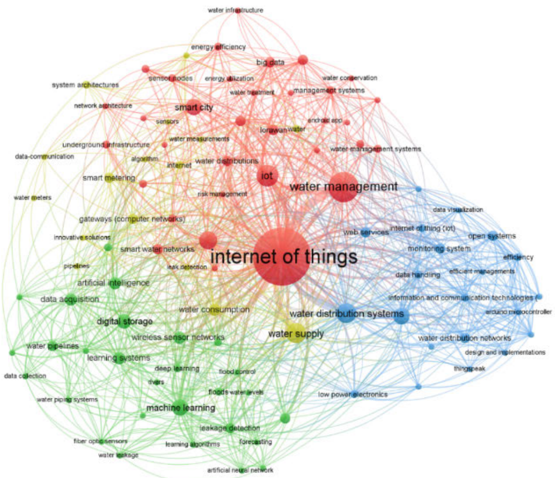

FIGURE 6. Co-occurrence network of keywords of IoT applications in water infrastructure management.

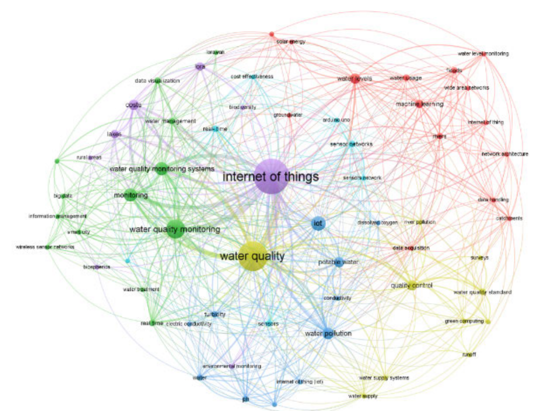

FIGURE 7. Co-occurrence network of keywords of IoT applications in water quality monitoring.

illustrates the strength of each keyword's burst, indicating the number of citations it received during its notable surge.

Notably, the keywords ''water quality'' (burst strength: 2.55; 2022–2023), ''sewers'' (2.54; 2018–2019), ''wireless sensor network'' (2.11; 2018–2019), and ''water'' (2.01; 2018–2019) exhibit the most pronounced burst strength.

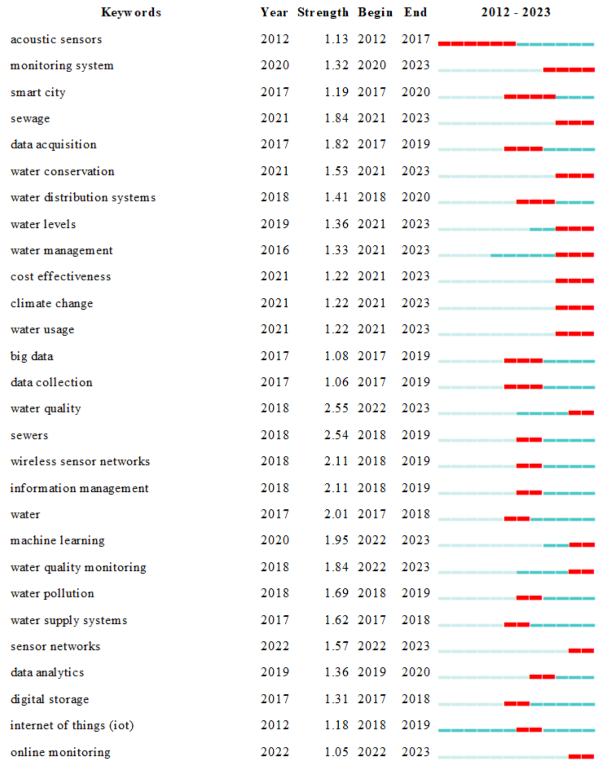

FIGURE 8. Top 28 keywords with the most substantial citation bursts on IoT applications in WWM-WQM research.

These findings underscore the significance of these research topics in IoT-based applications for wastewater and water infrastructure management and quality monitoring. Additionally, Fig. 8 reveals keywords that have received sustained research attention over more extended periods, ranging from 3 to 5 years. ''Acoustic sensor'' (burst strength: 1.13; 2012–2017), ''monitoring system'' (1.32; 2020–2023), and ''smart city'' (1.19; 2017–2020) have been subjects of continued investigation, indicating their enduring importance in the field. Furthermore, recent years have witnessed an increased interest in hot topics related to IoT-based applications in water and wastewater management, including ''water conservation'', ''smart city'', and ''sensor network''. These results suggest that research efforts have been directed toward achieving water conservation goals within the realm of smart cities by harnessing the capabilities of sensor networks.

IV. SYSTEMATIC ANALYSIS RESULTS AND DISCUSSION

The SRs' results are presented, focusing on the five common subcategories across the three main categories. The taxonomy of the systematic review and its various subcategories are illustrated in Fig. 2.

A. IoT-BASED WATER INFRASTRUCTURE MANAGEMENT

IoT technology has emerged as a promising approach for water infrastructure management by providing real-time data on water quality and distribution through sensors and other monitoring devices. This enables stakeholders to make informed decisions about resource allocation and conservation. This section will review the key components of IoT-based water infrastructure management, including sensors and sensing technologies, data acquisition and transmission, data analytics and visualization, applications, case studies, and limitations and gaps in current research. Our goal is to provide a concise and comprehensive overview of this field while highlighting opportunities for future research.

1) SENSORS AND SENSING TECHNOLOGIES

Sensors have risen to paramount importance for the real-time tracking of diverse parameters within water infrastructure. In this subsection, we delve into a comprehensive analysis of the existing literature that sheds light on the development and usage of sensors in water infrastructure management. Specifically, we explore research studies that discuss sensor design, creation, and characterization. We also examine the various sensors employed for effective water infrastructure management and evaluate their performance in real-world scenarios.

Based on the discussions on sensors for water infrastructure management, we can group the reviewed studies into three categories. The first category includes studies that mention using sensors without describing their design or fabrication. For example, Ebi et al. [52] and Mohanasundaram et al. [53] mentioned using sensors for monitoring various parameters. Still, they did not provide detailed descriptions of their design or fabrication. The second category consists of studies that describe the design and characterization of sensors. For instance, Trinchero and Stefanelli [54] described the design and fabrication of wireless sensors for water infrastructure management using a hydrophone and a radio frequency or microwave radio as a sensing and transmitting unit, respectively. Sacoto-Cabrera et al. [55] mentioned the design and manufacture of smart water meters by TARPUQ, which uses ultrasonic flow measurement technology. The third category comprises studies that mention commercial off-the-shelf sensors or in-house designed wireless sensor nodes. Li et al. [56] described using several sensors, including a C-class electromechanical integrated water meter and a low-discharge-sensing instrument for detecting water leakage. Mohanasundaram et al. [53] also described commercial off-the-shelf sensors and in-house designed wireless sensor nodes for water quality monitoring.

The literature review also shows that various sensors have been employed for water infrastructure management. Fig. 9 provides an overview of the sensors used in the reviewed studies. Flow sensors were the most frequently utilized, appearing in 15 papers. These sensors are valuable for measuring water flow and volume, which is crucial for monitoring water usage and detecting leaks. Pressure sensors ranked second in popularity, appearing in 11 papers. Ultrasonic, water level, and temperature sensors were each used in six papers. Acoustic sensors were also used in three papers to detect water leakage

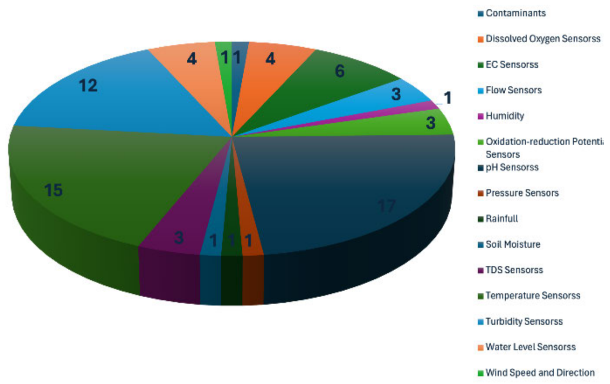

FIGURE 9. Types of sensors used in reviewed studies for water infrastructure management.

or infiltration. Conversely, other sensors such as turbidity, pH, conductivity, humidity, and soil moisture sensors found employment in a limited number of research endeavors. Specifically, soil moisture sensors are applied around water pipes for leak and exfiltration detection, while humidity sensors monitor the atmospheric conditions within pipes and tanks, further illustrating the tailored application of sensor technology in water infrastructure management.

Beyond the utilization of individual sensors, many studies have integrated different sensor types to create more comprehensive and effective water infrastructure management systems. These integrated systems offer a better understanding of water consumption patterns and network operational efficiency. To demonstrate the frequency of different sensor usage in the reviewed studies, we have presented Fig. 10, which depicts the distribution of studies based on the number of sensors used, ranging from single-sensor studies to those employing four or more sensors.

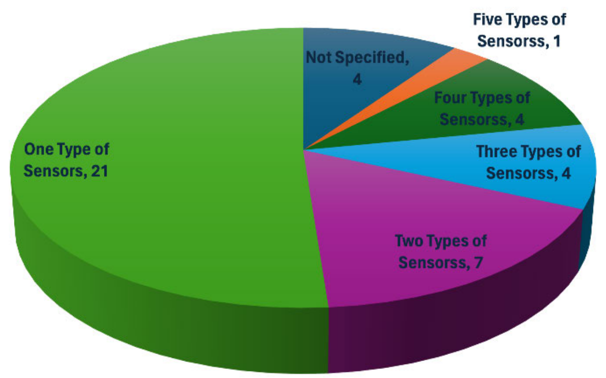

FIGURE 10. Distribution of reviewed studies based on the number of sensors used for water infrastructure management.

According to Fig. 10, twenty-one studies utilized a single type of sensor exclusively, while four studies did not specify the types of sensors they employed. In contrast, the rest of the research articles incorporated a range of two to five different sensor types. These findings underscore the importance of sensor selection tailored to specific applications, given that each sensor type possesses unique strengths and limitations. Simultaneously, using multiple sensors tailored to the physical characteristics of the water network can offer a comprehensive perspective on its quantitative status, a critical consideration in managing complex water infrastructure systems. For example, in the study by Mohanasundaram et al. [53], they utilized five different types of sensors, including turbidity, free residual chlorine, pressure, and temperature sensors, to monitor their smart water distribution network. Similarly, Mekruksavanich et al. [57] employed four sensor types to track floods within the water infrastructure, including water level, water flow velocity, humidity, and GPS location sensors. These studies effectively showcase the benefits of using multiple sensors for managing water infrastructure and emphasize the importance of selecting the most suitable sensors for each specific application.

Furthermore, it is vital to evaluate the reliability and accuracy of sensors used in water infrastructure management in real-world contexts and discuss their types and applications. The reviewed literature provides valuable insights into the research trends of sensor evaluation in practical scenarios. For example, Xie et al. [58] evaluated the performance of soil moisture sensors in terms of accuracy and reliability in an urban green infrastructure (UGI) system, where they compared the soil moisture data collected from the UGI system with the data collected from the control area. Similarly, Siek and Larry [59] evaluated the performance of a sensor network in a real-world scenario by analyzing the accuracy and reliability of the collected water-level data. Furthermore, several studies have assessed the performance of ultrasonic sensors in real-world settings, providing valuable insights into their accuracy, resolution, and measurement success rate under different supply voltage levels. For example, Chinnusamy et al. [60] reported an accuracy of 0.5 cm and a resolution of 0.1 cm for ultrasonic sensors. Correspondingly, Shi et al. [61] documented that ultrasonic probes are designed to prevent damage to pre-existing pipelines and the overall system circuit and can operate for a long time.

2) DATA ACQUISITION AND TRANSMISSION

Once this data is collected, it must be transmitted to a central database or cloud-based platform for storage, analysis, and visualization. This subsection will review the methods described in the literature for collecting and transmitting sensor data to a central database or cloud-based platform. We will also examine whether the reviewed studies assess the effectiveness of these communication technologies regarding metrics such as data transfer speed, reliability, and/or cost.

After conducting a systematic review, it has become evident that researchers utilize various techniques to collect and transmit data from sensors to a central database or cloud-based platform. To visually represent the trends in communication technology usage among the reviewed studies, Fig. 11 has been generated. The figure unveils that cellular, Wi-Fi, and LoRaWAN are the most frequently employed wireless communication technologies among IoT-based water infrastructure management endeavors. Among these, cellular technology has been used in 16 studies due to its high reliability, broad coverage, and low power consumption [56], while Wi-Fi and LoRaWAN have been used in 12 and 11 studies, respectively. Additionally, the figure indicates that some wireless communication technologies, such as Zigbee, and IoT-specific technologies, including Sigfox and Narrow Band IoT, have limited research on their use in IoT-based water infrastructure management, indicating potential research directions.

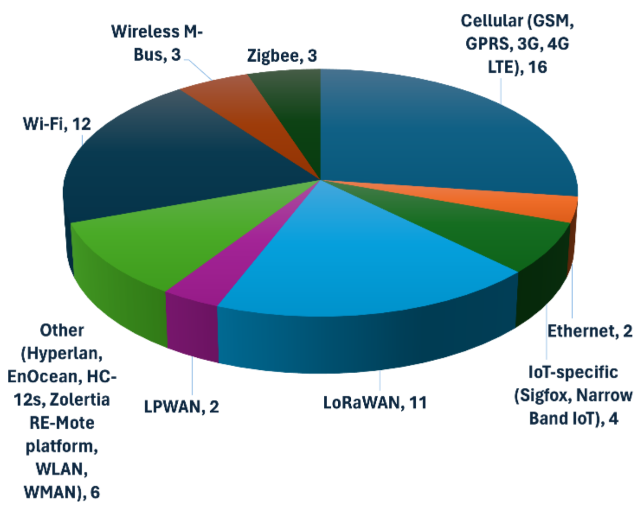

FIGURE 11. Types of wireless communication technologies used in reviewed studies for water infrastructure management.

The integration of different wireless communication technologies has also been explored in several studies for optimizing data acquisition and transmission in water infrastructure management applications. For instance, Mourtzios et al. (2021) discussed the integration of LoRaWAN, wM-bus, GSM, and NB-IoT technologies in hybrid telecommunication network nodes. Pindoriya et al. [63] proposed the integration of wired Ethernet, powerline communication, and wireless networks such as GSM, WiFi, and Zigbee for transferring data from sensors to cloud-based platforms. These studies demonstrated the benefits of integrating wireless communication technologies into water infrastructure management applications, improving data accuracy, higher efficiency, and cost savings.

In addition to the communication protocols detailed in Fig. 11, other communication protocols have also been utilized in water infrastructure management applications. For instance, in one study by Purkovic et al. [64], the EnOcean long-range, low-power communication protocol was utilized to transmit data over longer distances, allowing information collection from sensors placed in remote locations. Another commonly used protocol for data transmission is the MQTT messaging broker, where Arsene et al. [65] have employed this protocol to transmit data from the NodeMCU development board to a central database or cloud-based platform. Similarly, Afifi et al. [66] leveraged the MQTT IoT protocol to transmit data from sensing nodes to a central web server, providing a reliable and efficient method for data transmission. These research endeavors underscore the efficacy of EnOcean and MQTT protocols in enhancing data acquisition and transmission within water infrastructure management applications, culminating in improved efficiency, potential cost reductions, and heightened data precision.

Moreover, several research papers have proposed innovative techniques to collect and transmit data. For instance, Teruhi et al. [33] introduced a combination of drive-by and static data collection techniques to collect acoustic sensor data effectively. Trinchero and Stefanelli [54] showcased wireless sensor nodes establishing communication with stationary ground-based stations, responsible for aggregating measured data and forwarding them to an Internet gateway. Additionally, blockchain technology has arisen as a potential data management solution within the IoT framework. For example, Zeng et al. [67] proposed an efficient Blockchain-based monitoring architecture in IoT (EBMA-IoT) tailored for water management, which includes a monitoring node, a data-log engine, nodes clusters, and an analytics platform.

Another growing trend in these studies is using cloud-based platforms for data storage and management. Several researchers, including Kirar [68], Siek and Larry [59], and Mourtzios et al. [62], have described the use of a central database or cloud-based platform for storing sensor data. Similarly, Mohanasundaram et al. [53] and Narendrakumar and Pillai [69] have employed wireless sensor nodes and gateways for data collection and transmission to central servers. Furthermore, some studies have employed edge computing to preprocess sensor data before transmitting it to the cloud. For instance, Li and Chen [70] integrated a local gateway to preprocess sensor data before dispatching it to the cloud for analysis. This approach reduces the amount of data transmitted to the cloud, thus reducing the load on the cloud-based platform and improving the system's efficiency [71].

Lastly, assessing communication technologies is crucial to managing IoT-based water infrastructure. Among the 47 studies scrutinized, only five specifically evaluated the performance of different communication technologies regarding data transfer speed, reliability, and cost. Siek and Larry [59] studied Wi-Fi and cellular networks, while Mourtzios et al. [62] presented the hybrid gateway that connects terminal devices through LoRa and wM-Bus wireless protocols to cloud-based servers via NB-IoT and GSM cellular protocols. Meanwhile, Chinnusamy et al. [60] focused on the performance of LoRa in terms of its ability to communicate data over long distances and its low power consumption. Ebi et al. [52] compared the performance of LoRaWAN with the proposed synchronous LoRa mesh architecture. They revealed that the latter approach outperformed the former regarding packet delivery reliability when transmitting from range-critical locations. However, sub-surface nodes using the LoRaWAN standard suffered from an average five-fold higher data packet loss that increased with the distance from the gateway. In contrast, Purkovic et al. [64] did not assess the performance of different communication technologies. Still, they provided insights into the advantages of using the EnOcean protocol for transmitting data over longer distances.

3) DATA ANALYTICS AND VISUALIZATION

Efficient data analytics and visualization are crucial for IoT-based water infrastructure management systems. In this subsection, we examine the methods used to analyze and visualize water data collected from IoT-based systems, paying particular attention to machine learning algorithms and graphical and visual representations of data.

Based on the content analysis of the reviewed studies, insights are provided into how data analytics are used for IoT-based water infrastructure management systems. As summarized in Table 1, these methods can be grouped into two main categories: ML techniques and other methods. ML methods were prevalent in the reviewed studies, with a total frequency of 13 studies. Among the ML methods, deep learning was the most frequently used technique, with a frequency of 3 studies, followed by Artificial Neural Networks (ANN), Support Vector Machine (SVM), and Decision Trees (DT), which were also utilized in two studies each. Apart from ML, a diverse range of techniques was employed for data analysis, with a total frequency of 12 studies. Optimization and decision-making algorithms were the most frequently employed techniques, with three studies utilizing these methods. Other examples of techniques used included a fusion chart for analysis and visualization of water data collected from IoT-based water infrastructure management [72], a dynamic cloud-based knowledge-based system for storage and analysis of IoT sensor readings [73], and critical event detection algorithms to deliver prompt user alerts regarding emergency situations [66].

Utilizing graphical and visual representations emerges as a critical component of decision-making in IoT-based water infrastructure management systems, as underscored by several reviewed papers. For example, Mekruksavanich et al. [57] proposed employing a web-based dashboard displato monitor local flooding and alert users through SMS or Line notifications. Pérez-Padillo et al. [74] developed a system that sends real-time alarms via SMS/email when anomalous pressure data are detected to enable water supply companies to locate water leakage promptly and take appropriate measures. Another study by Zeng et al. [67] utilized an Analytics Platform (AP) responsible for visualizing and consuming IoT transactional information collected by nodes cluster, providing insights into Blockchain nodes and other network statistics.

TABLE 1. Methods of data analytics in IoT-based water infrastructure management.

	Method	Frequency	Reference
Machine Learning	Deep Learning Techniques (Feedforward Networks, LSTM, CNN, MLP, RNN)	3	[65], [75], [76]
	Support Vector Machine (SVM)	2	[33], [77]
	Artificial Neural Networks (ANNS)	2	[57], [78]
	Decision Trees (DT)	2	[65], [75]
	Clustering Algorithms	1	[62]
	Prediction Algorithms	1	[62]
	Regression-Based Machine Learning Algorithms	1	[79]
	Random Forests	1	[65]
Other Methods	Optimization and decision-making algorithms	3	[63], [80], [81]
	Dynamic cloud-based knowledge-based system	1	[73]
	Data fusion and analysis layer with hydraulic model	1	[82]
	Big data analysis	1	[56]
	Spectra correlation	1	[54]
	Fusion chart	1	[72]
	Middleware for data storage and web application	1	[83]
	Leak detection algorithm based on rules, context, and location	1	[71]
	REST API utilities for sensor control, data analysis, and storage, and failure identification algorithm	1	[81]
	Critical event detection algorithms	1	[66]

4) APPLICATIONS AND CASE STUDIES

This subsection delves into the practical applications, case studies, and real-world examples of IoT-based water infrastructure management, focusing on real-world instances and their outcomes. By analyzing these case studies documented in previous research articles, we aim to provide perspectives on the field's current state and how IoT-based water infrastructure management can help address critical challenges in water resource management.

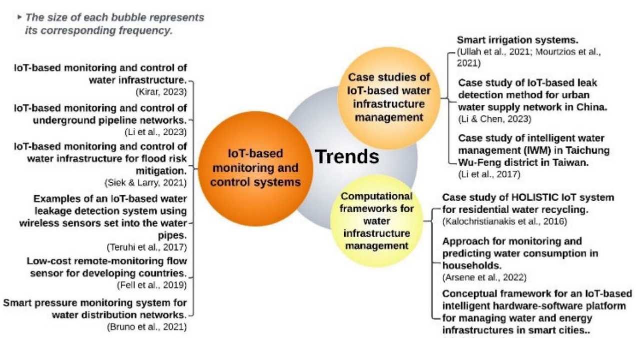

FIGURE 12. IoT-based trends in water infrastructure management.

Recent literature on water infrastructure management reveals several notable trends in IoT-based systems. Fig. 12 presents a comprehensive overview of these trends and provides some detailed insights. One of the most prominent is using IoT-based monitoring and control, which has been explored in various studies such as Kirar [68] for managing water infrastructure, Li et al. [84] for underground pipeline networks, Xie et al. [58] for urban green infrastructure management, and Siek and Larry [59] for flood risk mitigation. Another emerging trend involves the adoption of computational frameworks. For instance, Venkatasubramanian et al. [85] proposed computational frameworks for water infrastructure management, while Pindoriya et al. [63] introduced a conceptual framework for an intelligent hardware-software platform in IoT-based water and energy infrastructure management for smart cities.

Fig. 12 also highlights specific research projects and case studies related to IoT-based water infrastructure management, representing another notable trend. For instance, Amaxilatis et al. [86] reported a practical implementation in which 48 water meters were installed within a university campus. They employed commercially available WM-Bus water meters and an IoT architecture focused on edge processing for intelligent meter networks. Another study by Ebi et al. [52] offered two real-world field tests as instances, demonstrating the utilization of a synchronized LoRa mesh network for monitoring processes within the underground infrastructure.

In addition to the presented case studies, implementing IoT in water infrastructure has the potential to bring numerous benefits to real-world settings. These benefits can be broadly grouped into five categories, as shown in Fig. 13: improving efficiency and reliability, optimizing resource use, enhancing decision-making, reducing energy consumption and data communication, and increasing scalability and simplicity.

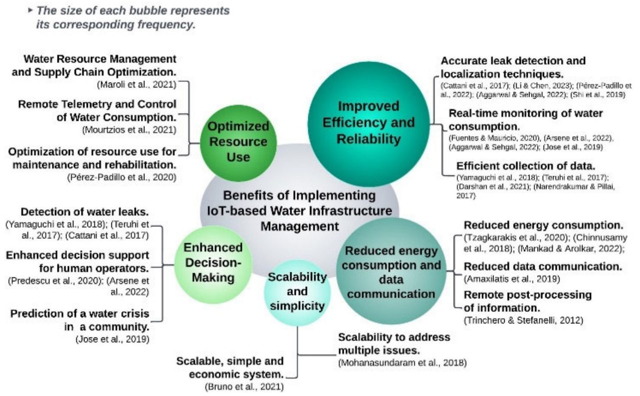

FIGURE 13. Potential benefits of IoT in water infrastructure management.

According to Fig. 13, implementing IoT-based water infrastructure management can bring numerous benefits to water management systems. It can enhance system efficiency and reliability by providing fault protection against various issues such as thermal overload, single-phasing, and voltage imbalance [68]. Real-time data collection and management, made possible by IoT, enables real-time fault detection and isolation of leaky pipes, further enhancing efficiency and reliability [85]. Moreover, Pérez-Padillo et al. [74] have reported that IoT-based monitoring systems can optimize resource use for maintenance and rehabilitation, improving system efficiency. IoT-based monitoring systems can also eliminate human intervention, reducing human errors and enhancing water management efficiency [78]. In addition to improving the infrastructure, IoT technology can improve the efficiency of the monitoring center, resulting in reduced economic loss associated with manual monitoring [87]. Also, IoT-based water infrastructure management optimizes resource use by enabling water resource management and supply chain optimization [88], remote telemetry and control of water consumption [62], and agricultural water management and coordination [67]. Furthermore, IoT technology facilitates objective data-based decision-making [74] and enhances decision-making by enabling flood forecasting and early warning [57], detecting water leaks [33], [77], [82], predicting a water crisis in an organization or a community [72], and providing decision support for human operators [75].

In addition to the benefits mentioned earlier, IoT-based water infrastructure management can also significantly reduce environmental impact by minimizing energy consumption and data communication. The implementation of IoT has been found to decrease energy consumption by using reliable wireless links and reducing data communication [86], [87]. This approach can also reduce economic loss and prevent human injury [77] while enhancing the monitoring center's efficiency [87]. Another advantage of IoT-based water infrastructure management is its scalability and simplicity, which allow it to address multiple problems simultaneously [53]. It provides an efficient means for data collection [33], [69], [77], [78], accurate leak detection and localization techniques [82], and optimization of water resource allocation [54], [56]. The technology also facilitates the easy and repeatable identification of the track and remote post-processing of information [54].

Overall, the comprehensive exploration of IoT-based water infrastructure management, depicted in Fig. 12 and Fig. 13, features a range of case studies, models, and advanced monitoring and control systems. A significant benefit from these research endeavors would be to improve the efficiency, resilience, and sustainability of water infrastructure management systems. Furthermore, the collective findings from these studies offer significant promise for IoT-based solutions to optimize resource allocation and minimize impact on the environment while reducing energy consumption.

5) LIMITATIONS AND GAPS

Despite the potential of IoT-based water infrastructure management, there are several challenges and limitations to overcome to fully realize its potential. The content analysis of the investigated literature revealed the challenges and limitations faced by previous researchers. The findings can be categorized into seven major groups, as illustrated in Fig. 14. These categories include challenges and limitations related to various aspects such as implementation and operation, network coverage, connectivity and stability, sensor reliability, accuracy and integration, data processing and analysis, user interface and data visualization, data security and privacy, as well as other challenges.

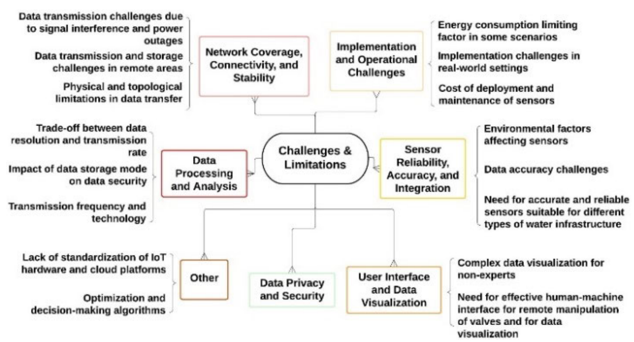

FIGURE 14. Challenges and limitations of implementing IoT in water infrastructure management.

One of the significant challenges identified was the impact of energy consumption on overall system performance in specific scenarios [56], [59], [89]. Additionally, regulatory compliance is critical, with potential legal and financial consequences for non-compliance [90]. Furthermore, deploying and maintaining sensors can be a significant barrier for many water utilities, particularly those operating on tight budgets [80], [85]. Also, challenges with radio propagation in underground water pipes [33] and radio transmission in metallic pipes [54] may limit the effectiveness of IoT-based smart water management systems.

Previous studies have highlighted various challenges and limitations associated with IoT-based smart water management systems. Notably, concerns have been raised about the reliability of communication networks, which can significantly affect the system's effectiveness, resulting in data loss and poor decision-making [63]. Additionally, data transmission and storage challenges in remote areas pose significant barriers to implementing these systems [57], [67]. The accuracy and integration of sensors for measuring water level and flow velocity are also essential for efficiently monitoring water infrastructure [57]. However, environmental factors such as humidity, temperature, and salinity can affect the sensors' accuracy [58]. Therefore, carefully selecting appropriate sensors that can provide precise and reliable data in dynamic environments is paramount [71].

Another crucial aspect highlighted in Fig. 14 pertains to the processing and analysis of data. Efficient processing and data analysis are essential for guaranteeing the precision and reliability of the monitoring system. Nevertheless, challenges within this category must be addressed to ensure an effective functioning system. One such challenge is to optimize the trade between data resolution and transmission rate, which is critical for optimizing data transmission technologies [82]. Additionally, developing effective data processing techniques is crucial for handling large volumes of data generated by sensors [67]. It is also essential to have efficient data analysis tools to identify patterns and trends in the data for predicting future events and making informed decisions [61].

In terms of user interface and data visualization, the complexity of visualizing data can overwhelm non-experts, leading to difficulties in interpreting and analyzing data [57]. Inadequate human-machine interfaces may also hinder remote operations and data visualization, ultimately limiting the effectiveness and efficiency of the system [60]. Moreover, data privacy and security concerns are significant challenges that must be addressed in IoT-based energy systems [16], [59], [71]. The lack of standardization of IoT hardware and cloud platforms also hinders the interoperability and scalability of these systems [91].

To address the challenges discussed earlier, various recommendations and potential solutions have been suggested in the reviewed literature. These solutions can be categorized into seven major groups, as illustrated in Fig. 15. These categories comprise data management and analytics, communication and data transmission, sensor technology and deployment, energy-efficient solutions, interoperability and standardization, security and encryption, and the use of low-cost hardware and open-source software.

Fig. 15 showcases the proposed recommendations and potential solutions for challenges and limitations. Such solutions include but are not limited to data management analytics, communication, and data transmission, energy-efficient solutions, utilizing low-cost hardware and open-source software, and deploying top-notch technology. As seen in Fig. 15, data management and analytics were some of the most widely recommended solutions in the reviewed literature. To make sense of complex data, user-friendly data analysis and visualization tools were recommended [58], as well as data compression techniques to reduce data volume. Efficient algorithms for processing and indexing data logs were also suggested to manage data effectively [67]. Additionally, ML algorithms were identified as a valuable tool for identifying patterns, predicting outcomes, and providing insights for decision-making [59], [62].

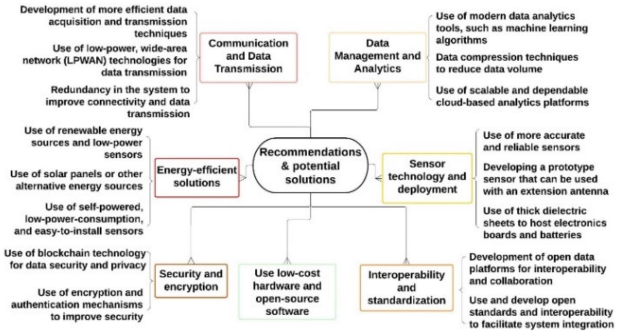

FIGURE 15. Proposed solutions for overcoming challenges in IoT-based water infrastructure management.

As discussed in the reviewed literature, various solutions are proposed to resolve the communication and data transmission challenges. It was recommended to implement redundant systems to facilitate data transmission reliability and enhance connectivity [59], [90]. As well as LPWANs, long-range wireless technologies, and low-power wireless technologies have been suggested to decrease energy consumption and increase transmission efficiency [52], [56], [62], [82]. Furthermore, a modular architecture incorporating sensors, actuators, and gateways can improve network flexibility and fault tolerance [82]. Concerning sensor technology and its deployment, it's imperative to prioritize accuracy and reliability as recommended by [60], [65], [78], [81], and [92]. According to the reviewed articles, ultrasonic sensors can provide more accurate water level measurements than float and board level gauges and dipsticks, and electromagnetic meters can provide precise flow readings [16]

Additional suggestions revolve around energy-conscious strategies, such as adopting renewable energy sources and low-power sensors [67], on-site distributed clean energy resources and energy storage devices, and integrating Battery Energy Storage (BES) technology and renewable energy sources [63]. Additionally, interoperability and standardization are also important categories to consider. This includes using open standards and interoperability to facilitate system integration [62], [80], developing open data platforms for interoperability and collaboration [71], and ensuring effective collaboration among stakeholders [53], [93]. To enhance

IoT-based system security and encryption, some researchers suggested the use of encryption and authentication mechanisms to improve security [59], blockchain technology for data security and privacy [71], and developing secure communication protocols to ensure network security [61].

In summary, the analysis of the challenges and limitations discussed in previous studies, as well as the potential solutions and recommendations, has revealed several gaps and unexplored avenues for advancing IoT-driven water infrastructure systems. These gaps encompass, among other aspects:

- Development of more accurate and reliable sensors for various purposes: While previous studies have mentioned challenges related to the accuracy and reliability of sensors, there is a gap in the suggested solutions list in addressing the need for sensors that can detect water leakage and suspicious conditions. Future research should focus on developing accurate, reliable, and versatile sensors to detect various potential issues.
- Integration of sensors with diverse communication protocols and platforms: Although challenges are associated with integrating sensors with various communication protocols and platforms, previous studies did not provide any solution for this problem.
- Integration of clean energy resources and energy storage devices: Although the recommendations of using renewable energy sources and low-power sensors, no previous studies have paid attention to integrating clean energy resources and energy storage devices, which could play a pivotal role in mitigating the energy consumption challenges associated with water management.
- Reliable communication networks: While previous research recommends strategies such as data compression, redundancy, and LPWAN technologies, there is a notable lack of solutions to tackle the vital issue of establishing specific recommendations for addressing the challenge of reliable communication networks. This challenge is of utmost importance for ensuring the accurate transmission of data and real-time monitoring. Further exploration is also required to apply IoT-specific technologies such as Sigfox and Narrow Band IoT. Moreover, there should be an emphasis on developing hybrid telecommunication network nodes that harness multiple wireless communication technologies to surpass the limitations associated with individual technologies.
- Multidisciplinary approach required for the implementation of IoT systems in real-world settings: While there are mentions of the need for a multidisciplinary approach for the employment of IoT systems in real-world settings, which involves collaboration between different fields such as engineering, computer science, and environmental science, previous studies did not provide any solution for this challenge. A potential solution is to establish interdisciplinary teams and partnerships between academia, industry, and government agencies to foster collaboration and knowledge-sharing.
- Combining diverse information sources to identify multiple concurrent failures: While there are suggestions related to the use of redundancy in the system to improve connectivity and data transmission, there is no specific mention of the need for combining diverse information sources to identify multiple concurrent failures, which is important for the early detection and prevention of water loss and other issues.

B. IoT-BASED WASTEWATER INFRASTRUCTURE MANAGEMENT

The emergence of IoT technology has provided new opportunities for wastewater infrastructure management through real-time monitoring and control. In this subsection, we delve into a comprehensive analysis of the existing literature that sheds light on the development and usage of sensors in wastewater infrastructure management, including the following aspects: the development and utilization of sensors and sensing technologies, data acquisition and transmission methods, data analytics and visualization techniques, real-world applications and case studies, and limitations and gaps in current research.

1) SENSORS AND SENSING TECHNOLOGIES

In recent years, IoT sensors have gained traction as a method for monitoring and controlling wastewater infrastructure parameters. Sensors enable real-time monitoring and detection of wastewater infrastructure issues, resulting in more efficient and effective management. This subsection presents an in-depth analysis of the existing literature highlighting the use and development of wastewater infrastructure sensors.

The reviewed literature can be categorized into two primary groups based on the use of sensors in wastewater management. The first set of studies primarily focuses on creating sensors specifically designed to monitor various wastewater parameters [94], [95], [96], [97]. For example, Depari et al. [98] designed a gas-sensing probe to detect odors, while Kumar et al. [99] developed a transmitter circuit that amalgamates LDR, water level, gas, and flow rate sensors. On the other hand, the second category of research papers focuses on utilizing sensors for real-time monitoring of wastewater infrastructure without explicitly addressing the development and manufacturing of the sensors [100], [101]. For example, previous studies [102], [103], [104] deployed a range of sensors, including Dissolved Oxygen (DO) sensors, pH sensors, ultrasonic sensors, and flow meters, to monitor the state of the sewage system.

Our investigation shows that various sensors have been used to monitor wastewater infrastructure management, as shown in Fig. 16. The most frequently used sensors are water level sensors and ultrasonic sensors (12), followed by temperature sensors (11), gas sensors (9), and flow sensors

(8). Other sensors, such as pH sensors, dissolved oxygen sensors, humidity sensors, turbidity sensors, soil moisture sensors, LDR sensors, conductivity sensors, force-sensitive resistors (FSR), capacitive probes, pressure sensors, and tilt sensors, are also crucial in monitoring wastewater infrastructure management parameters, but they are less commonly used.

Apart from individual sensor applications, several studies have incorporated multiple types of sensors to enhance the efficacy of wastewater infrastructure management systems. These integrated systems facilitate a more comprehensive and in-depth analysis of wastewater infrastructure performance. Fig. 17 illustrates the distribution of studies based on the number of sensors employed, ranging from single-sensor studies to those utilizing four or more sensors.

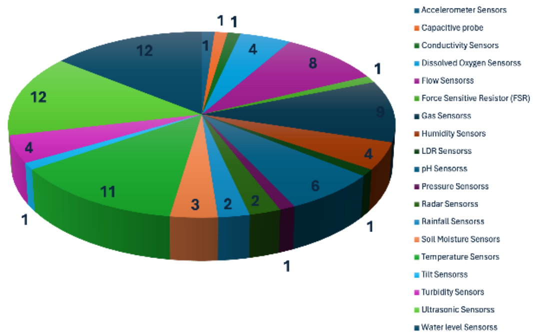

FIGURE 16. Types of sensors used in reviewed studies for wastewater infrastructure management.

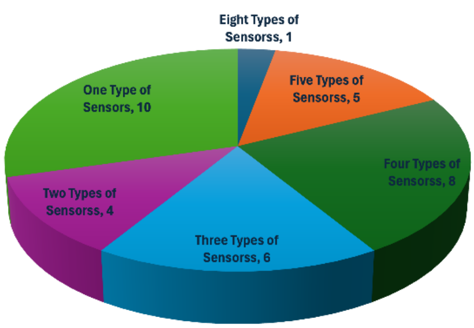

FIGURE 17. Distribution of reviewed studies based on the number of sensors used for wastewater infrastructure management.

According to Fig. 17, 10 studies utilized only one type of sensor, while eight studies used four. The remaining studies employed 3 to 5 sensor types, with one study utilizing eight different types of sensors. For instance, Ebi et al. [52] implemented an IoT-based wastewater management and monitoring system incorporating eight different sensors, including rainfall, water level, dielectric conductivity, air temperature, wastewater temperature, groundwater level, groundwater temperature, and groundwater conductivity sensors. In contrast, Dronavalli et al. [105], Samma et al. [106], and Hasan et al. [107] used five different sensor types, including gas sensors, temperature sensors, turbidity sensors, pH sensors, and dissolved oxygen sensors. Some studies focused on a specific sensor type, such as Oberascher et al. [108], who developed smart rain barrels using a single type of sensor.

Most of the reviewed literature addressed sensors used in wastewater management and their performance in real-world settings. These studies employed varying levels of experimentation, validation, and reliability testing to assess the accuracy and reliability of sensor readings [58], [98], [109], [110]. For example, Jeffery et al. [111] conducted laboratory and field tests to evaluate the performance of water level sensors, while Pérez-Padillo et al. [112] tested sensors in the field at a wastewater treatment plant, where the device was installed in a spillway. The authors found that sensors can accurately measure the occurrence, duration, and water level during discharge episodes.

2) DATA ACQUISITION AND TRANSMISSION

Effective control of wastewater infrastructure heavily relies on accurate and timely data collection and transmission from sensors to a central database or cloud-based platform. In this subsection, we will analyze papers that describe the methods used to collect and transmit data from sensors to a central database or cloud-based platform, papers that discuss the use of wireless communication technologies, and papers that evaluate the performance of different communication technologies in terms of data transfer speed, reliability, and/or cost.

After conducting a comprehensive review of the literature, it has become evident that researchers utilize various techniques to handle the data. To gain insight into the trends in communication technology usage among the reviewed studies, we have created Fig. 18. The figure reveals that cellular technology, including GSM, GPRS, 3G, and 4G, is the most commonly used wireless communication technology, with a frequency of 14. This finding aligns with earlier research documenting the widespread use of cellular technology in IoT-based systems [95], [113]. LoRaWAN and Wi-Fi emerged as the subsequent two most frequently employed wireless communication technologies, making appearances in the literature 6 and 12 times, respectively.

The use of cloud-based platforms is another trend observed in the reviewed papers. Various research works, including those by Nair et al. [97], Xiu and Dong [117], and Kumar and Hong [96], have implemented cloud-based platforms for tasks such as data storage, management, and processing. In addition, the reviewed studies have highlighted the development of innovative technologies and models to enhance wastewater infrastructure's overall performance. For instance, Edmondson et al. [94] employed smart sensors to facilitate real-time monitoring and immediate reporting of sewer system performance, where they developed a prototype, namely the Smart Sewer Asset Information Model, which seamlessly incorporates distributed intelligent sensors.

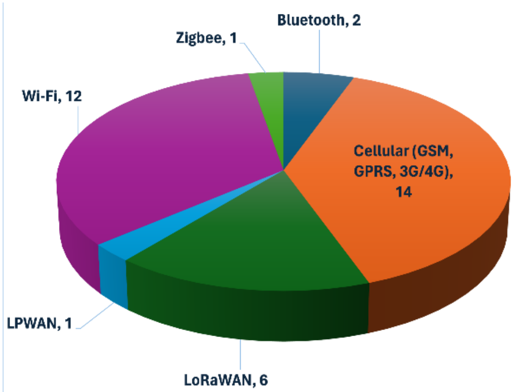

FIGURE 18. Types of wireless communication technologies used in reviewed studies for wastewater infrastructure management.

While the reviewed studies have paid significant attention to the integration of diverse communication technologies, there has been a limited evaluation of their effectiveness regarding speed, reliability, and cost. For example, Drenoyanis et al. [118] evaluated the performance of the LoRaWAN protocol, focusing on transmission distance and line-of-sight conditions. Similarly, Drenoyanis et al. [119], in their extensive communication study conducted in Australia, concluded that LPWAN utilizing the LoRaWAN protocol can achieve a maximum transmission distance of up to approximately 20 km within urban settings and up to 35 km under line-of-sight conditions.

3) DATA ANALYTICS AND VISUALIZATION

Developing effective methods for analyzing and visualizing this data is paramount in deriving substantial insights and supporting informed decision-making processes. In this subsection, we will delve into the existing body of literature concerning the approaches employed for data analysis and visualization within IoT-driven wastewater infrastructure management.

The literature on IoT-based wastewater infrastructure management and monitoring systems proposes various data analysis and visualization methodologies. Among the 38 studies reviewed, only 14 furnished comprehensive explanations and detailed descriptions of the methodologies they employed. A common trend among these studies is the use of simulation models to analyze the performance of wastewater systems under different scenarios. For instance, Alshami et al. [109] and Faris et al. [120]used data mining techniques and simulation to model sewage networks' performance under blockage situations, while Oberascher et al. [108] employed Python packages designed for SWMM5 and EPANET2 to simulate runoff processes within urban drainage and assess the consequences of altering water demands on the water supply system.

Moreover, some studies highlight data cleaning and processing as crucial steps. Nair et al. [97] discussed the cleaning and processing of sensor data. Similarly, Hasan et al. [107] filtered the data by establishing specific upper and lower boundaries for the parameters. In addition, the use of web-based IoT platforms, such as ThingSpeak, has emerged as a popular approach for data analysis and visualization, as appeared in the studies by Kumar et al. [99] and Soetedjo et al. [101].

Furthermore, several studies have discussed using graphical and visual data representations to enhance decision-making in IoT-based wastewater infrastructure management. Among these studies, Depari et al. [98] and Rahman et al. [113] have briefly mentioned using user-friendly dashboards without providing specific details on the use of graphical or visual representations of data. On the other hand, other studies have explicitly discussed the use of graphical representations of data, such as scatter plots, histograms, and graphs, to facilitate decision-making [58], [99], [101], [108]. Additionally, Sasirekha et al. [116] and Islam et al. [121] have presented graphical representations of real-time tracking and current environmental situations, respectively. On the other hand, Lorenz et al. [90] have introduced the use of a GIS-web-based frontend to visualize processed sensor events on the water network map.

4) SENSORS AND SENSING TECHNOLOGIES

This subsection will explore the practical applications of IoT-based wastewater infrastructure management by examining case studies and real-world examples. By analyzing the benefits and outcomes of implementing these systems in real-world settings, our objective is to acquire a more profound comprehension of their capability to enhance the efficiency and efficacy of wastewater infrastructure.

According to analyzing the current literature, several significant trends have been observed, as depicted in Fig. 19. A notable trend is the emergence of real-time monitoring and control systems that employ IoT technologies for tracking and monitoring parameters such as water quality, pressure, temperature, and flow rates. Several researchers have proposed or developed such systems ranging from small-scale urban infrastructure, such as smart rain barrels [108], to large communal wastewater treatment plants [101], [103], [122]. These systems are often utilized for detecting and preventing overflows, which can cause environmental contamination and the spread of waterborne diseases [102], [113], [116]. Furthermore, some studies have investigated implementing IoT-based sustainable stormwater management systems, which address deficiencies typically encountered in drainage systems [58], [121], [123].

Fig. 19 provides further insights into the development of IoT-based wastewater infrastructure management systems. The figure highlights the increasing deployment of smart sewerage systems in real-world settings, as reported by previous studies [58], [97], [101], [103], [109]. These case studies showcase the deployment of IoT-based systems for secure and efficient monitoring and control of wastewater treatment plants and sewage networks. Other studies [95], [113], [124],

[125] investigated the implementation of IoT-based systems for odor detection and prevention in sewerage systems as another emerging trend.

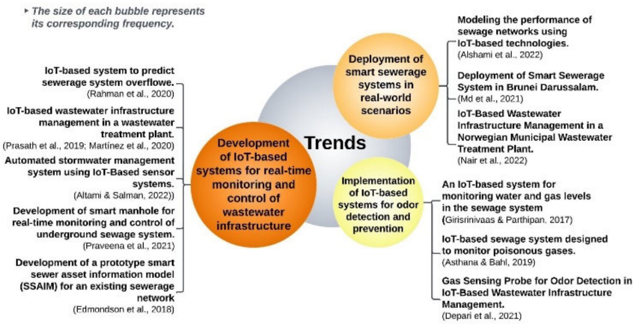

FIGURE 19. **IoT-based trends in wastewater infrastructure management.**

In addition to the aforementioned case studies, implementing IoT in wastewater infrastructure management systems can potentially provide significant benefits in real-world settings. These benefits can be broadly categorized into six areas, as illustrated in Fig. 20, with each bubble's size indicating the occurrence frequency. Real-time monitoring and control, a commonly cited benefit, enables continuous monitoring of the system's condition, facilitating timely detection and response to any anomalies or malfunctions. For instance, Rahman et al. [113] demonstrate how IoT-based wastewater infrastructure management can enable real-time flood prediction in the sewerage system of Bangladesh and track underground tunnels efficiently.

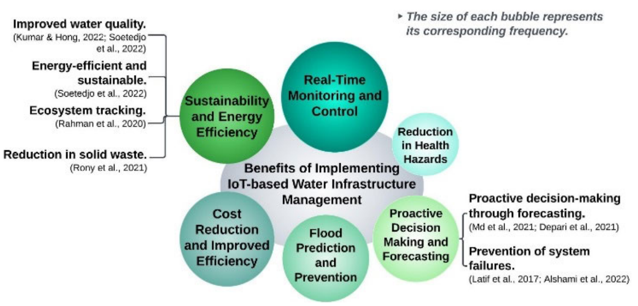

FIGURE 20. **Potential benefits of IoT in wastewater infrastructure management.**

Another significant benefit of IoT-based wastewater infrastructure management is enhancing sustainability and energy efficiency. These benefits include improved water quality [96], [101], ecosystem tracking [113], reduction in solid waste [114], reduction in potable water consumption for irrigation [104], and optimization of water resources [58]. Similarly, cost reduction and improved efficiency were mentioned in six papers, including those by Praveena et al. [102], Jeffery et al. [111], Latif et al. [100], Sasirekha et al. [116], Alshami et al. [109], and Pérez-Padillo et al. [112]. These studies suggested that IoT-based wastewater infrastructure management can significantly decrease operational costs and enhance overall efficiency, leading to better resource utilization and cost savings. Proactive decision-making, forecasting, flood prediction, and prevention were also identified as potential benefits of IoT-based wastewater infrastructure management. For instance, incorporating a forecasting mechanism in the smart sewerage system enables proactive decision-making [98], [111]. Additionally, flood prediction and prevention can be achieved by preventing system failures and overflows [100], [108], [109] Some studies also mentioned the reduction of health hazards, which is achieved by protecting water security and public health [103], [124], [125].

5) LIMITATIONS AND GAPS

Based The content analysis conducted on the literature has highlighted the challenges and limitations faced by previous researchers. The results can be classified into six main categories, as detailed in Fig. 21. The communication network is one of the most reported challenges in IoT-based wastewater infrastructure management. The reviewed studies have highlighted several limitations and difficulties, including the need to evaluate interface requirements, security threats associated with transmitting sensor data, range limitations of IoT communication technologies, and high costs and limited coverage of traditional SCADA and telemetry systems [52], [98], [103], [111].

Furthermore, other limitations in this field include the limited range and speed of Wi-Fi connections, connectivity issues between sensors and IoT systems, and the low information transmission rate allowed by certain communication systems [109], [123]. Another critical challenge, as indicated by prior research, pertains to sensor-related limitations and challenges. Prasath et al. [103], Lorenz et al. [90], Pérez-Padillo et al. [112], and Nair et al. [97] emphasized the limitations of available sensors and the need for improved sensor devices that can be deployed in different locations and harsh environments. Calibration and maintenance of sensors also pose significant challenges, as noted by Sasirekha et al. [116] and Dronavalli et al. [105].

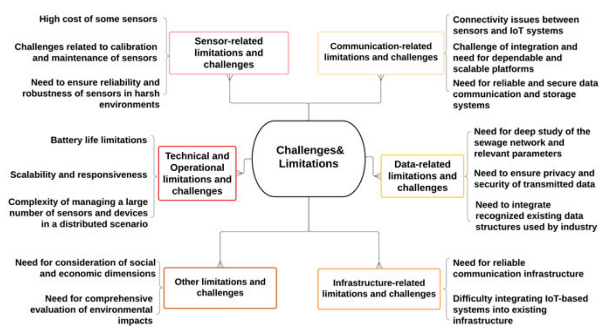

FIGURE 21. **Challenges and limitations of implementing IoT in wastewater infrastructure management.**

Implementing IoT-based wastewater infrastructure management also faces significant technical and operational limitations and challenges. Technical challenges include battery life limitations, the need to manage multiple transducers, and reliance on offline water analysis due to high capital and maintenance costs [97], [98], [123]. On the other hand, operational challenges involve managing a large number of sensors in a distributed scenario, complying with regulations, and ensuring system scalability, which are significant challenges that need to be addressed [90], [116], [122]. Moreover, the data-related aspects of IoT-based wastewater infrastructure management pose significant limitations and gaps that need to be addressed [97], [109]. Edmondson et al. [94] highlighted the lack of domain in IFC4 for defining data concepts related to wastewater and the need to integrate recognized existing data structures used by the industry. Infrastructure-related limitations and challenges also exist, such as the limitations in large-scale application scenarios such as blocks and cities [58], [111], the need for reliable communication infrastructure [111], and challenges in data acquisition and transmission in remote areas [107], [115].

The literature suggests several solutions to overcome the limitations and challenges associated with IoT-based wastewater infrastructure management, which can be categorized into seven major groups. These categories include improving sensor development, data analytics and management, network infrastructure, energy management, system design and scalability, and integration and standardization, as shown in Fig. 22.

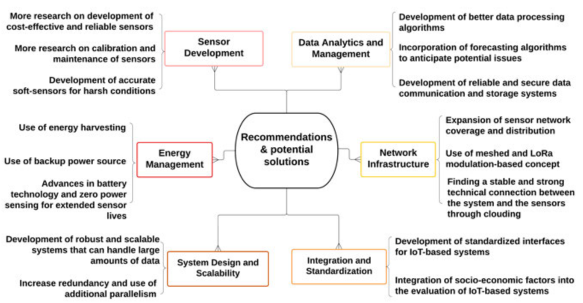

FIGURE 22. Proposed solutions for overcoming challenges in IoT-based wastewater infrastructure management.

The reviewed papers highlight data management and analytics as the most common areas for improvement in developing IoT systems. Strategies recommended to improve data management and analytics include integrating existing data structures, adopting device-to-server protocol (D2S) for IoT architecture, and using location technologies to send data observations to web-based cloud servers [94], [111]. Better data processing algorithms and technologies with exactly-once semantics are also suggested to enhance the accuracy and reliability of IoT data analysis [90]. Other areas for improvement include the development of zero-power sensing for extended sensor lifetimes, soft-sensors for harsh conditions, and expanding sensor network coverage and distribution [94], [97]. Using thermal sensors to monitor water velocity and hydrodynamic models is also suggested as a promising approach [126]. In terms of network infrastructure and expanding sensor network coverage and distribution, LoRa can be used for long-range and large-scale implementation, and versatile interface design can leverage volt-amperometric and resistance-to-time (integral) conversion methods to ensure comprehensive data acquisition and transmission [98], [109], [111], [114].

Another critical aspect is energy management, which has led to recommendations for the use of renewable energy sources such as solar panels and energy harvesting, the use of backup power sources, as well as advances in battery technology [94], [102], [114]. System design and scalability are two main areas that can also be improved. Therefore, developing robust and scalable systems capable of handling large quantities of data and increased redundancy and additional parallelism has been highly recommended [90], [116]. Moreover, the integration of socio-economic factors into the evaluation of IoT-based systems has been suggested [108], [116], [127].

In summary, examining the challenges and constraints discussed in prior research, as well as the prospective solutions and recommendations, has highlighted various gaps and future research avenues that can be conducted for advancing IoT-based wastewater infrastructure systems. Some of these gaps include, but are not limited to:

- Lack of sensor coverage and distribution: Some studies have recommended expanding sensor networks, but this will not directly solve the problem. Therefore, Future research should focus on new methods and technologies to improve sensor coverage and distribution.
- Sensor Challenges in Sewerage Systems: While the concept of precise soft-sensors for harsh environments has been introduced, the persistent issue of sensor components being obstructed by solid materials remains. Future research endeavors should explore innovative sensor designs and technologies to cope with this hurdle and elevate sensor precision.
- Increasing demand for reliable, cost-effective sensors: However, several previous studies have acknowledged the mere requirement for further research on developing reliable and cost-effective sensors, but none have specifically addressed a definitive solution to this problem. To tackle this concern, future research should prioritize exploring novel sensor designs and technologies capable of addressing this challenge.
- Connectivity issues between sensors and IoT systems: While most previous studies have recommended establishing a robust technical connection between sensors and IoT systems via clouding, they fail to provide a direct solution to connectivity issues between sensors and IoT systems. To overcome this challenge, future research should explore novel communication

protocols and technologies to enhance the connectivity between sensors and IoT systems such as Sigfox and Zigbee. For instance, Sigfox, a low-power, wide-area network technology, has not been utilized in wastewater management applications but could be a promising area for exploration due to its long-range, low-power, and cost-effective connectivity solutions for remote and decentralized applications [98].

- Need to optimize the use of energy resources: Although some studies have suggested using renewable energy sources such as solar panels, energy harvesting, and backup power sources, more research is required to identify the most effective energy management strategies for IoT-based sewer monitoring systems. Future research can explore new methods and technologies, such as advances in battery technology and zero-power sensing, for extended sensor lives.
- Managing many sensors and devices in a distributed scenario: Researchers suggested developing robust and scalable systems to handle large amounts of data, but it does not directly address the challenge of managing numerous sensors and devices in a distributed scenario. Future research could explore new system architectures and management strategies that can effectively handle the complexity of managing many sensors and devices in a distributed environment.
- Advanced data analysis and visualization techniques: However, researchers have suggested the application of forecasting algorithms for anticipating potential issues, but there remains a requirement for more comprehensive research in data cleansing and analysis domains to enable informed decision-making. Future studies should investigate the potential of employing machine learning algorithms to analyze extensive sensor data, discern patterns and irregularities, and forecast future system performance. Additionally, developing more advanced data visualization tools can aid in simplifying the interpretation of complex data, thereby enhancing decision-making processes.

C. IoT-BASED WATER QUALITY MONITORING

Water quality monitoring is a pivotal aspect of water resources management, and IoT technologies have significantly revolutionized it. Although traditional laboratory analyses remain necessary for a comprehensive assessment of water quality, the advent of sensor technologies presents an efficient alternative for monitoring specific parameters, reducing the reliance on time-intensive and costly manual sampling methods. In the next subsections, we will delve into conducting a comprehensive examination of the literature about IoT-driven water quality monitoring. These examinations will include several aspects, such as sensors and sensing technologies, data acquisition and transmission, data analytics and visualization, applications and case studies, and limitations and gaps.

1) SENSORS AND SENSING TECHNOLOGIES

Sensors and sensing technologies play a pivotal role in IoT-based water quality monitoring. These technologies facilitate real-time monitoring of key water quality parameters, including temperature, pH, turbidity, and dissolved oxygen, while the development of sensors for a broader range of contaminants is an ongoing area of research. This subsection provides a comprehensive insight into the evolution and application of sensors for infrastructure management, covering various aspects, including sensor design, manufacturing, diverse sensor types, and their empirical assessment in practical, real-world scenarios.

The literature reviewed on IoT-based water quality monitoring is categorized into two main categories. The first category comprises studies detailing developing and fabricating sensors explicitly designed to monitor water quality [55], [128]. For instance, Blanco-Gómez et al. [129] designed a low-cost prototype device capable of continuously measuring electrical conductivity (EC) and temperature, while Abbas et al. [130] developed a suite of sensors, including a water flow sensor, a waterproof ultrasonic sensor, and two temperature sensors, designed for the measurement of both water and ambient temperatures. On the other hand, the second category of studies focuses on utilizing commercially available kits and commercial off-the-shelf sensors for water quality monitoring [131], [132], [133], [134]. For example, Kumar et al. [135] utilized the Libelium smart water kit to monitor various water quality parameters such as pH, temperature, dissolved oxygen, conductivity, and oxidation-reduction potential, while Syrmos et al. [136] integrated multiple water quality sensors to measure parameters such as turbidity, pH, conductivity, and dissolved oxygen.

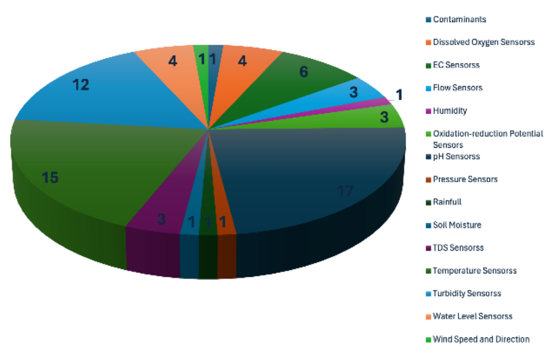

FIGURE 23. Types of sensors used in reviewed studies for water quality monitoring.

Furthermore, after analyzing the reviewed studies, it becomes evident that various sensors have been employed, as shown in Fig. 23. Among the sensors, pH and temperature were the most commonly utilized, featured in 17 and 15 papers, respectively. Turbidity and EC sensors were employed in 12 and 9 studies to measure water quality, respectively. Other sensors were less frequently used, such as dissolved oxygen, ultrasonic, water level, total dissolved solids (TDS), flow, and pressure sensors.

In addition to using individual sensors, integrating multiple types of sensors has also been explored in various studies to enhance the effectiveness of water quality monitoring systems. As shown in Fig. 24, most of the reviewed studies utilized multiple sensors, with pH, temperature, and turbidity sensors being the most commonly used in combination with other types of sensors [32], [136], [137], [138]. For instance, Campagnaro et al. [128] employed six different sensors, including temperature, pressure, pH, turbidity, dissolved oxygen, and EC sensors, while Kumar et al. [135] utilized five different types of sensors, including temperature, pH, conductivity, dissolved oxygen, and Eh potential sensors, to measure different water quality parameters. Other frequently used sensor combinations include dissolved oxygen, conductivity, and water level sensors [128], [139]. However, the choice of sensors used in these studies varies depending on the specific application and variables being monitored.

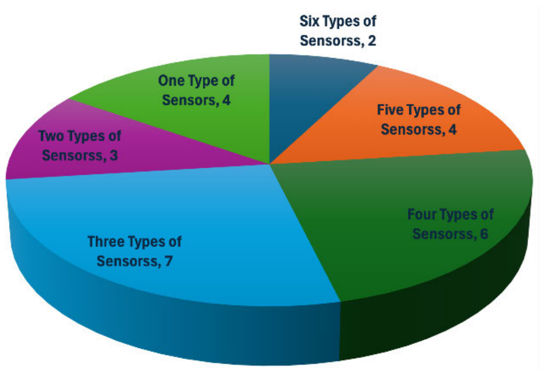

FIGURE 24. Distribution of reviewed studies based on the number of sensors used for water quality monitoring.

The reviewed literature has also extensively covered the use of sensors and their performance in real-world settings. Researchers have utilized varying levels of experimentation, validation, and reliability testing to evaluate the accuracy and reliability of sensor readings [64], [134], [135], [138], [140]. In this regard, Wong et al. [141] conducted a calibration and validation study on turbidity and ultrasonic water level sensors. Unlike the contact-type sensor, the non-contact sensor consistently provided accurate measurements for at least two months without requiring monthly maintenance. Similarly, Malissovas et al. [142] evaluated the performance of sensors in harsh environmental conditions without periodic maintenance for six months. These studies showcase the significance of reliability and calibration in using sensors for water quality monitoring.

2) DATA ACQUISITION AND TRANSMISSION

Efficient data acquisition and transmission are crucial for any IoT-based water quality monitoring system. Reliable and accurate data collected from a network of sensors must be transmitted to a central database or cloud-based platform for analysis, storage, and visualization. In this subsection, we will focus on the literature's methods for collecting and transmitting sensor data and evaluate the studies for their detailed descriptions of communication mechanisms used and their evaluations of the performance of these mechanisms.

The content analysis identified various data collection and transmission methods from sensors to a central database or cloud-based platform. To discern the patterns in the use of communication technologies among the studies, we created Fig. 25. The figure indicates that Wi-Fi and LoRaWAN are the most commonly used wireless communication technologies in IoT-based water infrastructure management, with a frequency of 12 and 6, respectively. On the other hand, Zigbee technology has been used in only three studies. Also, a few studies have employed other technologies such as Cellular, NB-IoT, Wireless Smart Utility Networks (Wi-SUN), and TV White Space (TVWS).

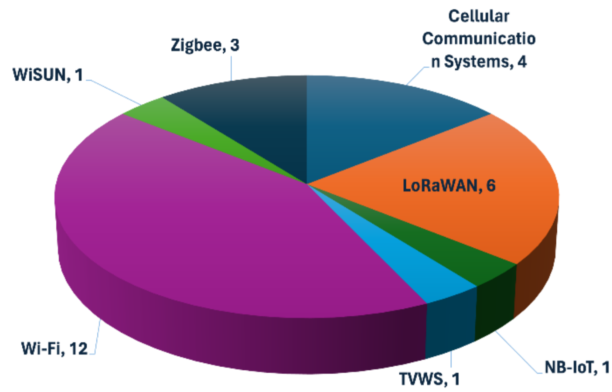

FIGURE 25. Types of wireless communication technologies used in reviewed studies for water quality monitoring.

In addition to the communication protocols discussed in Fig. 25, a noteworthy trend among the reviewed studies is the use of cloud-based platforms for data storage and management. Several researchers, such as Al-Khashab et al. [143] and Campagnaro et al. [128], have emphasized the benefits of utilizing cloud-based platforms for collecting and analyzing sensor data. Additionally, various IoT platforms have been employed for data acquisition and transmission. For instance, Kabi and Maina [131] used a LoRa network server offered by The Things Network to relay data packets from fixed-position nodes to an InfluxDB database in a Google Cloud virtual machine instance. Similarly, Madhurima et al. [132] and Pasika and Gandla [144] used the Wi-Fi module ESP8266 to connect the sensor hub to an IoT cloud and read data back from ThingSpeak. Moreover, a noticeable trend is emerging with the integration of cloud infrastructure for database storage and the continuous upkeep of dashboards presenting real-time measurements. As an illustration, Kumar et al. [145] and Pasika and Gandla [144] utilized a Node MCU for sensor data monitoring and value management, coupled with integrating cloud infrastructure for database storage and maintaining real-time dashboards.

Communication mechanisms' effectiveness in speed, reliability, and cost has also been evaluated in some reviewed studies [32], [130], [134], [142]. Researchers such as Abdullah et al. [146] and Ngom et al. [133] have evaluated the performance of LoRa transmission technology through signal propagation, coverage tests, and packet error rates. On the other hand, Wong et al. [141] evaluated the performance of Wi-Fi communication technology and concluded that it is a reliable and cost-effective approach for transmitting data to a cloud-based platform.

3) SENSORS DATA ANALYTICS AND VISUALIZATION

In IoT-based water quality monitoring, effective methods for data analysis are essential to obtain meaningful insights and make informed decisions. One prominent trend in recent years has been using ML algorithms to analyze and predict water quality parameters. This includes clustering, classification, predictive approaches, and artificial neural networks (ANNs), described in several studies [57], [131], [136], [147]. For example, Ahmed et al. [139] compared 16 different ML algorithms for potability prediction and found that a one-dimensional convolutional neural network (CNN) performed significantly better than other classifiers. However, while ML algorithms are gaining popularity, traditional statistical methods remain prevalent in water quality monitoring research [135], [140]. For instance, Al-Khashab et al. [143] used MATLAB to analyze and display the collected data, while Zakaria et al. [148] utilized statistical methods such as coefficient of variation, standard deviation, and mean for data analysis.

The reviewed studies have employed diverse graphical representations depicting IoT sensor-derived water quality data. These representations encompass line charts, bar charts, scatter plots, heat maps, and time series plots. Real-time data visualizations have been facilitated through various dashboards, including platforms such as ThingSpeak display, web-based user interface, mobile application, and RESTful API [131], [132], [137], [138], [149]. The use of these visualizations assists end-users in promptly detecting any irregular trends and subsequently making well-timed decisions. For example, Ahmed et al. [139] developed a user interface module that enables end-users to view the water potability result on both a website and a mobile app. Similarly, Chen and Han [138] designed a web-based user interface that displays real-time water quality data through heatmaps and time series plots.

4) APPLICATIONS AND CASE STUDIES

The growing number of case studies and practical applications within IoT-based water quality monitoring underscores the growing significance of this field. This subsection provides comprehensive insights into the present status of the discipline and its capability to confront water quality management challenges by exploring real-world applications and case studies.

The reviewed studies in the context of IoT-based water quality monitoring can be categorized based on two principal criteria, as depicted in Fig. 26. The first categorization is rooted in the specific environments where water quality monitoring is implemented. These environments encompass urban, rural, residential, commercial, and other areas. Studies by Nordin et al. (2018) and Revathi et al. (2021) have demonstrated IoT systems' effectiveness in monitoring water quality in rural and remote regions. Similarly, Oberascher et al. [127] and Wong et al. [141] have exhibited IoT-driven water quality monitoring systems deployed in industrial and agricultural contexts. Additionally, studies by Sacoto-Cabrera et al. [55] and Saravanan et al. [32] documented that IoT-based water quality monitoring systems have improved water quality management in urban areas. The second categorization is rooted in the purpose of the IoT monitoring system, which includes surface water quality monitoring [128], [129], [131], [138], drinking water quality monitoring [32], [135], [143], water quality monitoring during floods [146], agricultural water quality monitoring [133], [141], and method-oriented water quality monitoring without any implementation [130], [139].

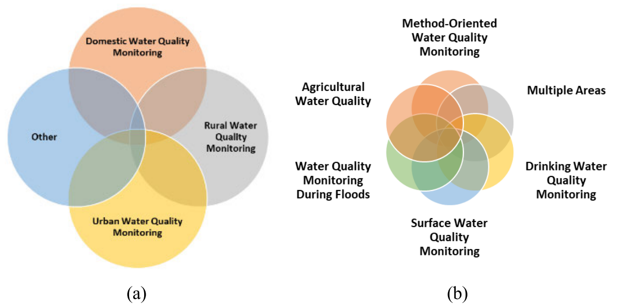

FIGURE 26. **IoT-based water quality monitoring trends by (a) setting (b) purpose.**

The analyzed studies have also utilized various methods to evaluate the performance of IoT-based water quality monitoring systems, showcasing their potential for managing water quality challenges. These methods vary based on the research objectives and system features. Commonly used methods include prediction accuracy, real-time data collection, and anomaly detection [57], [140], [142]. For instance, Chen and Han [138] reported the effectiveness of their system in providing real-time and high-frequency water quality data. This data played a pivotal role in identifying sources of pollution and managing water resources efficiently. Furthermore, other studies by Shanmugam et al. [151] and Oberascher et al. [127] evaluated the cost-efficiency and affordability of IoT-driven water quality monitoring systems, where both demonstrated that their systems offered a cost-effective alternative to commercial solutions.

5) LIMITATIONS AND GAPS

Previous studies have identified various challenges and limitations within IoT-based water quality monitoring, where these discoveries can be categorized into six primary groups, as depicted in Fig. 27. Among the most note-worthy challenges reported in the literature is the need for comprehensive data analysis methods, a concern raised by several studies [128], [134], [138], [144], [148]. For instance, Saravanan et al. [32] highlighted the necessity of a more comprehensive water quality analysis and the integration of AI and ML technologies in water quality management. Communication-related challenges, including technical issues with LoRaWAN technology [127] and network coverage limitations in remote areas [146], [148], have been identified as significant obstacles.

IoT-based water quality monitoring is also associated with several technical and operational challenges. Technical issues include high installation costs, intensive computer processing requirements, and vulnerability to vandalism [130], [131]. Moreover, additional challenges include accommodating more end devices by gateways and relying solely on LoRaWAN infrastructures for real-time or critical services [136]. On the other hand, operational challenges related to potential interference from other environmental factors may affect measurement accuracy and long-term deployability due to battery-powered devices [127], [130], [135]. Lastly, sensor limitations such as limited accuracy and reliability, the need for regular calibration, false readings due to environmental factors, and lack of full waterproofing pose additional challenges [134], [144], [151].

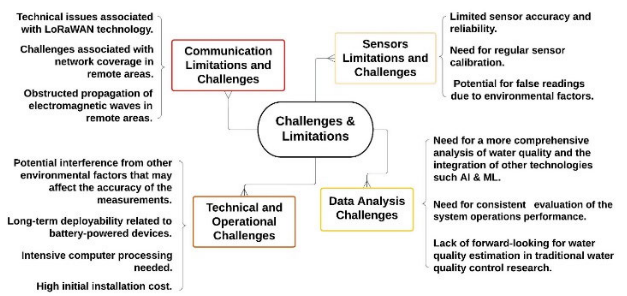

FIGURE 27. Challenges and limitations of implementing IoT in water quality monitoring.

Various solutions have been suggested in the literature to overcome the challenges linked to monitoring water quality using IoT. These solutions can be broadly categorized into four groups: connectivity enhancement, enhancing data management and analysis, sensors development and use, and system design and implementation strategies (Fig. 28). To enhance connectivity, researchers have recommended exploring alternative wireless backbone technologies, expanding wireless infrastructure, and conducting further research on propagation modeling for NB-IoT in remote areas with thick and tall foliage [87], [148]. Additionally, implementing cloud-based platforms for data storage and analysis, along with the use of open data formats and open-source software, has been suggested to improve data management and analysis [32], [137], [145], [149]. On the other hand, low-cost, reliable, and fully waterproof sensors have been proposed to improve the sensors used in IoT-based systems [139], [142], [151]. Furthermore, some studies suggested using solar-powered IoT devices and event detection methods to reduce labor-intensive interventions in the field and involve stakeholders to improve system design and implementation strategies [137], [142].

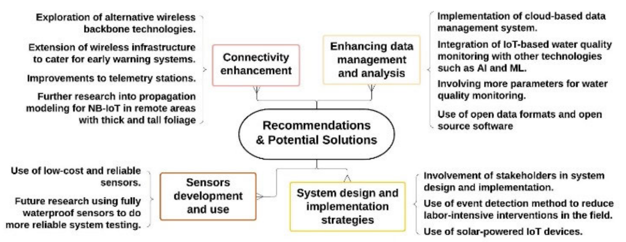

FIGURE 28. Proposed solutions for overcoming challenges in IoT-based water quality monitoring.

Overall, the proposed solutions have significantly progressed in mitigating the challenges of implementing IoT-based systems for water quality monitoring. Nonetheless, several unresolved gaps remain, necessitating further research and investigation. Some of these gaps include, but are not limited to:

- Lack of low-cost, reliable, and accurate sensors: Proposed solutions suggest using battery-powered sensors, but these have limitations regarding long-term deployability and potential interference from other environmental factors. To address these challenges, there is a need for low-cost and reliable sensors for water quality monitoring that can achieve long-term performance in harsh environmental conditions without periodic maintenance. Further research is needed to develop low-power, sustainable, and integrated underwater and above-water IoT sensor networks suitable for various conditions.
- Challenges associated with data acquisition and transmission: Although some proposed solutions suggest the need for secure and reliable communication channels, they do not fully address the technical issues associated with wireless link limitations and network coverage in remote areas. Further research is needed to investigate different communication mechanisms, such as Zigbee, Sigfox, and NB-IoT, and to integrate various techniques to generate a more integrated system. Moreover, there is a need to migrate to LTE network infrastructure, and technical challenges associated with LoRaWAN technology, such as obstructed propagation of electromagnetic waves in remote areas, need to be addressed.
- Comprehensive analysis of water quality: While some solutions propose the integration of AI and ML in water quality management, a more thorough analysis of water quality is still needed. Traditional manual monitoring

schemes lack sufficient detail about diurnal fluctuations in water quality. Further research is necessary to improve the accuracy and depth of water quality analysis.

- Lack of standardization: The lack of standardization in data collection, analysis, and reporting limits the interoperability of IoT-based systems for water quality monitoring. This issue could be addressed by developing standard protocols for sensor calibration, data processing, and quality assurance. In addition, developing a centralized database that collects and stores data from different monitoring stations could facilitate data sharing and analysis. Additionally, the collaboration between stakeholders such as water resource management agencies, researchers, and technology developers could help develop a standardized data collection and sharing framework.

V. CONCLUSION

This review highlights IoT's substantial potential in transforming water and wastewater management and water quality monitoring. Employing a hybrid methodology that combines ChatGPT and manual processes, we identified and analyzed 119 relevant articles from an initial set of 496 through rigorous screening and snowballing techniques.

The SA explores IoT research in water-related domains spanning 2012 to 2023. Notably, IoT research witnessed a substantial surge in 2017, peaking at 24 articles in 2021. Since 2017, an annual average of 15 articles underscores the growing significance of IoT-based sensor technologies in three research domains. Employing keyword co-occurrence analysis, the study unveils trends and hotspots. Distinct keyword clusters emerged, particularly emphasizing IoT applications in water management and IoT-based water quality monitoring. Separate analyses for IoT-based wastewater management, water management, and water quality monitoring provide deeper insights into these domains.

In the SR part, we categorized articles into three dimensions, which offer a nuanced understanding of the various applications of IoT within these realms. Each dimension further uncovers insights across subcategories, highlighting the significance of sensors and sensing technologies, data acquisition and transformation, data analytics and visualization, application and case studies, and existing limitations and research gaps. The SR results indicate equal research focus across the three domains. Many studies (20 for water management, 24 for wastewater management, and 32 for water quality) involve multiple sensors. Water level, flow, and pH sensors are frequently used (12, 15, and 17 articles, respectively). This detailed analysis enhances our understanding of IoT's multifaceted benefits and challenges. The prevalence of sensors, particularly flow and pH sensors, is crucial in the context of surface water monitoring, where real-time data acquisition plays a pivotal role in managing water quality and facilitating informed decision-making, thereby enhancing the effectiveness of water and wastewater management practices in such environments.

The findings of this comprehensive review have uncovered shared research challenges, gaps, and limitations across the three dimensions of IoT applications. Notably, the need for cost-effective and robust sensors capable of functioning in diverse conditions, the challenge of ensuring stable and reliable technical connections in remote or underground locations, and the pressing concern of addressing energy consumption and optimizing power sources are among these common hurdles. Furthermore, the lack of standardization in data collection and analysis practices hampers interoperability, and fostering interdisciplinary collaboration remains underrepresented in current research efforts. While regular monitoring practices are crucial for maintaining water quality, it's important to note that the response to pollution episodes often lacks standardized protocols, necessitating adaptable and situational monitoring strategies to effectively address such unpredictable events. These shared challenges and gaps emphasize the necessity for innovative solutions, such as improved sensor technologies, enhanced connectivity, sustainable energy management, standardized data practices, and greater interdisciplinary cooperation to fully harness the potential of IoT in water infrastructure management and monitoring.Contributing significantly to the field, this review serves as a guiding reference for both researchers and practitioners. It not only directs efforts towards impactful research but also advocates for the integration of sustainability principles. By recognizing IoT's transformative potential alongside advancements in AI and ML, our work propels water infrastructure towards enhanced efficiency, resilience, and environmental stewardship.

Moving forward, we propose actionable recommendations for future research directions. First and foremost, there is a pressing need for concerted efforts in developing more cost-effective and robust sensor technologies capable of operating in diverse conditions. Additionally, researchers should focus on ensuring stable and reliable technical connections, especially in remote or underground locations, and addressing the challenge of energy consumption by optimizing power sources. Standardization in data collection and analysis practices is paramount for fostering interoperability. Future studies should prioritize the establishment of common protocols to enhance the compatibility of diverse IoT applications in water-related domains. Moreover, interdisciplinary collaboration must be actively encouraged and facilitated. The integration of expertise from diverse fields, including water management, engineering, data science, and environmental science, will be instrumental in tackling shared challenges and advancing the field cohesively. In conclusion, as we confront escalating water-related challenges globally, this review not only delineates the current landscape but also charts a course for future endeavors. By implementing these recommendations, researchers can propel IoT in water infrastructure management towards greater innovation, effectiveness, and sustainability, ensuring the resilience of our water resources in the digital age.

REFERENCES

[1] P. H. Gleick, "Basic water requirements for human activities: Meeting basic needs," *Water Int.*, vol. 21, no. 2, pp. 83–92, Jun. 1996.

[2] W. J. Cosgrove and D. P. Loucks, "Water management: Current and future challenges and research directions," *Water Resour. Res.*, vol. 51, no. 6, pp. 4823–4839, Jun. 2015, doi: 10.1002/2014wr016869.

[3] P. Greve, T. Kahil, J. Mochizuki, T. Schinko, Y. Satoh, P. Burek, G. Fischer, S. Tramberend, R. Burtscher, S. Langan, and Y. Wada, "Global assessment of water challenges under uncertainty in water scarcity projections," *Nature Sustainability*, vol. 1, no. 9, pp. 486–494, Sep. 2018, doi: 10.1038/s41893-018-0134-9.

[4] S. H. A. Koop and C. J. van Leeuwen, "Assessment of the sustainability of water resources management: A critical review of the city blueprint approach," *Water Resour. Manage.*, vol. 29, no. 15, pp. 5649–5670, Dec. 2015, doi: 10.1007/s11269-015-1139-z.

[5] R. K. Mazumder, A. M. Salman, Y. Li, and X. Yu, "Performance evaluation of water distribution systems and asset management," *J. Infrastruct. Syst.*, vol. 24, no. 3, Sep. 2018, Art. no. 03118001, doi: 10.1061/(ASCE)IS.1943-555X.0000426

[6] M. Santora and R. Wilson, "Resilient and sustainable water infrastructure," *J. Amer. Water Works Assoc.*, vol. 100, no. 12, pp. 40–42, Dec. 2008, doi: 10.1002/j.1551-8833.2008.tb09798.x.

[7] S. Shin, S. Lee, D. Judi, M. Parvania, E. Goharian, T. McPherson, and S. Burian, "A systematic review of quantitative resilience measures for water infrastructure systems," *Water*, vol. 10, no. 2, p. 164, Feb. 2018, doi: 10.3390/w10020164.

[8] V. Srinivasan, M. Konar, and M. Sivapalan, "A dynamic framework for water security," *Water Secur.*, vol. 1, pp. 12–20, Jul. 2017, doi: 10.1016/j.wasec.2017.03.001.

[9] C. M. Brown, J. R. Lund, X. Cai, P. M. Reed, E. A. Zagona, A. Ostfeld, J. Hall, G. W. Characklis, W. Yu, and L. Brekke, "The future of water resources systems analysis: Toward a scientific framework for sustainable water management," *Water Resour. Res.*, vol. 51, no. 8, pp. 6110–6124, Aug. 2015, doi: 10.1002/2015wr017114.

[10] D. Butler, S. Ward, C. Sweetapple, M. Astaraie-Imani, K. Diao, R. Farmani, and G. Fu, "Reliable, resilient and sustainable water management: The safe & SuRe approach," *Global Challenges*, vol. 1, no. 1, pp. 63–77, Jan. 2017, doi: 10.1002/gch2.1010.

[11] H. Ramos, A. McNabola, P. López-Jiménez, and M. Pérez-Sánchez, "Smart water management towards future water sustainable networks," *Water*, vol. 12, no. 1, p. 58, Dec. 2019, doi: 10.3390/w12010058.

[12] M. Ait-Kadi, "Water for development and development for water: Realizing the sustainable development goals (SDGs) vision," *Aquatic Proc.*, vol. 6, pp. 106–110, Aug. 2016, doi: 10.1016/j.aqpro.2016.06.013.

[13] H. M. K. Delanka-Pedige, S. P. Munasinghe-Arachchige, I. S. A. Abeysiriwardana-Arachchige, and N. Nirmalakhandan, "Wastewater infrastructure for sustainable cities: Assessment based on UN sustainable development goals (SDGs)," *Int. J. Sustain. Develop. World Ecol.*, vol. 28, no. 3, pp. 203–209, Apr. 2021, doi: 10.1080/13504509.2020.1795006.

[14] J. Weststrate, G. Dijkstra, J. Eshuis, A. Gianoli, and M. Rusca, "The sustainable development goal on water and sanitation: Learning from the millennium development goals," *Social Indicators Res.*, vol. 143, no. 2, pp. 795–810, Jun. 2019, doi: 10.1007/s11205-018-1965-5.

[15] E. Aivazidou, G. Banias, M. Lampridi, G. Vasileiadis, A. Anagnostis, E. Papageorgiou, and D. Bochtis, "Smart technologies for sustainable water management: An urban analysis," *Sustainability*, vol. 13, no. 24, p. 13940, Dec. 2021, doi: 10.3390/su132413940.

[16] U. Mankad and H. Arolkar, "Smart water metering implementation," in *Proc. Smart Trends Comput. Commun.*, 2022, pp. 721–731, doi: 10.1007/978-981-16-9967-2_68.

[17] L. S. Pereira, I. Cordery, and I. Iacovides, "Improved indicators of water use performance and productivity for sustainable water conservation and saving," *Agricult. Water Manage.*, vol. 108, pp. 39–51, May 2012, doi: 10.1016/j.agwat.2011.08.022.

[18] X. Xiang, Q. Li, S. Khan, and O. I. Khalaf, "Urban water resource management for sustainable environment planning using artificial intelligence techniques," *Environ. Impact Assessment Rev.*, vol. 86, Jan. 2021, Art. no. 106515, doi: 10.1016/j.eiar.2020.106515.

[19] C. W. K. Chow, J. Liu, J. Li, N. Swain, K. Reid, and C. P. Saint, "Development of smart data analytics tools to support wastewater treatment plant operation," *Chemometric Intell. Lab. Syst.*, vol. 177, pp. 140–150, Jun. 2018, doi: 10.1016/j.chemolab.2018.03.006.

[20] S. J. McIlroy, A. Starnawska, P. Starnawski, A. M. Saunders, M. Nierychlo, P. H. Nielsen, and J. L. Nielsen, "Identification of active denitrifiers in full-scale nutrient removal wastewater treatment systems," *Environ. Microbiol.*, vol. 18, no. 1, pp. 50–64, Jan. 2016, doi: 10.1111/1462-2920.12614.

[21] E. Neczaj and A. Grosser, "Circular economy in wastewater treatment plant-challenges and barriers," *Proceedings*, vol. 2, no. 11, p. 614, Jul. 2018, doi: 10.3390/proceedings2110614.

[22] P. F. Boulos and A. T. Walker, "Fixing the future of wastewater systems with smart water network modeling," *J. Amer. Water Works Assoc.*, vol. 107, no. 4, pp. 72–80, Apr. 2015, doi: 10.5942/jawwa.2015.107.0057.

[23] L. Hoang and R. A. Fenner, "System interactions of stormwater management using sustainable urban drainage systems and green infrastructure," *Urban Water J.*, vol. 13, no. 7, pp. 739–758, Oct. 2016, doi: 10.1080/1573062x.2015.1036083.

[24] S. Perales-Momparler, I. Andrés-Doménech, C. Hernández-Crespo, F. Vallés-Morán, M. Martín, I. Escuder-Bueno, and J. Andreu, "The role of monitoring sustainable drainage systems for promoting transition towards regenerative urban built environments: A case study in the valencian region, Spain," *J. Cleaner Prod.*, vol. 163, pp. S113–S124, Oct. 2017, doi: 10.1016/j.jclepro.2016.05.153.

[25] S. R. Mohandes, A. F. Kineber, S. Abdelkhalek, K. Kaddoura, M. Elsayed, M. R. Hosseini, and T. Zayed, "Evaluation of the critical factors causing sewer overflows through modeling of structural equations and system dynamics," *J. Cleaner Prod.*, vol. 375, Nov. 2022, Art. no. 134035, doi: 10.1016/j.jclepro.2022.134035.

[26] K. B. Adedeji, "Performance evaluation of data compression algorithms for IoT-based smart water network management applications," *J. Appl. Sci. Process Eng.*, vol. 7, no. 2, pp. 554–563, Oct. 2020, doi: 10.33736/jaspe.2272.2020.

[27] I. S. Herath, "Smart water buddy: IoT based intelligent domestic water management system," in *Proc. Int. Conf. Advancements Comput. (ICAC)*, Dec. 2019, pp. 380–385, doi: 10.1109/ICAC49085.2019.9103379.

[28] M. Xiaocong, Q. Xin Jiao, and S. Shaohong, "An IoT-based system for water resources monitoring and management," in *Proc. 7th Int. Conf. Intell. Human-Machine Syst. Cybern.*, Aug. 2015, pp. 365–368, doi: 10.1109/IHMSC.2015.150.

[29] A. S. Ali, M. N. Abdelmoez, M. Heshmat, and K. Ibrahim, "A solution for water management and leakage detection problems using IoTs based approach," *Internet Things*, vol. 18, May 2022, Art. no. 100504, doi: 10.1016/j.iot.2022.100504.

[30] F. Jan, N. Min-Allah, and D. Düştegör, "IoT based smart water quality monitoring: Recent techniques, trends and challenges for domestic applications," *Water*, vol. 13, no. 13, p. 1729, Jun. 2021, doi: 10.3390/w13131729.

[31] E. B. Priyanka, S. Thangavel, V. Madhuvishal, S. Tharun, K. V. Raagul, and C. S. S. Krishnan, "Application of integrated IoT framework to water pipeline transportation system in smart cities," in *Proc. Intell. Big Data Technol. Beyond Hype*, 2021, pp. 571–579, doi: 10.1007/978-981-15-5285-4_57.

[32] K. Saravanan, E. Anusuya, R. Kumar, and L. H. Son, "Real-time water quality monitoring using Internet of Things in SCADA," *Environ. Monitor. Assessment*, vol. 190, no. 9, p. 556, Sep. 2018, doi: 10.1007/s10661-018-6914-x.

[33] S. Teruhi, Y. Yamaguchi, and J. Akahani, "Water leakage detection system for underground pipes by using wireless sensors and machine learning," *J. Disaster Res.*, vol. 12, no. 3, pp. 557–568, Jun. 2017, doi: 10.20965/jdr.2017.p0557.

[34] F. Jan, N. Min-Allah, S. Saeed, S. Z. Iqbal, and R. Ahmed, "IoT-based solutions to monitor water level, leakage, and motor control for smart water tanks," *Water*, vol. 14, no. 3, p. 309, Feb. 2022, doi: 10.3390/w14030309.

[35] J. K. Roy and S. C. Mukhopadhyay, "Monitoring water in treatment and distribution system," in *Proc. Smart Sensors, Meas. Instrum.*, vol. 16, Cham, Switzerland: Springer, 2016, pp. 257–287, doi: 10.1007/978-3-319-21671-3_12.

[36] H. Ali and J.-H. Choi, "A review of underground pipeline leakage and sinkhole monitoring methods based on wireless sensor networking," *Sustainability*, vol. 11, no. 15, p. 4007, Jul. 01, 2019, doi: 10.3390/su11154007.

[37] G. Hancke, B. Silva, and G. Hancke, "The role of advanced sensing in smart cities," *Sensors*, vol. 13, no. 1, pp. 393–425, Jan. 2013, doi: 10.3390/s130100393.

[38] S. A. Palermo, M. Maiolo, A. C. Brusco, M. Turco, B. Pirouz, E. Greco, G. Spezzano, and P. Piro, "Smart technologies for water resource management: An overview," *Sensors*, vol. 22, no. 16, p. 6225, Aug. 2022, doi: 10.3390/s22166225.

[39] S. Drost, C. Malewski, and S. Jirka, "Sensor web and Internet of Things technologies for hydrological measurement data," in *Instrumentation and Measurement Technologies for Water Cycle Management* (Springer Water). Cham, Switzerland: Springer, 2022, pp. 279–293, doi: 10.1007/978-3-031-08262-7_12.

[40] M. R. Barbhuiya, M. Bhardwaj, S. Shukla, A. T. Kibret, and G. Panda, "IoT technology-based urban water management strategies using Indian traditional knowledge system," in *IoT and IoE Driven Smart Cities* (EAI/Springer Innovations in Communication and Computing). Cham, Switzerland: Springer, 2022, pp. 275–291.

[41] S. R. Mounce, "Data science trends and opportunities for smart water utilities," in *The Handbook of Environmental Chemistry*, vol. 102. Cham, Switzerland: Springer, 2020, pp. 1–26, doi: 10.1007/698_2020_482.

[42] A. Hangan, C.-G. Chiru, D. Arsene, Z. Czako, D. F. Lisman, M. Mocanu, B. Pahontu, A. Predescu, and G. Sebestyen, "Advanced techniques for monitoring and management of urban water infrastructures—An overview," *Water*, vol. 14, no. 14, p. 2174, Jul. 01, 2022, doi: 10.3390/w14142174.

[43] A. Niknam, H. K. Zare, H. Hosseininasab, A. Mostafaeipour, and M. Herrera, "A critical review of short-term water demand forecasting tools—What method should I use?" *Sustainability*, vol. 14, no. 9, p. 5412, Apr. 01, 2022, doi: 10.3390/su14095412.

[44] T. Ercan and M. Kutay, "Smart utilities," in *Solving Urban Infrastructure Problems Using Smart City Technologies: Handbook on Planning, Design, Development, and Regulation*. Amsterdam, The Netherlands: Elsevier, 2021, pp. 293–328, doi: 10.1016/B978-0-12-816816-5.00014-0.

[45] J. L. Webber, T. Fletcher, R. Farmani, D. Butler, and P. Melville-Shreeve, "Moving to a future of smart stormwater management: A review and framework for terminology, research, and future perspectives," *Water Res.*, vol. 218, Jun. 30, 2022, Art. no. 118409, doi: 10.1016/j.watres.2022.118409.

[46] C. Peoples, "Priority activities for smart cities and the infrastructure," in *Solving Urban Infrastructure Problems Using Smart City Technologies: Handbook on Planning, Design, Development, and Regulation*. Amsterdam, The Netherlands: Elsevier, 2020, pp. 159–182, doi: 10.1016/B978-0-12-816816-5.00008-5.

[47] A. Alshami, M. Elsayed, E. Ali, A. E. E. Eltoukhy, and T. Zayed, "Harnessing the power of ChatGPT for automating systematic review process: Methodology, case study, limitations, and future directions," *Systems*, vol. 11, no. 7, p. 351, Jul. 2023, doi: 10.3390/systems11070351.

[48] C. Wohlin, "Guidelines for snowballing in systematic literature studies and a replication in software engineering," in *Proc. 18th Int. Conf. Eval. Assessment Softw. Eng.* New York, NY, USA: ACM, May 2014, pp. 1–10, doi: 10.1145/2601248.2601268.

[49] I. A. Shaban, A. E. E. Eltoukhy, and T. Zayed, "Systematic and scientometric analyses of predictors for modelling water pipes deterioration," *Autom. Construct.*, vol. 149, May 2023, Art. no. 104710, doi: 10.1016/j.autcon.2022.104710.

[50] M. Hussein, A. E. E. Eltoukhy, A. Karam, I. A. Shaban, and T. Zayed, "Modelling in off-site construction supply chain management: A review and future directions for sustainable modular integrated construction," *J. Cleaner Prod.*, vol. 310, Aug. 2021, Art. no. 127503, doi: 10.1016/j.jclepro.2021.127503.

[51] C. Tao, X. Ling, S. Guofeng, Y. Hongyong, and H. Quanyi, "Architecture for monitoring urban infrastructure and analysis method for a smart-safe city," in *Proc. 6th Int. Conf. Measuring Technol. Mechatronics Autom.*, Jan. 2014, pp. 151–154, doi: 10.1109/ICMTMA.2014.40.

[52] C. Ebi, F. Schaltegger, A. Rüst, and F. Blumensaat, "Synchronous LoRa mesh network to monitor processes in underground infrastructure," *IEEE Access*, vol. 7, pp. 57663–57677, 2019, doi: 10.1109/ACCESS.2019.2913985.

[53] S. V. Mohanasundaram, A. Joyce, K. S. Naresh, G. Gokulkrishnan, A. Kale, T. Dwarakanath, and P. Haribabu, "Smart water distribution network solution for smart cities: Indian scenario," in *Proc. Global Internet Things Summit (GIoTS)*, Jun. 2018, pp. 1–6, doi: 10.1109/GIOTS.2018.8534524.

[54] D. Trinchero and R. Stefanelli, "Integration between Internet of Things and Internet of Services for an enhanced optimization of water and gas distribution," in *Proc. IEEE Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2012, pp. 1–6, doi: 10.1109/WOWMOM.2012.6263788.

[55] E. J. Sacoto-Cabrera, I. Castillo, W. Pauta, P. Trelles, P. Tamariz, and L. Guambana, "SMART-WATER: Digital transformation of urban water measurement," in *Proc. 11th IEEE Conf. Andean Council*, M. C. Lozada and P. S. Mendoza, Eds., Nov. 2022, pp. 1–6, doi: 10.1109/ANDESCON56260.2022.9989581.

[56] E. Y. Li, W.-H. Wang, and Y.-S. Hsu, "Adopting IoT technology to optimize intelligent water management," in *Proc. 17th Int. Conf. Electron. Bus., Smart Cities*, E. Y. Li and K. N. Shen, Eds., 2017, pp. 38–46. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85057752995&partnerID=40&md5=4b945551c73875b0a875cdfa20989146

[57] S. Mekruksavanich, K. Sooksomsatarn, and A. Jitpattanakul, "Flooding forecasting system based on water monitoring with IoT technology," in *Proc. IEEE 12th Int. Conf. Softw. Eng. Service Sci. (ICSESS)*, Aug. 2021, pp. 247–250, doi: 10.1109/ICSESS52187.2021.9522266.

[58] M. Xie, R. Wang, J. Yang, and Y. Cheng, "A monitoring and control system for stormwater management of urban green infrastructure," *Water*, vol. 13, no. 11, p. 1438, May 2021, doi: 10.3390/w13111438.

[59] M. Siek and L. Larry, "Design and implementation of Internet of Things and cloud technology in flood risk mitigation," in *Proc. 3rd Int. Conf. Cybern. Intell. Syst. (ICORIS)*, Oct. 2021, pp. 1–6, doi: 10.1109/ICORIS52787.2021.9649589.

[60] S. Chinnusamy, P. Mohandoss, and P. Paul, "IoT enabled monitoring and control of water distribution network," in *Proc. WDSA/CCWI Joint Conf.*, 2018, pp. 1–8.

[61] Z. Shi, M. Wang, H. Lin, H. Lin, Z. Gao, and L. Huang, "NB-IoT pipeline water leakage automatic monitoring system based on cloud platform," in *Proc. IEEE 13th Int. Conf. Anti-counterfeiting, Secur., Identificat. (ASID)*, Oct. 2019, pp. 272–276, doi: 10.1109/ICASID.2019.8925228.

[62] C. Mourtzios, D. Kourtesis, N. Papadimitriou, G. Antzoulatos, I.-O. Kouloglou, S. Vrochidis, and K. Ioannis, "Work-in-progress: SMART-WATER, a novel telemetry and remote control system infrastructure for the management of water consumption in Thessaloniki," in *Proc. Internet Things, Infrastructures Mobile Appl.*, 2021, pp. 962–970, doi: 10.1007/978-3-030-49932-7_89.

[63] N. Pindoriya, M. Duchon, P. K. Gupta, V. Pampana, S. N. Singh, J. Giza, B. Hackenberg, A. K. Rajput, and J. Jethi, "Intelligent hardware–software platform for efficient coupling of water-energy Nexus in smart cities: A conceptual framework," in *Proc. Mobility Internet Things*, 2018, pp. 217–231, doi: 10.1007/978-3-030-30911-4_15.

[64] D. Purkovic, L. Coates, M. Hönsch, D. Lumbeck, and F. Schmidt, "Smart river monitoring and early flood detection system in Japan developed with the EnOcean long range sensor technology," in *Proc. 2nd Int. Colloq. Smart Grid Metrology (SMAGRIMET)*, Apr. 2019, pp. 1–6, doi: 10.23919/SMAGRIMET.2019.8720390.

[65] D. Arsene, A. Predescu, B. Pahonţu, C. G. Chiru, E.-S. Apostol, and C.-O. Truică, "Advanced strategies for monitoring water consumption patterns in households based on IoT and machine learning," *Water*, vol. 14, no. 14, p. 2187, Jul. 2022, doi: 10.3390/w14142187.

[66] M. Afifi, M. F. Abdelkader, and A. Ghoneim, "An IoT system for continuous monitoring and burst detection in intermittent water distribution networks," in *Proc. Int. Conf. Innov. Trends Comput. Eng. (ITCE)*, Feb. 2018, pp. 240–247, doi: 10.1109/ITCE.2018.8316632.

[67] H. Zeng, G. Dhiman, A. Sharma, A. Sharma, and A. Tselykh, "An IoT and blockchain-based approach for the smart water management system in agriculture," *Expert Syst.*, vol. 40, no. 4, Nov. 2021, Art. no. e12892, doi: 10.1111/exsy.12892.

[68] M. K. Kirar, "IoT based remote monitoring, control, and protection of irrigation water pumping system," *J. Operation Autom. Power Eng.*, vol. 11, no. 1, pp. 69–75, Apr. 2023, doi: 10.22098/JOAPE.2023.9265.1647.

[69] T. Narendrakumar and A. S. Pillai, "Smart connected campus," in *Proc. Int. Conf. Intell. Comput., Instrum. Control Technol. (ICICICT)*, Jul. 2017, pp. 1591–1596, doi: 10.1109/ICICICT1.2017.8342808.

[70] L. Li and H. Chen, "Artificial intelligence and Internet of Things-based leak detection method for the water supply network," *Int. Trans. Electr. Energy Syst.*, vol. 2023, pp. 1–11, Feb. 2023, doi: 10.1155/2023/3443047.

[71] H. Fuentes and D. Mauricio, "Smart water consumption measurement system for houses using IoT and cloud computing," *Environ. Monitor. Assessment*, vol. 192, no. 9, p. 602, Sep. 2020, doi: 10.1007/s10661-020-08535-4.
[72] D. P. Jose, A. L. D'Souza, A. A. Thomas, and D. Daniel, "IoT based water management using HC-12 and Django," in *Proc. Int. Conf. Data Sci. Commun. (IconDSC)*, Mar. 2019, pp. 1–6, doi: 10.1109/IconDSC.2019.8816917.
[73] H. Sammaneh and M. Al-Jabi, "IoT-enabled adaptive smart water distribution management system," in *Proc. Int. Conf. Promising Electron. Technol. (ICPET)*, Oct. 2019, pp. 40–44, doi: 10.1109/ICPET.2019.00015.
[74] J. Pérez-Padillo, J. García Morillo, J. Ramirez-Faz, M. Torres Roldán, and P. Montesinos, "Design and implementation of a pressure monitoring system based on IoT for water supply networks," *Sensors*, vol. 20, no. 15, p. 4247, Jul. 2020, doi: 10.3390/s20154247.
[75] A. Predescu, C.-O. Truică, E.-S. Apostol, M. Mocanu, and C. Lupu, "An advanced learning-based multiple model control supervisor for pumping stations in a smart water distribution system," *Mathematics*, vol. 8, no. 6, p. 887, Jun. 2020, doi: 10.3390/math8060887.
[76] A. Predescu, M. Mocanu, and C. Lupu, "Application of advanced learning methods for detecting network configuration in a smart water distribution system," in *Proc. IEEE Int. Conf. Autom., Quality Test., Robot. (AQTR)*, May 2020, pp. 1–6, doi: 10.1109/AQTR49680.2020.9129956.
[77] Y. Yamaguchi, Y. Fujino, H. Katsuda, M. Nakano, H. Fukumoto, S. Teruhi, K. Akabane, and S. Yoshino, "Underground infrastructure management system using Internet of Things wireless transmission technology," *IEICE Trans. Electron.*, vol. 101, no. 10, pp. 727–733, 2018, doi: 10.1587/transele.e101.c.727.
[78] R. S. Darshan, H. Pavan, R. Pratheesh, M. S. Raj, K. V. Suresh, and C. Prathap, "An IoT enabled water management system with water usage prediction using ANN," in *Proc. 2nd Global Conf. Advancement Technol. (GCAT)*, Oct. 2021, pp. 1–7, doi: 10.1109/GCAT52182.2021.9587502.
[79] S. Aggarwal and S. Sehgal, "Automation of water distribution system by prediction of water consumption and leakage detection using machine learning and IoT," in *Proc. 12th Int. Conf. Cloud Comput., Data Sci. Eng. (Confluence)*, Jan. 2022, pp. 345–350, doi: 10.1109/Confluence52989.2022.9734192.
[80] S. Alvisi, F. Casellato, M. Franchini, M. Govoni, C. Luciani, F. Poltronieri, G. Riberto, C. Stefanelli, and M. Tortonesi, "Wireless middleware solutions for smart water metering," *Sensors*, vol. 19, no. 8, p. 1853, Apr. 2019, doi: 10.3390/s19081853.
[81] J. Pérez-Padillo, F. Puig, J. García Morillo, and P. Montesinos, "IoT platform for failure management in water transmission systems," *Expert Syst. Appl.*, vol. 199, Aug. 2022, Art. no. 116974, doi: 10.1016/j.eswa.2022.116974.
[82] M. Cattani, C. A. Boano, D. Steffelbauer, S. Kaltenbacher, M. Günther, K. Römer, D. Fuchs-Hanusch, and M. Horn, "Adige: An efficient smart water network based on long-range wireless technology," in *Proc. 3rd Int. Workshop Cyber-Phys. Syst. Smart Water Netw.* New York, NY, USA: ACM, Apr. 2017, pp. 3–6, doi: 10.1145/3055366.3055367.
[83] M. Kalochristianakis, D. Katrinakis, G. Atsali, A. Malamos, T. Manios, and S. Panagiotakis, "HOLISTIC: An IoT system for residential water recycling based on open source technologies," in *Proc. Int. Conf. Telecommun. Multimedia (TEMU)*, Jul. 2016, pp. 1–6, doi: 10.1109/TEMU.2016.7551940.
[84] W. Li, Z. Ye, Y. Wang, H. Yang, S. Yang, Z. Gong, and L. Wang, "Development of a distributed MR-IoT method for operations and maintenance of underground pipeline network," *Tunnelling Underground Space Technol.*, vol. 133, Mar. 2023, Art. no. 104935, doi: 10.1016/j.tust.2022.104935.
[85] N. Venkatasubramanian, C. A. Davis, and R. T. Eguchi, "Designing community-based intelligent systems for water infrastructure resilience," in *Proc. 3rd ACM SIGSPATIAL Int. Workshop Adv. Resilient Intell. Cities*, B. Kar, X. Ye, S. Mohebbi, and G. Fu, Eds. New York, NY, USA: Association for Computing Machinery, Nov. 2020, pp. 62–65, doi: 10.1145/3423455.3430318.
[86] D. Amaxilatis, I. Chatzigiannakis, C. Tselios, and N. Tsironis, "Sparks-edge: Analytics for intelligent city water metering," in *Proc. Joint Poster Workshop Sessions, Eur. Conf. Ambient Intell.*, E. C. Strinati, D. Charitos, I. Chatzigiannakis, P. Ciampolini, F. Cuomo, D. Gavalas, S. Hanke, A. Komninos, and G. Mylonas, Eds., 2019, pp. 19–29. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85074845730&partnerID=40&md5=0a80b5dfc6898399dec4cd23a393c0db
[87] R. Nordin, H. Mohamad, M. Behjati, A. H. Kelechi, N. Ramli, K. Ishizu, F. Kojima, M. Ismail, and M. Idris, "The world-first deployment of narrowband IoT for rural hydrological monitoring in UNESCO biosphere environment," in *Proc. IEEE 4th Int. Conf. Smart Instrum., Meas. Appl. (ICSIMA)*, Nov. 2017, pp. 1–5, doi: 10.1109/ICSIMA.2017.8311981.
[88] A. A. Maroli, V. S. Narwane, R. D. Raut, and B. E. Narkhede, "Framework for the implementation of an Internet of Things (IoT)-based water distribution and management system," *Clean Technol. Environ. Policy*, vol. 23, no. 1, pp. 271–283, Jan. 2021, doi: 10.1007/s10098-020-01975-z.
[89] R. Ullah, A. W. Abbas, M. Ullah, R. U. Khan, I. U. Khan, N. Aslam, and S. S. Aljameel, "EEWMP: An IoT-based energy-efficient water management platform for smart irrigation," *Sci. Program.*, vol. 2021, pp. 1–9, Apr. 2021, doi: 10.1155/2021/5536884.
[90] F. Lorenz, M. Geldenhuys, H. Sommer, F. Jakobs, C. Lüring, V. Skwarek, I. Behnke, and L. Thamsen, "A scalable and dependable data analytics platform for water infrastructure monitoring," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, X. Wu, C. Jermaine, L. Xiong, X. T. Hu, O. Kotevska, S. Lu, W. Xu, S. Aluru, C. Zhai, E. Al-Masri, Z. Chen, and J. Saltz, Eds., Dec. 2020, pp. 3488–3493, doi: 10.1109/BigData50022.2020.9378138.
[91] H. Y. El Sayed, M. Al-Kady, and Y. Siddik, "Management of smart water treatment plant using IoT cloud services," in *Proc. Int. Conf. Smart Appl., Commun. Netw. (SmartNets)*, Dec. 2019, pp. 1–5, doi: 10.1109/SmartNets48225.2019.9069763.
[92] J. Fell, J. Pead, and K. Winter, "Low-cost flow sensors: Making smart water monitoring technology affordable," *IEEE Consum. Electron. Mag.*, vol. 8, no. 1, pp. 72–77, Jan. 2019, doi: 10.1109/MCE.2018.2867984.
[93] F. Bruno, M. De Marchis, B. Milici, D. Saccone, and F. Traina, "A pressure monitoring system for water distribution networks based on Arduino microcontroller," *Water*, vol. 13, no. 17, p. 2321, Aug. 2021, doi: 10.3390/w13172321.
[94] V. Edmondson, M. Cerny, M. Lim, B. Gledson, S. Lockley, and J. Woodward, "A smart sewer asset information model to enable an 'Internet of Things' for operational wastewater management," *Autom. Construct.*, vol. 91, pp. 193–205, Jul. 2018, doi: 10.1016/j.autcon.2018.03.003.
[95] N. Asthana and R. Bahl, "IoT device for sewage gas monitoring and alert system," in *Proc. 1st Int. Conf. Innov. Inf. Commun. Technol. (ICIICT)*, Apr. 2019, pp. 1–7, doi: 10.1109/ICIICT1.2019.8741423.
[96] P. M. Kumar and C. S. Hong, "Internet of Things for secure surveillance for sewage wastewater treatment systems," *Environ. Res.*, vol. 203, Jan. 2022, Art. no. 111899, doi: 10.1016/j.envres.2021.111899.
[97] A. Nair, A. Hykkerud, and H. Ratnaweera, "Estimating phosphorus and COD concentrations using a hybrid soft sensor: A case study in a Norwegian municipal wastewater treatment plant," *Water*, vol. 14, no. 3, p. 332, Jan. 2022, doi: 10.3390/w14030332.
[98] A. Depari, P. Bellagente, P. Ferrari, A. Flammini, M. Pasetti, S. Rinaldi, and E. Sisinni, "Versatile and low-cost sensor interface for IoT-ready odor monitoring in wastewater management," in *Proc. IEEE Sensors Appl. Symp. (SAS)*, Aug. 2021, pp. 1–6, doi: 10.1109/SAS51076.2021.9530094.
[99] N. D. Kumar, R. Ramanathapuram, P. Rangi, and T. Sheoran, "Zigbee-based smart sewer," *Int. J. Innov. Technol. Exploring Eng.*, vol. 8, no. 8, pp. 995–998, 2019. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85067857046&partnerID=40&md5=67e7d7201bff2a222b32fac0a2099722
[100] S. Latif, H. Afzaal, and N. A. Zafar, "Modeling of sewerage system using Internet of Things for smart city," in *Proc. Int. Conf. Frontiers Inf. Technol. (FIT)*, Dec. 2017, pp. 46–51, doi: 10.1109/FIT.2017.00016.
[101] A. Soetedjo, E. Hendriarianti, S. A. Wibowo, J. Novrian, A. B. Nugroho, M. F. Roby, O. V. Dewi, R. S. Apriliansyah, A. Mustofa, R. I. Sari, and F. Y. Wijayanto, "Real-time implementation of wastewater monitoring system on the communal wastewater treatment plant using the IoT technology," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 1030, no. 1, Jun. 2022, Art. no. 012006, doi: 10.1088/1755-1315/1030/1/012006.
[102] B. A. Praveena, B. P. Shetty, M. S. S. Kalasi, S. S. Yadav, M. Prasad, M. N. Sujith, N. Reddy, and L. Mallikarjun, "Design and development of smart manhole," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 1013, no. 1, p. 12006, 2021, doi: 10.1088/1757-899X/1013/1/012006.
[103] J. S. Prasath, S. Jayakumar, and K. Karthikeyan, "Real-time implementation for secure monitoring of wastewater treatment plants using Internet of Things," *Int. J. Innov. Technol. Exploring Eng.*, vol. 9, no. 1, pp. 2997–3002, 2019, doi: 10.35940/ijitee.A9123.119119.

[104] M. Oberascher, J. Zischg, S. A. Palermo, C. Kinzel, W. Rauch, and R. Sitzenfrei, "Smart rain barrels: Advanced LID management through measurement and control," in *New Trends in Urban Drainage Modelling*. Cham, Switzerland: Springer, 2019, pp. 777–782, doi: 10.1007/978-3-319-99867-1_134.
[105] R. Dronavalli, K. Seelam, P. Maganti, J. Gowineni, and S. D. Challamalla, "IoT-based automatic manhole observant for sewage worker's safety," in *Proc. Int. Conf. Autom., Comput. Renew. Syst. (ICACRS)*, Dec. 2022, pp. 310–316, doi: 10.1109/ICACRS55517.2022.10029252.
[106] M. A. Samma, S. Vagrecha, R. Mathur, and L. Khan, "Intelligent wastewater treatment system with IoT based monitoring for smart cities," in *Proc. 3rd Smart Cities Symp. (SCS)*, vol. 2020, Sep. 2020, pp. 83–88, doi: 10.1049/icp.2021.0941.
[107] M. S. Hasan, S. Khandaker, Md. S. Iqbal, and M. M. Kabir, "A real-time smart wastewater monitoring system using IoT: Perspective of Bangladesh," in *Proc. 2nd Int. Conf. Sustain. Technol. Ind. 4.0 (STI)*, Dec. 2020, pp. 1–6, doi: 10.1109/STI50764.2020.9350459.
[108] M. Oberascher, C. Kinzel, W. Rauch, and R. Sitzenfrei, "Model-based upscaling of the IoT-based smart rain barrel an integrated analysis of the urban water cycle," in *Proc. World Environmental Water Resour. Congr., Planning Resilient Future Along America's Freshwaters*, L. A. Baldwin and V. G. Gude, Eds., 2021, pp. 262–269, doi: 10.1061/9780784483466.024.
[109] A. Alshami, M. Elsayed, S. R. Mohandes, A. F. Kineber, T. Zayed, A. Alyanbaawi, and M. M. Hamed, "Performance assessment of sewer networks under different blockage situations using Internet-of-Things-based technologies," *Sustainability*, vol. 14, no. 21, p. 14036, Oct. 2022, doi: 10.3390/su142114036.
[110] A. Alshami, M. Elsayed, E. Ali, A. E. E. Eltoukhy, and T. Zayed, "Monitoring blockage and overflow events in small-sized sewer network using contactless flow sensors in Hong Kong: Problems, causes, and proposed solution," *IEEE Access*, vol. 11, pp. 87131–87149, 2023, doi: 10.1109/ACCESS.2023.3305275.
[111] D. N. S. B. P. M. Jeffery, S. H. S. Newaz, S. Shams, N. Guillou, and N. S. Nafi, "LoRaWAN-based smart sewerage monitoring system," in *Proc. Int. Conf. Electron., Commun. Inf. Technol. (ICECIT)*, Sep. 2021, pp. 1–6, doi: 10.1109/ICECIT54077.2021.9641263.
[112] J. Pérez-Padillo, M. Ikegawa, J. P. Lucena, P. Montesinos, and J. G. Morillo, "Design and implementation of an IoT device for measuring discharges in sanitation networks," *Environ. Sci. Proc.*, vol. 21, no. 1, p. 38, Oct. 2022, doi: 10.3390/environsciproc2022021038.
[113] M. M. Rahman, M. A. Kashem, M. Mohiuddin, M. A. Hossain, and N. N. Moon, "Future city of bangladesh: IoT based autonomous smart sewerage and hazard condition sharing system," in *Proc. IEEE Int. Women Eng. (WIE) Conf. Electr. Comput. Eng. (WIECON-ECE)*. Dec. 2020, pp. 126–130, doi: 10.1109/WIECON-ECE52138.2020.9397950.
[114] J. H. Rony, N. Karim, M. A. Rouf, M. M. Islam, J. Uddin, and M. Begum, "A cost-effective IoT model for a smart sewerage management system using sensors," *J*, vol. 4, no. 3, pp. 356–366, Jul. 2021, doi: 10.3390/j4030027.
[115] P. Chaudhari, A. K. Tiwari, S. Pattewar, and S. N. Shelke, "Smart infrastructure monitoring using LoRaWAN technology," in *Proc. Int. Conf. Syst., Comput., Autom. Netw. (ICSCAN)*, Jul. 2021, pp. 1–6, doi: 10.1109/ICSCAN53069.2021.9526490.
[116] N. Sasirekha, Karthika, V, M. Tamilselvi, D. Sasirekha, and C. Paul, "An integrated approach for wastewater treatment system using IoT for green infrastructure using sensor," in *Proc. Int. Conf. Innov. Comput., Intell. Commun. Smart Electr. Syst. (ICSES)*, Jul. 2022, pp. 1–8, doi: 10.1109/ICSES55317.2022.9914375.
[117] C. Xiu and L. Dong, "Design of sewage treatment monitoring system based on Internet of Things," in *Proc. Chin. Control Decis. Conf. (CCDC)*, Jun. 2019, pp. 960–964, doi: 10.1109/CCDC.2019.8832470.
[118] A. Drenoyanis, R. Raad, I. Wady, and C. Krogh, "Implementation of an IoT based radar sensor network for wastewater management," *Sensors*, vol. 19, no. 2, p. 254, Jan. 2019, doi: 10.3390/s19020254.
[119] A. Drenoyanis, R. Raad, I. Wady, and C. Krogh, "Wastewater management: An IoT approach," in *Proc. IEEE Region Ten Symp. (Tensymp)*, Jul. 2018, pp. 291–292, doi: 10.1109/TENCONSPRING.2018.8692045.
[120] N. Faris, T. Zayed, E. Aghdam, A. Fares, and A. Alshami, "Real-time sanitary sewer blockage detection system using IoT," *Measurement*, vol. 226, Feb. 2024, Art. no. 114146, doi: 10.1016/j.measurement.2024.114146.
[121] S. Islam, M. Ohee, and S. Sultana, "IoT based stormwater management system," *Advancement Comput. Technol. Appl.*, vol. 5, no. 3, pp. 1–9, 2022.
[122] R. Martínez, N. Vela, A. E. Aatik, E. Murray, P. Roche, and J. M. Navarro, "On the use of an IoT integrated system for water quality monitoring and management in wastewater treatment plants," *Water*, vol. 12, no. 4, p. 1096, Apr. 2020, doi: 10.3390/w12041096.
[123] S. A. Altami and B. Salman, "Implementation of IoT-based sensor systems for smart stormwater management," *J. Pipeline Syst. Eng. Pract.*, vol. 13, no. 3, Aug. 2022, doi: 10.1061/(asce)ps.1949-1204.0000647.
[124] S. P. K. Ramadhin, S. Anand, R. Aishwarya, and Y. R, "Smart drainage and health monitoring system of manual scavenger using IoT," in *Proc. 5th Int. Conf. Intell. Comput. Control Syst. (ICICCS)*, May 2021, pp. 412–416, doi: 10.1109/ICICCS51141.2021.9432211.
[125] R. Girisrinivaas and V. Parthipan, "Drainage overflow monitoring system using IoT (DOMS)," in *Proc. IEEE Int. Conf. Power, Control, Signals Instrum. Eng. (ICPCSI)*, Sep. 2017, pp. 2133–2137, doi: 10.1109/ICPCSI.2017.8392094.
[126] J. Rocher, J. L. Garcia-Navas, O. Romero, and J. Lloret, "A WSN-based monitoring system to control sewerage," in *Proc. 6th Int. Conf. Internet Things, Syst., Manage. Secur.*, M. Alsmirat and Y. Jararweh, Eds., Oct. 2019, pp. 277–282, doi: 10.1109/IOTSMS48152.2019.8939269.
[127] M. Oberascher, C. Kinzel, U. Kastlunger, M. Kleidorfer, C. Zingerle, W. Rauch, and R. Sitzenfrei, "Integrated urban water management with micro storages developed as an IoT-based solution—The smart rain barrel," *Environ. Model. Softw.*, vol. 139, May 2021, Art. no. 105028, doi: 10.1016/j.envsoft.2021.105028.
[128] F. Campagnaro, N. Toffolo, A. Pozzebon, R. Francescon, A. Barausse, L. Airoldi, and M. Zorzi, "A network infrastructure for monitoring coastal environments and study climate changes in marine systems," in *Proc. OCEANS, Hampton Roads*, Oct. 2022, pp. 1–8, doi: 10.1109/OCEANS47191.2022.9977287.
[129] P. Blanco-Gómez, J. Luis Jiménez-García, and J. M. Cecilia, "Low-cost automated GPS, electrical conductivity and temperature sensing device (EC+T track) and Android platform for water quality monitoring campaigns," *HardwareX*, vol. 13, Mar. 2023, Art. no. e00381, doi: 10.1016/j.ohx.2022.e00381.
[130] S. Abbas, A. Ehsan, S. Ahmed, S. A. Khan, T. M. Jadoon, and M. H. Alizai, "ASHRAY: Enhancing water-usage comfort in developing regions using data-driven IoT retrofits," *ACM Trans. Cyber-Phys. Syst.*, vol. 6, no. 2, pp. 1–28, Apr. 2022, doi: 10.1145/3491242.
[131] J. Kabi and C. Maina, "Leveraging IoT and machine learning for improved monitoring of water resources—A case study of the Upper Ewaso Nyiro River," in *Proc. IST-Africa Conf. (IST-Africa)*, May 2021, pp. 1–8.
[132] P. Madhurima, K. Yadav, R. Gupta, and J. S. Jadon, "Real time smart water management system using IoT," in *Proc. Int. Mobile Embedded Technol. Conf.*, Mar. 2022, pp. 563–566, doi: 10.1109/MECON53876.2022.9752141.
[133] B. Ngom, M. Diallo, B. Gueye, and N. Marilleau, "LoRa-based measurement station for water quality monitoring: Case of botanical garden pool," in *Proc. IEEE Sensors Appl. Symp. (SAS)*, Mar. 2019, pp. 1–4, doi: 10.1109/SAS.2019.8705986.
[134] O. Mendoza-Cano, R. Aquino-Santos, J. L.-D. la Cruz, R. M. Edwards, A. Khouakhi, I. Pattison, V. Rangel-Licea, E. Castellanos-Berjan, M. A. Martinez-Preciado, P. Rincón-Avalos, P. Lepper, A. Gutiérrez-Gómez, J. M. Uribe-Ramos, J. Ibarreche, and I. Perez, "Experiments of an IoT-based wireless sensor network for flood monitoring in Colima, Mexico," *J. Hydroinform.*, vol. 23, no. 3, pp. 385–401, May 2021, doi: 10.2166/hydro.2021.126.
[135] M. Kumar, T. Singh, M. K. Maurya, A. Shivhare, A. Raut, and P. K. Singh, "Quality assessment and monitoring of river water using IoT infrastructure," *IEEE Internet Things J.*, vol. 10, no. 12, pp. 10280–10290, Jun. 2023, doi: 10.1109/JIOT.2023.3238123.
[136] E. Syrmos, V. Sidiropoulos, D. Bechtsis, F. Stergiopoulos, E. Aivazidou, D. Vrakas, P. Vezinias, and I. Vlahavas, "An intelligent modular water monitoring IoT system for real-time quantitative and qualitative measurements," *Sustainability*, vol. 15, no. 3, p. 2127, Jan. 2023, doi: 10.3390/su15032127.
[137] J. Salgado, C. Pizarro, L. Wong, and J. Castillo, "IoT watercare: Water quality control system in unofficial settlements of Peru based in an IoT architecture," in *Proc. 31st Conf. Open Innov. Assoc. (FRUCT)*, Apr. 2022, pp. 277–288, doi: 10.23919/FRUCT54823.2022.9770881.

[138] Y. Chen and D. Han, "Water quality monitoring in smart city: A pilot project," *Autom. Construct.*, vol. 89, pp. 307–316, May 2018, doi: 10.1016/j.autcon.2018.02.008.
[139] M. S. Ahmed, E. Y. Al Bloushi, M. A. Al Bloushi, and A. Ali, "Case study for the deployment of private LPWA (low power wide area) network in ADNOC onshore for remote monitoring and operations," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, Oct. 2022, Art. no. D011S013R001, doi: 10.2118/211848-ms.
[140] D. Zhang, X. Han, Q. Zhong, S. Wang, L. Ding, Y. Liu, Q. Chen, and F. Wang, "Online monitoring and sampling analysis of siltation in the middle route of the south-to-north water diversion project," *Frontiers Environ. Sci.*, vol. 10, pp. 1149–1160, Jul. 2022, doi: 10.3389/fenvs.2022.927588.
[141] Y. J. Wong, R. Nakayama, Y. Shimizu, A. Kamiya, S. Shen, I. Z. M. Rashid, and N. M. Nik Sulaiman, "Toward industrial Revolution 4.0: Development, validation, and application of 3D-printed IoT-based water quality monitoring system," *J. Cleaner Prod.*, vol. 324, Nov. 2021, Art. no. 129230, doi: 10.1016/j.jclepro.2021.129230.
[142] A. Malissovas, N. Narayan, T. Boonen, and S. Patki, "A scalable, low-maintenance, smart water quality monitoring system," in *Proc. IEEE Sensors*, Oct. 2022, pp. 1–4, doi: 10.1109/SENSORS52175.2022.9967336.
[143] Y. Al-Khashab, R. Daoud, M. Majeed, and M. Yasen, "Drinking water monitoring in Mosul city using IoT," in *Proc. Int. Conf. Comput. Inf. Sci. Technol. Their Appl. (ICCISTA)*, Mar. 2019, pp. 1–5, doi: 10.1109/ICCISTA.2019.8830662.
[144] S. Pasika and S. T. Gandla, "Smart water quality monitoring system with cost-effective using IoT," *Heliyon*, vol. 6, no. 7, Jul. 2020, Art. no. e04096, doi: 10.1016/j.heliyon.2020.e04096.
[145] G. R. Kumar, D. Kishore, G. V. M. G. Kumar, J. Avila, K. Thenmozhi, R. Amirtharaja, and P. Praveenkumar, "Waste contamination in water—A real-time water quality monitoring system using IoT," in *Proc. Int. Conf. Comput. Commun. Informat. (ICCCI)*, Jan. 2021, pp. 1–4, doi: 10.1109/ICCCI50826.2021.9402704.
[146] N. F. Abdullah, H. A. H. Alobaidy, and R. Nordin, "Wireless airborne IoT network for rural water quality monitoring," in *Proc. IEEE 20th Student Conf. Res. Develop. (SCOReD)*, Nov. 2022, pp. 190–194, doi: 10.1109/SCOReD57082.2022.9974083.
[147] S. P. W. Wu and M. A. Rau, "Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations," *Learn. Instruct.*, vol. 55, pp. 93–104, Jun. 2018, doi: 10.1016/j.learninstruc.2017.09.010.
[148] M. S. Zakaria, R. Nordin, and M. S. Ruslan, "IoT infrastructure for environmental monitoring: A case at tasik chini biosphere reserve," in *Proc. IEEE Conf. E-Learning, E-Management E-Services (IC3e)*, Nov. 2020, pp. 43–48, doi: 10.1109/IC3e50159.2020.9288403.
[149] S. Geetha and S. Gouthami, "Internet of Things enabled real time water quality monitoring system," *Smart Water*, vol. 2, no. 1, p. 1, Dec. 2016, doi: 10.1186/s40713-017-0005-y.
[150] N. Revathi, P. Sengottuvelan, and J. T. Raja, "A survey on modern day trends in water level and quality analysis system," in *Proc. 1st Int. Conf. Adv. Comput. Sci. Eng.*, vol. 1964, K. Loganathan, M. Mohanraj, P. Sakthivel, and M. Sivakumar, Eds., Jul. 2021, Art. no. 042078, doi: 10.1088/1742-6596/1964/4/042078.
[151] K. Shanmugam, M. E. Rana, D. T. Zi Xuen, and S. Aruljodey, "Water quality monitoring system: A smart city application with IoT innovation," in *Proc. 14th Int. Conf. Develop. eSystems Eng. (DeSE)*, Dec. 2021, pp. 571–576, doi: 10.1109/DeSE54285.2021.9719480.

AHMAD ALSHAMI received the bachelor's degree in civil engineering from The University of Jordan and the master's degree in construction and real estate management from The Hong Kong Polytechnic University. He is currently pursuing the Ph.D. degree with Florida State University, majoring in construction management. His main research interests include the integration of computer science and construction management, including intelligent infrastructure monitoring systems, heavy machinery guidance systems, and automation in construction.

ESLAM ALI received the B.Sc. degree in civil engineering from Cairo University, Egypt, the M.Sc. degree in geoinformatics engineering, and the Ph.D. degree from The Hong Kong Polytechnic University. He is currently an Assistant Professor with the Civil Engineering Department, Cairo University. His research interests include localization and mapping, intelligent infrastructure monitoring, asset management, remote sensing applications, geoinformatics, big data, and monitoring natural hazards.

MOUSTAFA ELSAYED received the B.Sc. degree in civil engineering from The University of Jordan and the M.Sc. degree in urban informatics and smart cities from The Hong Kong Polytechnic University. He is currently pursuing the Ph.D. degree with Florida A&M University, specializing in construction management. His primary research interests include sustainable construction practices and smart infrastructure management, including the implementation of smart infrastructure systems, sustainable construction management strategies, and sustainable demolition practices.

ABDELRAHMAN E. E. ELTOUKHY received the B.Sc. degree in production engineering from Helwan University, Egypt, the M.Sc. degree in engineering and management from Politecnico di Torino, Italy, and the Ph.D. degree from The Hong Kong Polytechnic University, Hong Kong. Before joining The Hong Kong Polytechnic University, he was an Assistant Professor with the Systems Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. Later, he moved to the Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, as a Research Assistant Professor. Currently, he is an Assistant Professor with the Management Science and Engineering Department, Khalifa University. His current research interests include airline schedule planning, logistics and supply chain management, operations research, simulation, AI optimization, and robot localization and mapping.

TAREK ZAYED received the B.Sc. and M.Sc. degrees in construction engineering and management and the Ph.D. degree in construction engineering and management from Purdue University, West Lafayette, IN, USA, in May 2001. He is currently a Professor and the Associate Head (Research) of the Department of Building and Real Estate, The Hong Kong Polytechnic University. He is a P.E. and P.Eng. He conducted research on infrastructure/asset management; simulation, fuzzy, optimization, risk assessment, data mining, and artificial intelligence applications in construction; and performance, budget allocation, and life cycle cost analysis for municipal underground systems. He has more than 30 years of professional experience working in the construction industry training and academic posts in USA, Canada, and Hong Kong. He has published around 500 journal and conference papers and performed research with a significant amount of funding from government and private funding agencies. He is a fellow of American Society of Civil Engineers (ASCE) and Canadian Society for Civil Engineering (CSCE). He is ranked in the top 2.0% of scholars in civil engineering worldwide based on a study by Stanford University. He is serving as an Associate Editor for ASCE's *Journal of Pipeline Systems Engineering and Practice* and *Canadian Journal of Civil Engineering*.