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Review

Development of Internet of Things and Artificial Intelligence for intelligent sanitation systems: A literature review

Yirui Jiang*, Trung Hieu Tran, Matt Collins, Leon Williams

Centre for Design Engineering, Cranfield University, Bedfordshire MK43 0AL, UK
*** Corresponding authors:** Yirui Jiang, yirui.jiang@cranfield.ac.uk

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Abstract: Adequate sanitation is crucial for human health and well-being, yet billions worldwide lack access to basic facilities. This comprehensive review examines the emerging field of intelligent sanitation systems, which leverage Internet of Things (IoT) and advanced Artificial Intelligence (AI) technologies to address global sanitation challenges. The existing intelligent sanitation systems and applications is still in their early stages, marked by inconsistencies and gaps. The paper consolidates fragmented research from both academic and industrial perspectives based on PRISMA protocol, exploring the historical development, current state, and future potential of intelligent sanitation solutions. The assessment of existing intelligent sanitation systems focuses on system detection, health monitoring, and AI enhancement. The paper examines how IoT-enabled data collection and AI-driven analytics can optimize sanitation facility performance, predict system failures, detect health risks, and inform decision-making for sanitation improvements. By synthesizing existing research, identifying knowledge gaps, and discussing opportunities and challenges, this review provides valuable insights for practitioners, academics, engineers, policymakers, and other stakeholders. It offers a foundation for understanding how advanced IoT and AI techniques can enhance the efficiency, sustainability, and safety of the sanitation industry.

Keywords: Artificial Intelligence (AI); data-driven solution; health monitoring; intelligent sanitation; Internet of Things (IoT); smart sanitation; smart system; sustainable development

1. Introduction

Facilitating access to safe, clean, and adequate sanitation facilities is crucial in promoting human health and overall well-being for development, but it is still lagging behind schedule (Daudey, 2018; Mara and Evans, 2018). The lack of sanitation facilities is a significant global challenge affecting 3.6 billion individuals, while 1.7 billion people do not have access to basic sanitation services (The World Bank, 2023). This deficiency results in various problems, including malnutrition, stunted growth, and illnesses caused by water-borne and vector-borne diseases, which have been estimated to cause 2.9 million cases of diseases and 95,000 deaths each year (Mara, 2017; Sarkar and Bharat, 2021; World Health Organization, 2022). Sanitation is far more than a matter of convenience or development; it is a fundamental human right recognized globally (Guedes et al., 2024). Its significance for humanity extends well beyond basic hygiene, serving as a cornerstone of public health, social equality, and sustainable development. The current sanitation challenges necessitate the development of advanced technologies and infrastructure. The shortcomings of conventional sanitation systems, including inefficiencies in management, monitoring, labor intensity, and absence of data.

By integrating the Internet of Things (IoT) and advanced Artificial Intelligence (AI) techniques, the shortcomings can be addressed. IoT brings forth a multitude of benefits across various sectors (Liao et al., 2018; Lin et al., 2017). IoT devices can monitor and control machinery, processes, and systems in real-time. This leads to improved efficiency, reduced downtime, and increased productivity. Sensors can collect data on equipment performance, temperature, humidity, energy consumption, and more. The massive amount of data generated by IoT devices can be analyzed to gain valuable insights into operations, consumer behavior, and market trends. This data-driven approach supports better decision-making and innovation. The synergy between AI's cognitive capabilities and IoT's expansive data network lays the foundation for intelligent systems (Adi et al., 2020; Bharadwaj et al., 2021; Cui et al., 2018). By analyzing the continuous stream of data from IoT-connected sensors and devices, AI algorithms can swiftly identify anomalies and accurately predict equipment failures. Through AI, machines learn from historical IoT data, enabling them to evolve their actions and responses based on past outcomes. This results in more intelligent and context-aware automation.

Advanced sanitation systems are equipped with instrumentation, interconnectivity, and intelligence to enable comprehensive monitoring, analysis of status, forecasting of changes, and optimization of troubleshooting. These modern data-driven systems enable real-time data collection and decision making, resulting in improved sanitation facility availability, accessibility, acceptability, and accountability (Ahmed et al., 2017; Kassab et al., 2020; Ray, 2018). Several case studies demonstrate the tangible impact of intelligent sanitation systems in various communities. In Kenya, the implementation of eSOS smart toilets equipped with sensors and data analytics has resulted in hygienic, safe, and affordable sanitation facilities. These smart toilets not only provide improved sanitation services but also collect valuable data to support their operation and facilitate efficient waste management. The eSOS system maximizes the use of smart technologies for faecal and septic sludge treatment, enabling comprehensive monitoring, effective operation, and timely maintenance (Aqua for All, 2024). In Pune, India, a pioneering smart toilet project was implemented by MIT's Civic Data Design Lab in collaboration with the Indian NGO Shelter Associates. The project involved installing sensors in community toilets across the city's slums to collect data on usage frequency, water consumption, and maintenance needs. Initially deployed in 12 community toilets with plans to expand to over 100, the smart toilet system improves the availability and cleanliness of public sanitation facilities, provides urban planners with data-driven insights, and enhances resource allocation efficiency, such as optimizing cleaning staff schedules (Coalition, 2018). Xiaomi's smart toilet for home use demonstrates the potential of IoT in personal sanitation. The toilet seat includes sensors that monitor various health metrics, including urine flow rate, body temperature, and stool consistency. Data is sent to a smartphone app, allowing users to track their health over time (Xiaomi Community, 2024; Yang et al., 2021). These examples underscore the potential of intelligent sanitation to address critical challenges in both developing and developed urban contexts, demonstrating improvements in resource efficiency, public health, and quality of life.

Intelligent sanitation systems can leverage the valuable data generated by sanitation facilities to optimize performance, anticipate system failure, detect potential health risks, support decision-making, and inform sanitation improvements. However, the conventional sanitation industry is unable to fully leverage IoT and its associated data. Intelligent sanitation is still in its early stages, with limited research, sluggish advancement, and fragmented contributions.

To consolidate the fragmented research work, this paper undertakes a thorough review of intelligent sanitation papers from both academic and industrial perspectives. The review explores the historical development, system detection, health monitoring, AI integration, opportunities, and challenges of intelligent sanitation. Existing research studies are examined in detail, knowledge gaps are identified, and the potential of intelligent sanitation is discussed alongside its limitations. Furthermore, this paper examines the state-of-the-art architecture, applications, and services of intelligent sanitation solutions to assess the opportunities and challenges. This paper provides practitioners, academics, engineers, technicians, policymakers, and other stakeholders with insights into how to use advanced IoT and advanced AI techniques to improve the efficiency, sustainability, and safety of the sanitation industry for development. This paper categorizes intelligent sanitation systems driven by IoT and AI into three main areas: system detection, health monitoring, and AI enhancement (**Figure 1**). These categories encompass the key functionalities and applications of modern intelligent sanitation technologies.

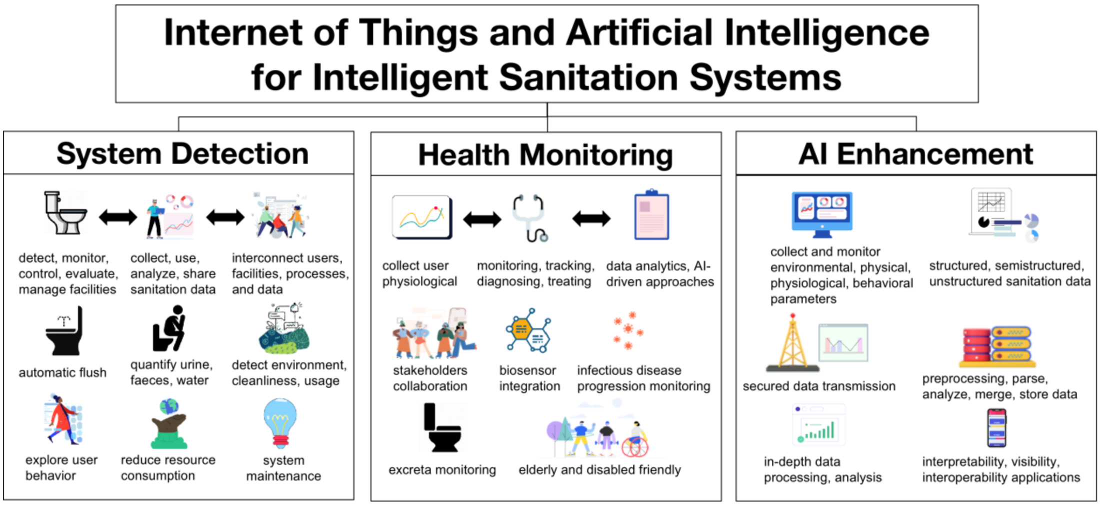


Figure 1. Internet of Things and Artificial Intelligence for intelligent sanitation systems with system detection, health monitoring, and AI enhancement.

In summary, this paper makes the following contributions:

i. Conducting the comprehensive review, summary, and analysis of intelligent sanitation;

ii. Examining state-of-the-art intelligent sanitation solutions for system detection;

iii. Studying the latest intelligent sanitation solutions for health monitoring;

iv. Investigating intelligent sanitation solutions that are AI powered;

v. Exploring advanced IoT and AI techniques to assess the opportunities and challenges associated with intelligent sanitation solutions.

The remainder of the paper is organized as follows: Section 2 outlines the methodology of the literature review and evaluates the findings of the review. Section 3 provides a summary of the techniques, methods, and applications utilised by intelligent sanitation for system detection. Section 4 explores the latest processes, technologies, and systems employed by intelligent sanitation for health monitoring. Section 5 presents various intelligent sanitation solutions empowered by AI to enhance system efficiency and user well-being. Section 6 leverages insights derived from advanced IoT and AI techniques to explore potential opportunities and challenges for intelligent sanitation. The conclusions are presented in Section 7.

2. Review method and results

2.1. Review approaches

The inclusion and exclusion criteria from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines are applied to conduct a thorough literature review (Liberati et al., 2009). The PRISMA flow diagram illustrates the different phases of materials being identified, screened, analyzed, included, and excluded (see **Figure 2**). To identify high-impact intelligent sanitation research findings, the literature review approach is as below:

- Identify relevant databases (ACM, IEEE Xplore, PubMed, and Science Direct) and keywords “sanitation” OR “toilet” AND (“intelligent” OR “smart” OR “IoT” OR “internet of things” OR “sensor”) are used in the search for journals, papers, articles, studies, reports and proceedings from both academic and industrial perspectives. ACM, IEEE Xplore, PubMed, and ScienceDirect were selected because they are highly relevant to our review’s focus on IoT and AI for intelligent sanitation systems, offering specialized and pertinent articles. While Scopus and Web of Science are extensive, the chosen databases better align with the study’s key areas.
- Screen the resulting articles based on inclusion and exclusion criteria (published in English from 2000 to 2022 are included; peer-reviewed literature, grey literature, reputable articles, and authoritative reports are included; textbooks, industrial documentation, schematics, patents and low-quality material are excluded; sanitation related literature that does not incorporate advanced electronic, IoT and advanced AI techniques is excluded).
- The initial review process involves screening the titles and abstracts of literature and eliminating those that do not match the intelligent sanitation topics. The assessment of full-text articles involves considering the type of publication, type of study, and quality of the article.
- Extract data from the included articles and synthesize the findings.
- Analyze and interpret the literature review results.

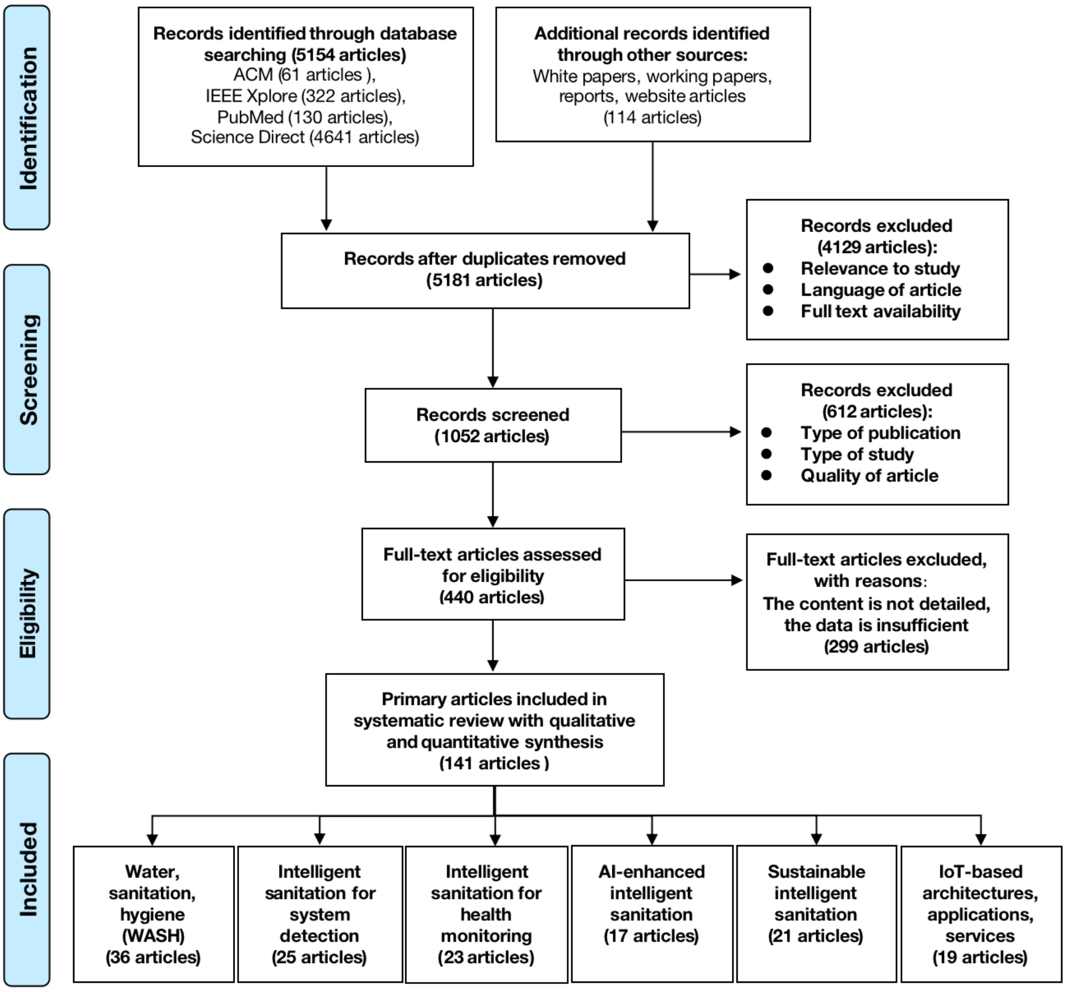


Figure 2. The PRISMA flowchart of the article selection process.

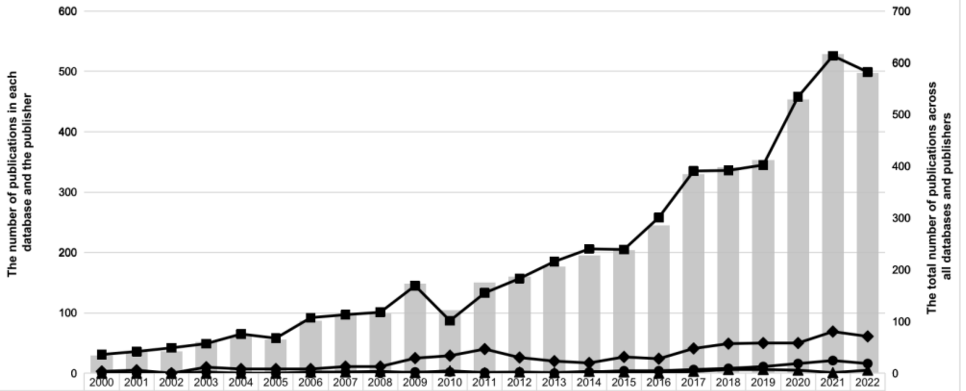
2.2. Information extraction and quality assessment

The relevance of the study, type of publication, availability of full text, quality and language of materials are considered when evaluating literature. High-quality, high-cited journals and articles, reputable reports published by organizations and governments, as well as inspiring and innovative material are included. Unpublished papers, industrial documents, non-peer reviewed material, generic and uninnovative articles, non-English written papers, low-quality and low-citation articles are excluded. In accordance with the PRISMA protocol, the process for including studies in the review was conducted with the input of two authors. In cases where there was a disagreement between the two authors regarding the inclusion of a study, a third reviewer was consulted to make the final decision on whether or not to include the study.

2.3. Review results analysis

To consolidate the fragmented research work, this paper thoroughly reviews more than 141 sanitation and toilet-related papers from 2000 to 2022, selected from an initial pool of 5154 articles retrieved from the ACM, IEEE Xplore, PubMed, and ScienceDirect databases. The intelligent sanitation solutions have been reviewed from system detection, health monitoring, and AI enhancement standpoints. Intelligent sanitation, also known as smart sanitation, intelligent toilets, smart toilets, or electronic toilets, refers to sanitation systems that integrate advanced technologies such as sensors, automation, IoT and AI techniques to enhance efficiency, hygiene, and resource management (Gong et al., 2020). Intelligent sanitation encompasses features such as self-cleaning capabilities, automated system operation, water-saving flushes, and health monitoring. Over the past two decades, there has been a significant increase in the quantity and quality of papers published on intelligent sanitation (see **Figure 3** and **Table 1**). Between 2000 and 2005, sanitation, as a topic, has received relatively little attention, and they do not specifically focus on the area of intelligent sanitation. However, from 2005 to 2015, there was a gradual increase in attention to this field, with a slow and steady rise in the number of relevant publications. Starting from 2005, the field of electronics integrated sanitation systems began to gain traction in databases related to computer science, electrical engineering, and electronics, such as ACM and IEEE Xplore. From 2000 to 2015, there were few studies on intelligent sanitation for health monitoring in life sciences and biomedical-related databases such as PubMed. From 2015 to 2020, there was a notable surge in the number of studies conducted on intelligent sanitation. This increase can be attributed to the development of advanced architecture, applications, and services of IoT and AI techniques, which in turn attracted more researchers to this field of study.

Since 2022, with the evolution of technology such as ubiquitous computing, commodity sensors, embedded systems, wireless networks, and machine learning, intelligent sanitation has gained greater recognition and adoption (Singh and Jayaram, 2022). Advanced AI brings great potential for intelligent sanitation. AI can be used to control and optimize various components of intelligent sanitation systems, including water flow, temperature, and waste management. By analyzing data from sensors and other sources, algorithms can adjust system parameters in real-time, ensuring optimal performance and resource efficiency. Predictive maintenance can predict and prevent equipment failures and maintenance issues, reducing downtime and minimizing repair costs. User behavior analysis can be used to optimize system design, improve user experience, and promote better hygiene and sanitation practices. Health monitoring can help to identify potential outbreaks of infectious diseases and enable early intervention and treatment. While intelligent sanitation is gaining increasing attention, it still remains underdeveloped when compared to other smart industrial applications.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
All databases and publishers	34	41	42	61	72	65	101	112	115	173	122	175	187	206	228	238	286	385	399	412	529	617	581
ACM	0	0	0	0	0	0	2	2	3	1	4	1	2	1	3	2	0	3	6	6	5	1	5
IEEE Xplore	3	5	0	10	7	7	7	11	11	25	29	40	26	20	17	27	24	41	49	50	50	69	61
PubMed	0	0	0	2	0	0	0	2	0	2	2	1	2	0	2	4	4	6	8	11	16	21	16
Science Direct	31	36	42	49	65	58	92	97	101	145	87	133	157	185	206	205	258	335	336	345	458	526	499

Figure 3. Annual publications on intelligent sanitation between 2000 and 2022.

Table 1. Summary of intelligent sanitation literature.

Reference	Sanitation Purposes		Sanitation Services		Sanitation Parameters											Artificial Intelligence
	Pub.	Hou.	Sys.	Hea.	Liq.	Uri.	Fec.	Gre.	Usa.	Env.	ECG.	Urn.	Fae.	Res.	Oth.	
Kim et al. (2006)		✓		✓							✓					
Tanaka et al. (2006)		✓		✓							✓					
Molenbroek and De Bruin (2011)	✓	✓		✓											✓	
Panek et al. (2011)		✓		✓											✓	
Schlebusch (2011)		✓		✓							✓					
Huang et al. (2012)	✓	✓		✓							✓					✓
Amat Azhar et al. (2013)	✓	✓	✓		✓				✓							
Atta (2013)	✓	✓	✓		✓											
Wan Mohammed et al. (2013)	✓		✓		✓				✓	✓						
Taniguchi et al. (2014)	✓	✓		✓											✓	✓
Dutta (2016)	✓		✓		✓											
Kim and Allen (2016)		✓		✓								✓				
Kodali and Ramakrishna (2017)	✓		✓												✓	
Pilissy et al. (2017)	✓	✓	✓												✓	
Zakaria et al. (2017)	✓	✓	✓												✓	
Bae & Lee (2018)		✓		✓								✓				
Boonyakan et al. (2018)	✓	✓	✓		✓				✓							
Namekar and Karthikeyan (2018)	✓		✓							✓						
Ramasamy et al. (2018)	✓		✓						✓	✓						

Table 1. (*Continued*).

Reference	Sanitation Purposes		Sanitation Services		Sanitation Parameters											Artificial Intelligence
Yoon et al. (2018)	✓	✓		✓											✓	✓
Zakaria et al. (2018)	✓		✓		✓	✓	✓	✓								
Balaceanu et al. (2019)	✓	✓	✓	✓											✓	
Cai et al. (2019)	✓		✓		✓				✓							
Mannopantar et al. (2019)		✓		✓											✓	
Mohanty and Mohanty (2019)		✓		✓											✓	
Shaikh et al. (2019)	✓		✓						✓	✓						
Shinganwade et al. (2019)	✓		✓									✓				
Tsuchiyama and Kajiwara (2019)		✓		✓										✓		✓
Wu and Sun (2019)		✓		✓											✓	
Cid et al. (2020)	✓		✓		✓											
Deshmukh et al. (2020))	✓		✓							✓						✓
Liang (2020)		✓	✓		✓				✓							
Park et al. (2020)		✓		✓								✓	✓			✓
Raendran et al. (2020)	✓		✓		✓					✓						
Rary et al. (2020)		✓		✓								✓				
Syafaah et al. (2020)		✓		✓											✓	✓
Turman-Bryant et al. (2020)	✓		✓		✓	✓	✓									✓
Wang et al. (2020)	✓			✓											✓	✓
Cotera Rivera and Bilton (2021)		✓	✓		✓				✓	✓						
Zhang et al. (2021)		✓		✓							✓	✓				✓

Table 1. (*Continued*).

Reference	Sanitation Purposes		Sanitation Services		Sanitation Parameters											Artificial Intelligence
Akaho and Yoshioka (2022)		✓		✓										✓		✓
Bimantara et al. (2022)	✓		✓		✓				✓	✓						
Ganesapillai et al. (2022)	✓	✓	✓													✓
Ge et al. (2022)	✓	✓		✓								✓				
Kumar et al. (2022)		✓	✓		✓				✓							
Lokman et al. (2022)	✓	✓		✓							✓					✓
See-To et al. (2022)	✓		✓												✓	✓
Swathy et al. (2022)		✓		✓											✓	
Tasoglu (2022)		✓		✓											✓	✓
Zhang et al. (2022)		✓	✓		✓											
Zhao et al. (2022)	✓			✓											✓	✓

Where pub. = public sanitation, hou. = household sanitation, sys. = system detection, hea. = health monitoring, liq. = liquid volume in the water tank, uri. = urine volume, fec. = fecal volume, gre. = grey water volume, usa. = usage detection (infrared sensor, motion sensor), env. = environmental monitoring (air quality, cleanliness, user number), ECG. = ECG monitoring, urn. = urine monitoring, fae. = faecal monitoring, res. = respiratory monitoring, oth. = others.

3. Intelligent sanitation for system detection

Intelligent sanitation has the potential to significantly improve system and operation efficiency, safety, and performance. The systems equipped with sensors and software for data collection and exchange. Household intelligent sanitation systems incorporated sensors for automated functions. Atta (2013) used pH sensors for automatic flushing, while Amat Azhar et al. (2013) integrated infrared and float sensors. Boonyakan et al. (2018) designed a microcontroller-based system for cleanliness-based flushing. Intelligent systems can detect anomalies and emergencies (Cid et al., 2020; Zakaria et al., 2018). User behavior analysis enhances system performance, as demonstrated by Cotera Rivera and Bilton's (2021) multi-sensor toilet. Public sanitation facilities benefit from IoT-based monitoring and control. Wan Mohammed et al. (2013) created a sensor-equipped public toilet for automated operations. Dutta (2016) focused on automatic flushing for cleaner public facilities. Karthikeyan and Namekar (2018) developed a sensor-rich public toilet for environmental monitoring. Advanced mobile devices enable user participation in maintaining public sanitation (Shaikh et al., 2019).

Sanitation data is employed to monitor and manage intelligent assets, enabling users to gain a more comprehensive understanding of sanitation facilities (Amat Azhar et al., 2013; Atta, 2013; Boonyakan et al., 2018). Data collected from various sources is used to detect possible issues and inefficiencies in the sanitation system, leading to enhanced system performance and reduced chances of breakdowns (Dutta, 2016; Wan Mohammed et al., 2013). Sensors can detect changes in the sanitation environment and automatically make adjustments to the system, decreasing the necessity for manual labor and boosting system efficiency (Deshmukh et al., 2020; Ramasamy et al., 2018; Shaikh et al., 2019). Intelligent sanitation systems provide cleaners with the most up-to-date toilet cleanliness data via an interactive app, reducing unnecessary over-cleaning and increasing sanitation resource management flexibility. Users can view toilet occupancy rates to reduce queuing and increase usage (Cai et al., 2019; Namekar and Karthikeyan, 2018; Raendran et al., 2020). Intelligent sanitation systems have the capability to notify operators, users, and managers of any possible issues. The system can promptly send alerts to concerned parties, enhancing safety, taking appropriate measures, mitigating accident risks, and addressing issues in a timely manner (Cid et al., 2020; Cotera Rivera and Bilton, 2021; Zakaria et al., 2018). Intelligent sanitation systems can acquire valuable insights into how users interact with facilities, services, and applications. These insights can be leveraged to enhance user experiences and promote user safety. By analyzing user behavior patterns, these systems can identify areas for improvement and make necessary adjustments, resulting in a more optimal user experience (Bimantara et al., 2022; Liang, 2020; Lokman and Ramasamy, 2019; Turman-Bryant et al., 2020; Zhang et al., 2022).

4. Intelligent sanitation for health monitoring

Intelligent sanitation for continuous health monitoring detects disease at an earlier stage, greatly benefiting public health. By connecting sanitation facilities to the internet, doctors and patients can track vital signs, monitor treatments, and receive remote medical advice (Huang et al., 2012; Tasoglu, 2022; Tanaka et al., 2006).

Tanaka et al. (2006) developed a toilet for continuous blood pressure monitoring. Huang et al. (2012) created an intelligent toilet that detects unconscious biosignals, including ECG for cardiac performance, bio-impedance for body composition analysis, and pressure sensors for weight measurement. These advancements enable timely treatment, accurate decisions, and comprehensive health insights, especially beneficial for the elderly.

Human excreta, such as urine and faeces, contain a wealth of information and are produced in large quantities on a daily basis, but it is not used, monitored, or analysed. Early intelligent toilets only measured the colour of the urine and required the user to manually sample, resulting in a poor user experience (Temirel et al., 2021). With advanced IoT technologies, the latest intelligent toilets are now fully automated and capable of measuring dozens of health parameters, such as white blood cells, red blood cells, glucose, and bilirubin (Oyaert and Delanghe, 2019). Kim and Allen (2016) developed a low-cost urine glucose analysis toilet. Bae and Lee (2018) created a system separating urine for health analysis and faeces for biofertilizer. Intelligent sanitation enables remote monitoring for chronic patients, reducing healthcare costs. Park et al. (2020) proposed a toilet for non-invasive, continuous health monitoring through excreta measurement.

Cloud platforms, machine learning, and computer vision are integrated with intelligent toilets to provide comprehensive insights into user health (Park et al., 2020). Given that toilet use is an inherently intimate activity, the development of intelligent toilets must take into account user expectations, acceptance, and privacy concerns (Sulmasy et al., 2017). Some privacy protection methods are used to prevent personal health data from being leaked, and user information is only shared with authorized stakeholders (Bettiga et al., 2020). Future advanced intelligent toilets will incorporate security protocols, access control mechanisms, regulatory protection, encryption algorithms, and blockchain technologies to securely manage health data (Esposito et al., 2018; Maher et al., 2019; Schönberger, 2019; Wang et al., 2019; Xiao et al., 2012).

Personal diagnosis and community health monitoring are improved by intelligent sanitation facilities (Rary et al., 2020). During COVID-19, the Coronavirus: Integrated Diagnostic (COV-ID) toilet is proposed to replace traditional nasopharyngeal swab-based flow testing for SARS-COV-2 detection (Ge et al., 2022). The intelligent toilet is suitable for both public and private restrooms (Kumar et al., 2022). The intelligent sanitation has given the elderly and disabled unprecedented freedom and independence. The elderly and disabled have easier and more convenient access to sanitation facilities and services than ever before (Molenbroek et al., 2011; Mohanty and Mohanty, 2019; Panek et al., 2011; Pilissy et al., 2017; Swathy et al., 2022; Yoon et al., 2018). Furthermore, the intelligent sanitation systems can be linked to home security systems, allowing the elderly and disabled to live safely and securely even when living alone (Akaho and Yoshioka, 2022; Balaceanu et al., 2019; Taniguchi et al., 2014; Tsuchiyama and Kajiwara, 2019). The EU's 'Friendly Rest Room' project aims to enhance autonomy and safety for elderly and disabled users. Molenbroek and De Bruin (2011) explored cross-disciplinary technologies for efficient, user-friendly facilities. Taniguchi et al. (2014) developed a camera-based system to detect falls and monitor elderly users' proximity to danger zones. The majority of existing studies on intelligent sanitation for health monitoring are randomized and small-scale, have not been developed, deployed, or tested in the field, and are still in the conceptual stage. The incorporation of biosensors into sanitation facilities is a novel topic that has the potential to improve global health systems.

5. Intelligent sanitation with Artificial Intelligence

AI-enhanced intelligent sanitation can lead to improved decision making, automated actions, predictive maintenance, and better customer experience. Algorithms can identify patterns in data, detect correlations, and predict system performance (See-To et al., 2022; Turman-Bryant et al., 2020). The IoT, data analytics and machine learning are powerful tools that can be used in tandem to interpret, learn, analyse, and predict the sanitation environment. Sensors detect environmental changes and measure physical properties such as temperature, odour, and cleanliness. Machine learning is used to forecast the future sanitation environment by analysing historical data (Deshmukh et al., 2020). Computer vision is becoming increasingly important in health analysis. Excrement image analysis detects abnormalities in urine and faeces faster than traditional manual analysis, allowing for more timely and effective treatment (Park et al., 2020; Syafaah et al., 2020; Wang and Camilleri, 2020). It is critical to ensure that sanitation data is properly secured and that privacy is maintained. Data encryption, authentication, anonymization, and pseudonymization are essential to prevent unauthorised parties from accessing the health data (Ganesapillai et al., 2022; Zhang et al., 2021).

AI-enhanced solutions can be used to monitor sanitation system performance in real-time and identify any potential issues or component failures. Intelligent systems can analyze large volumes of data generated by the sanitation facilities and provide alerts or notifications when any anomalies are detected. Turman-Bryant et al. (2020) used machine learning algorithms to predict tank overflow risk and optimize waste collection in intelligent toilets. The Lasso regression, multivariate adaptive regression, and random forests algorithms are used to develop predictive models. Using machine learning, the toilets were able to balance waste collection efficiency and the frequency of overflow events. Intelligent sanitation provides environmental sensing to improve visibility, reduce costs and manage operations. Deshmukh et al. (2020) proposed an intelligent sanitation solution to monitor the cleanliness of public toilets. The system involves the installation of odor and air sensors, and an autoregressive integrated moving average (ARIMA) model is utilised to analyze historical time series data, enabling the prediction of future trends in the surrounding environment. See-To et al. (2022) deployed a range of sensing technologies, including environmental, odor, and light sensors, electrical operation meters, and water capacity meters, on public sanitation facilities. To predict the operational status, the systems employed a convolutional bidirectional long short-term memory model. This model analyses time-series data from the various sensors, enabling the accurate prediction of future trends and facilitating more efficient management of public sanitation facilities.

The combination of AI and intelligent sanitation solutions has the potential to bring about significant improvements to the overall health and wellbeing of individuals and communities. Computer vision algorithms can be used to analyze the color and shape of excrement for the purpose of detecting health status. This approach is still in the early stages of development and further research is needed to determine its effectiveness and feasibility as a diagnostic tool. Syafaah et al. (2020) installed a camera as a color sensor in a toilet to collect images of urine samples and a Raspberry Pi as the main control unit. The camera captures images to generate a red-green-blue (RGB) color model. This RGB model is then analyzed and clustered using the K-means algorithm, which enabled the classification of the urine as either diabetic or normal. This approach shows promise as a potential non-invasive and cost-effective diagnostic tool for diabetes, although further research is needed to validate its accuracy and reliability. Park et al. (2020) utilised computer vision techniques to measure urine flow by analyzing camera-captured urine depth information and constructing a 3D model of the urine stream using geometric averages. In addition, they used a convolutional neural network (CNN) to classify feces images as constipated, normal, or diarrheal, achieving an average accuracy of 64.28%. These approaches have potential applications in the diagnosis and monitoring of various urinary and bowel disorders.

Intelligent sanitation has the potential to revolutionize the way of health monitoring by providing real-time data on individual bodily functions. This approach has several advantages, including non-invasiveness, ease of use, and low cost. While intelligent sanitation systems have great potential for health care, they also pose significant challenges in terms of data privacy and security. Storage and protection of sensitive data collected by sensors and actuators are main challenges. As this data is typically stored on different system components, the security configuration of these assets may be weak and vulnerable to attack. Attackers may attempt to steal historical system operational data and patient physiology data, potentially compromising the privacy of health information. Furthermore, transferring healthcare data from physical devices to remote servers with lax security measures can raise the risk of data leakage. This is particularly concerning as health data is highly sensitive and should be protected against unauthorized access or disclosure. To address these challenges, it is essential to implement robust data security and privacy protection measures, such as encryption, access controls, and secure data storage. Additionally, it is crucial to comply with relevant data protection regulations and standards, such as the General Data Protection Regulation (GDPR). Zhang et al. (2021) proposed an intelligent toilet that addresses privacy concerns by identifying the user using frictional electrical sensors instead of traditional camera or RFID technology. The system transmits urine and feces analysis results to a cloud system, which are then displayed on mobile devices in a secure manner. By implementing robust data security and privacy protection measures, researchers and healthcare professionals can leverage intelligent sanitation systems to gain valuable insights into health status while ensuring the protection of sensitive health information.

6. Discussion

Intelligent sanitation systems collect, store, exchange, and act on sanitation data, allowing for unprecedented automation and optimization. The IoT and advanced AI techniques provide users with accessibility, functionality and analyzability for sanitation facilities. Intelligent sanitation systems bring numerous opportunities in smart assets, data storage, data processing, data analysis, and intelligent service (Li et al., 2018; Pal, 2022; Srivastava et al., 2020). They also present several challenges, such as coverage and communication, compatibility and interoperability, privacy and security, scalability and deployment (Alwarafy et al., 2020; Koohang et al., 2022; Kouicem et al., 2018; Ogonji et al., 2018; Othman et al., 2022; Yang et al., 2020). This section provides a comprehensive analysis of intelligent sanitation systems, evaluating their current strengths and weaknesses while exploring future opportunities and challenges. By examining both present capabilities and potential developments, we offer a balanced perspective on the evolving landscape of smart sanitation technologies.

6.1. Strengths and weaknesses of current intelligent sanitation systems

Strengths: Intelligent sanitation systems represent a significant leap forward in resource management and public health. These systems leverage real-time monitoring and automated control to optimize the usage of critical resources, particularly water and energy. This optimization not only reduces waste but also substantially lowers operational costs, making sanitation more sustainable and economically viable. By facilitating timely cleaning and maintenance, intelligent sanitation systems play a crucial role in public health management. They can detect potential health hazards early, enabling swift interventions that prevent the spread of diseases. This capability is particularly valuable in urban environments, where the rapid identification of pathogens or disease markers can lead to more effective and targeted public health measures. Moreover, the wealth of data collected by these systems serves as a powerful tool for urban planners and policymakers. It provides invaluable insights that inform decision-making processes in various areas, from resource allocation to public health policy formulation. This data-driven approach ensures that urban development and public health initiatives are more responsive to actual needs and challenges.

Weaknesses: The implementation of these intelligent sanitation systems comes with substantial financial implications. The integration of intelligent sanitation infrastructure, especially in public spaces, often requires significant upfront investments. These costs encompass not only the installation of new technology but also its integration with existing infrastructure, which can be particularly challenging in older urban environments. Moreover, the reliance on technology introduces new vulnerabilities to the sanitation sector. Intelligent systems depend on a constant power supply, which can be problematic in areas with unreliable electricity infrastructure. This dependence not only limits the geographical applicability of these systems but also raises concerns about service continuity during power outages. The maintenance of intelligent sanitation systems presents another set of challenges. These advanced systems often require specialized expertise for repairs and upkeep, which can lead to longer downtimes compared to traditional sanitation facilities. This complexity not only increases operational costs but also demands a workforce with new skill sets, potentially creating challenges in areas lacking such specialized technical knowledge.

The increased complexity of intelligent sanitation systems makes them potential targets for cyber-attacks, which could disrupt essential sanitation services and compromise user data. The collection of personal health data and usage patterns, while valuable for health monitoring and system optimization, raises critical questions about data security and user anonymity. Ensuring the protection of this sensitive information remains a formidable challenge, particularly in an era of increasing cyber threats. There are also significant social and ethical considerations. The advanced nature of intelligent sanitation systems may inadvertently widen the digital divide, potentially excluding populations without access to or familiarity with smart devices. This technological barrier could exacerbate existing inequalities, particularly in less developed regions or among older populations. The use of AI in health monitoring and decision-making within these systems raises profound ethical questions. Issues of personal autonomy, informed consent, and the potential for algorithmic bias must be carefully considered. As these systems become more prevalent, society must grapple with the balance between technological advancement and individual rights, ensuring that the benefits of intelligent sanitation are realized without compromising fundamental ethical principles.

6.2. Opportunities for future intelligent sanitation systems

Smart assets: Smart sanitation assets play a critical role in the development of intelligent sanitation systems. Smart assets are equipped with sensors that can sense, measure, detect, and monitor a range of variables, including operational and mode information, temperature, pressure, speed, vital signs, and user behavior. Embedded sensors are becoming more affordable, smaller, more accurate, and more efficient, making it possible to deploy intelligent sanitation facilities on a larger scale.

With advanced network communications, low bandwidth costs, and stable data transmission, smart assets are becoming more connected, facilitating the seamless sharing of data. Smartphones are also becoming more widely available, improving the interaction between humans and machines. Sensors monitor systems, users, and environments, enabling informed decisions and better resource utilisation such as industrial automation, energy efficiency, water management, and waste management.

AI-enabled smart assets can analyze collected data to identify patterns, predict future events, identify potential issues, and develop efficient solutions. Additionally, smart assets are continuously improving hardware to support a wide range of innovative sanitation solutions. Smart sanitation assets are essential in the development of intelligent sanitation systems that promote sustainable and efficient resource utilisation while improving the quality of user life.

Data pre-processing: Sanitation data often comes from multiple sources and is in different formats, making it challenging to extract, transform, and load into a data storage destination. Data pre-processing is essential to ensure the accuracy and consistency of sanitation data, which allows stakeholders to analyze the data, identify trends, and provide users with timely and efficient information (Sreemathy et al., 2021).

Sanitation smart assets collect a large amount of data, which frequently contains low-quality data. This necessitates data quality management to ensure that the data is of sufficient quality to derive meaningful insights. The quality of the data directly influences the quality of the insights obtained from data analysis. Data cleaning is a critical step in data quality management, as it can identify the data source, verify data accuracy and security, and remove inaccurate, incomplete, and irrelevant data.

Manual data cleaning can be less efficient and requires extensive knowledge of the data context. Automated tools, such as data wrangling software or batch processing via scripting, can quickly identify and eliminate errors and inconsistencies. Data cleaning involves replacing, modifying, and deleting dirty or coarse data, as well as organizing data into meaningful formats. This improves the accuracy and reliability of data analysis and ensures that the insights derived from the data are accurate and actionable (Chu et al., 2016; Hajjaji et al., 2021; Majeed et al., 2021).

Data storage: Advanced technologies are shaping data storage trends. Edge computing stores sanitation data at the edge of the network, closer to the source of data generation, reducing latency, accelerating data processing, and enabling smart assets to make faster decisions. Edge computing does not send data over the Internet, which reduces the risk of data leakage and provides more control and security for data management (Chang et al., 2021; Shi et al., 2016; Yu et al., 2017).

Distributed storage stores sanitation data across a network of multiple locations to provide data availability, reliability, and scalability. Sanitation data is stored redundantly across multiple nodes in a network of interconnected devices, so that if one node fails, the others can still access it normally (Tajeddine et al., 2018).

Cloud storage is a secure and reliable way to remotely store, access, back up, and manage sanitation data over the internet. Cloud storage solutions reduce the cost of data management by eliminating the need for expensive storage equipment and instead relying on secure and cost-effective products developed by cloud providers (Ren et al., 2021; Yang et al., 2020).

Flash storage devices are a popular choice for data storage due to their small size, fast speeds, and low power consumption (Raza et al., 2016). Blockchain enables users and stakeholders to verify data integrity by providing a secure, tamper-proof method of storing and managing data (Novo, 2018; Reyna et al., 2018; Wang et al., 2020). End-to-end encryption protocols and strong authentication methods are deployed to protect data. AI is used to automate repetitive tasks to analyse and interpret data more quickly. Machine learning storage solutions offer improved data compression, deduplication, and real-time analytics capabilities (Adi et al., 2020; Al-Turjman et al., 2022; Hua et al., 2022; Hussain et al., 2020).

Data analytics: Sophisticated techniques, technologies, and computational models are employed to extract insights, identify patterns and associations, and make informed decisions from sanitation data. To examine massive and rapidly evolving sanitation data, a range of statistical methods and machine learning algorithms such as clustering analysis, cohort analysis, regression analysis, neural networks, factor analysis, data mining, text analysis, time series analysis, decision trees, and conjoint analysis are frequently utilised (LaValle et al., 2011; Li et al., 2021; Tsai et al., 2015).

The use of AI and machine learning will be the primary focus for data analytics in the future. These technologies will automate analysis and decision-making, as well as uncover patterns that may not be detectable by humans. Predictive analytics will forecast future trends and behaviours based on historical sanitation data, while sanitation equipment will predict failures by utilizing previous performance to avoid damage. AI will also identify patterns and trends in sanitation facility operations to automate equipment calibration and maintenance, reducing time, labour, and expenses related to sanitation network management (Ghosh et al., 2018). By combining data security and analytics, the risk of data breaches and cyber attacks is reduced. Data encryption, authentication protocols, and access controls ensure that data remains secure and is only accessible to authorized users (Mohanta et al., 2020).

Intelligent service: The intelligent sanitation enables a wide variety of applications and services, such as remote monitoring and control, interactive visualisation, predictive maintenance, optimised resource usage, and improved healthcare. Remote monitoring and control enable users to monitor and manage sanitation systems from a distance, increasing efficiency and reducing maintenance costs. Interactive visualisation tools provide real-time insights into sanitation data, helping users to understand the system performance and identify areas for improvement. Predictive maintenance uses artificial intelligence algorithms to forecast equipment failures based on historical data, allowing users to take preventive measures before any issues occur. Predictive maintenance can reduce the risk of facility failure, save time and cost, and increase user satisfaction (Dalzochio et al., 2020). Optimised resource usage ensures that sanitation facilities operate at maximum efficiency, reducing water and energy usage and lowering operational costs. Intelligent sanitation can also improve public health by monitoring and controlling infectious diseases, detecting and responding to outbreaks, and ensuring the cleanliness of public spaces. Intelligent sanitation can provide more efficient, effective and patient-centred healthcare solutions. It tracks vital signs, monitors health status and alerts to potential illnesses. Historical medical data is securely stored and shared, allowing medical personnel to diagnose and treat patients quickly and accurately. The smart asset in intelligent sanitation systems can be accessed, managed, and monitored remotely, and the sensors and actuators installed in the system have real-time automatic control and adjustment capabilities. This allows for efficient and effective management of sanitation systems, reducing the need for manual intervention and improving overall system performance.

6.3. Challenges for future intelligent sanitation systems

Coverage and communication: The physical coverage and network communication limitations of sanitation networks can be a challenge for the deployment of intelligent sanitation systems. Sanitation facilities are often spread across large areas and located in complex environments, such as urban areas with high-rise buildings and underground infrastructure, which can hinder the deployment and operation of network access points, sensors, and other equipment. In addition, the terrain, weather conditions, and other factors can also affect the performance and reliability of the communication networks used to connect the various components of the system.

As the number of interconnected smart assets increases, establishing reliable, low-latency connectivity between them can become a significant challenge. Collecting and transforming large amounts of data between smart assets can also give rise to several issues. The data may need to be standardized, cleaned, and preprocessed before it can be analyzed effectively. In addition, data privacy and security concerns may arise due to the large amount of sensitive information being transmitted between devices.

Some sanitation facilities are deployed in locations with poor signal, small spaces blocked by walls and obstructions, resulting in poor data transmission performance. Existing wireless technologies are prone to interference and signal degradation, making it impossible to send and receive data consistently. The reliability of wireless communication can be affected by many factors such as signal interference, attenuation, and obstacles. In areas with poor signal strength, the transmission of data between smart assets can be particularly challenging. Walls, buildings, and other obstructions can block or weaken wireless signals, which can lead to inconsistent or slow data transmission.

Compatibility and interoperability: The lack of standardisation in the sanitation sector poses a significant challenge for intelligent sanitation. Different manufacturers may use different protocols, data formats, communication speeds, and operating systems, making it difficult to share data and communicate between smart sanitation facilities. This lack of interoperability can lead to data loss, misplacement, and incorrect transmission. To address this challenge, industry-wide standards and protocols need to be developed to ensure seamless communication and data sharing between sanitation solutions.

To ensure seamless communication between different types of smart assets and systems, it is essential to establish a unified architecture that utilises common languages, protocols, and open source standards. This can help ensure compatibility between different devices, platforms, and technologies and enable easy exchange of information. Without such integration, communication gaps, interoperability issues, and difficulty exchanging information can arise, which can hinder the effectiveness of intelligent sanitation solutions.

Researchers develop standard protocols such as MQTT, CoAP, and AMQP to enable stable and reliable communication between different smart assets. System designers develop common open architectures to allow for seamless data exchange between various devices and services. Cloud-based solutions like Amazon Web Services (AWS) and Microsoft Azure enable cross-platform device connectivity and facilitate data transfer.

Privacy and security: The implementation of advanced intelligent sanitation solutions raises concerns regarding privacy and security. To protect sanitation networks from damage and prevent data leaks and cyber-attacks, it is essential to establish robust security protocols and methods to ensure the confidentiality, integrity, and availability of sanitation data. This includes measures such as access control, encryption, authentication, and regular security audits to identify vulnerabilities and potential threats.

The establishment of secure connections between smart assets and the protection of sanitation data from unauthorized access is critical in sensitive information. This involves implementing robust security measures to prevent both external and internal threats such as security breaches, malicious attacks, privacy breaches, and weak authentication protocols. Measures such as encryption, firewalls, intrusion detection and prevention systems, and secure authentication protocols can help mitigate these risks. Regular security audits and vulnerability assessments can also help identify and address potential weaknesses in the system.

Robust data protection and attack prevention measures are crucial for the effective implementation of advanced intelligent sanitation solutions. This includes the development and implementation of security policies and laws, privacy-enhancing technologies, tools, and standards, secure network connections, and controllable private information sharing. Additionally, the development of privacy policies and guidelines can help ensure that personal information is collected, used, and stored in compliance with legal and ethical standards. Moreover, ensuring the security and privacy of user data should be a top priority, and the development of transparent and understandable privacy policies and guidelines can help build trust among users. By adopting a comprehensive approach to security and privacy, stakeholders can ensure that advanced intelligent sanitation solutions deliver their intended benefits without compromising user trust and system security.

Scalability and deployment: The evolution of intelligent sanitation has resulted in the integration of more facilities, devices, data, and users, which poses a challenge in scaling up the system effectively. As the system grows, it becomes more complex, and there is an increased need for coordination among different stakeholders, including government agencies, utilities, and private companies. Scaling up the system requires careful planning and coordination to ensure that the necessary infrastructure is in place to support increased data collection, processing, and storage. This may require upgrading or replacing existing infrastructure, implementing new technologies, and developing new policies and guidelines. Additionally, stakeholders must address issues related to data ownership, sharing, and management to ensure that the system operates smoothly and efficiently.

The successful scaling of intelligent sanitation systems requires a comprehensive and collaborative approach that addresses issues related to interoperability, data quality, and network scalability. Interoperability is a key requirement for scaling up intelligent sanitation systems. As the number of facilities, devices, and data sources increases, it becomes increasingly important for these systems to communicate and exchange data accurately. This requires the development of standard protocols, interfaces, and data formats that allow different components of the system to interoperate seamlessly. Moreover, as the volume of data packets increases, scalable solutions must be able to avoid network congestion while maintaining a good user experience. By adopting best practices and leveraging innovative technologies, stakeholders can ensure that the system operates efficiently, effectively, and sustainably, while delivering meaningful benefits to users and the environment.

7. Conclusion and future work

This paper presents an extensive review of the literature on intelligent sanitation solutions, with a particular focus on system detection, health monitoring, and AI enhancement. Using PRISMA methods, this paper critically evaluated the strengths and weaknesses of the intelligent sanitation systems. This paper provides a comprehensive review of over 141 studies related to intelligent sanitation systems, spanning the years 2000 to 2022. These studies were carefully selected from an initial pool of 5154 articles sourced from ACM, IEEE Xplore, PubMed, and ScienceDirect databases. The review addresses intelligent sanitation solutions through various perspectives, including system detection, health monitoring, and the integration of artificial intelligence. This consolidation of research offers valuable insights into the advancements and current trends in the field of intelligent sanitation. This paper provided a detailed discussion of the service, technology, device, and application of various intelligent sanitation systems. The technical components of the systems, including sensors, communication protocols, and data processing techniques are investigated, to assess their efficiency and effectiveness. The findings of this review can guide policymakers, practitioners, and researchers in designing, implementing, and evaluating intelligent sanitation systems that can promote sustainable and equitable sanitation practices.

The use of advanced AI techniques in IoT-based sanitation applications offers numerous benefits, including optimizing resource allocation, analysing real-time sensor data, developing predictive maintenance models, assessing and mitigating risks, integrating into decision support systems, and forecasting demand for sanitation services. These techniques enhance efficiency, cost-effectiveness, and resilience in sanitation systems, benefiting both individuals and communities.

The implementation of intelligent sanitation solutions with the IoT and advanced AI techniques has the potential to revolutionize the way humans interact with sanitation facilities. By employing smart assets that can monitor and detect systems and their surroundings, data analysis can be used to make better decisions, automate processes, and increase operational efficiency. Furthermore, integrating biosensors, analyzing excreta, and continuous infectious disease monitoring can significantly benefit public healthcare, improve quality of life, and increase patient engagement. AI can further enhance the automation process, decrease manual workload, increase resource utilization, improve personalized user experience, and reduce potential risks. Intelligent sanitation solutions also enable the sanitation industry to monitor and track resources more effectively, leading to responsible and sustainable resource utilization, waste reduction, and alignment with SDGs.

The paper explores various opportunities in the field of intelligent sanitation, including smart assets, data storage, data processing, data analysis, and intelligent services. Smart assets such as sensors and IoT devices can be utilized to monitor and detect sanitation systems and their surroundings. Data storage, processing, analytics capabilities can help to manage and analyze the large amounts of data generated by these systems, allowing for better decision-making and operational efficiency. Intelligent services can be developed to provide real-time system performance and personalized experiences for users, as well as optimize resource utilization and waste reduction.

There are several challenges that need to be addressed for successful implementation of intelligent sanitation solutions. These challenges include coverage and communication issues, compatibility and interoperability of different systems, ensuring privacy and security of sensitive data, and scalability and deployment of these solutions. Addressing these challenges will require collaboration between various stakeholders, including industry experts, policymakers, and technology developers.

Further research and development are necessary to address these challenges and unlock the full potential of intelligent sanitation.

Future research directions for intelligent sanitation systems should encompass technological, social, and ethical aspects. On the technological front, efforts should focus on developing more accurate, durable, and cost-effective sensors to improve the precision of data collection and enhance overall system performance, particularly in challenging environments. Simultaneously, exploring novel encryption methods and privacy-preserving technologies is crucial to ensure the security of user data without compromising system functionality. Social research should delve into user acceptance of intelligent sanitation systems and their impact on user behavior and hygiene habits, which is essential for effective implementation and improved public health outcomes. Furthermore, future work should explore how to integrate intelligent sanitation systems with other smart city technologies and health monitoring systems, leading to more comprehensive urban health and sanitation solutions. Developing adaptive designs for intelligent sanitation systems that can effectively operate in diverse cultural, economic, and geographical environments is another important area for investigation, ensuring broader applicability and impact of these technologies. The formulation of comprehensive ethical guidelines and policy frameworks to guide the development and deployment of intelligent sanitation systems is crucial, ensuring fairness, transparency, and responsible innovation in the field.

This paper offered valuable insights for practitioners, academics, engineers, technicians, policymakers, and other stakeholders on how to leverage the IoT and advanced AI techniques to enhance the efficiency, sustainability, and safety of the sanitation industry. The comprehensive review of intelligent sanitation solutions and the identification of knowledge gaps, opportunities, and challenges provide a solid foundation for future research and development in this field. By highlighting the benefits of integrating intelligent sanitation solutions, this paper can guide decision-making and strategy development in the sanitation industry, leading to better system performance, waste reduction, and improved public health outcomes.

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Development of Internet of Things and Artificial Intelligence for intelligent sanitation systems: a literature review

Jiang, Yirui

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