INTEGRATION OF INDUSTRY 4.0 TECHNOLOGIES IN ENVIRONMENTAL SANITATION: A SYSTEMATIC REVIEW

Adrielle Fidelis Gonçalves [1]*; Bruno Sousa Lima[1]; Leonardo Rabello Benevides Cardoso[1]; Moises Ferreira Eleuterio Silva2; Luara Batalha-Vieira2; Mariana da Penha Novaes2

1 Civil Engineering student; SENAI CIMATEC University Center. adrielle.goncalves@aln.senaicimatec.edu.br*
1 Civil Engineering student; SENAI CIMATEC University Center;
1 Civil Engineering student; SENAI CIMATEC University Center
2 Department of Civil Construction/ SENAI CIMATEC University - 1845 Orlando Gomes Avenue, Piatã, 41650-010, Salvador, BA, Brazil

Abstract: Environmental sanitation faces challenges arising from uncontrolled urban growth, increased pollution, inadequate monitoring methods, increased demand for clean water, insufficient sewage treatment capacity, and lack of maintenance on aging systems. Industry 4.0, through technological innovations such as the Internet of Things (IoT), microcontrollers, and sensors, seeks to solve problems related to sewage management, given the increased demand for water resources and the poor performance of existing treatment plants. Therefore, this study aims to explore the scientific literature on the application of Industry 4.0 principles in the context of sanitation, with a specific focus on optimizing sewage network monitoring through IoT and technologies aimed at automation and process improvement. To this end, a string search strategy was adopted to select articles related to the topic. Initially, a set of approximately seventy articles was analyzed based on keywords, of which thirty-seven presented contents aligned with the proposed application of Industry 4.0 in environmental sanitation. After detailed analysis, ten articles were selected as the basis for this study. Thus, the article seeks to propose solutions, using emerging technologies, to address the shortcomings still present in the urban sanitation sector. Through this, it aims to reduce damage to infrastructure and public health, optimize operational costs, improve the efficiency of treatment plants, and enhance water infrastructure management with artificial intelligence.
Keywords: Industry 4.0; Environmental Sanitation; Internet of Things (IoT); Sewage Network Monitoring; Process Automation.

1. INTRODUCTION

Water is an extremely important resource for life and socioeconomic development, serving as a source for irrigation, industry, and human and animal consumption [1]. However, population growth and increasing demand raise concerns about limited resources and water scarcity [2]. Among the Sustainable Development Goals (SDGs), SDG 6 advocates for universal access to water and sanitation, with targets to manage water resources, improve water quality, and reduce untreated water.

According to Chavhan et al. [1] and Alprol et al. [3], several basins face water shortages due to pollution, intensified by agricultural expansion, industrialization, and rampant urbanization. According to the World Health Organization (WHO) in 2021, globally, 269 billion m³ of sewage are generated per year and only 53% are correctly treated [2]. Thus, 47% of the effluents do not undergo adequate treatment when released into the environment.

This contamination impacts public health, agriculture, ecosystems, and socioeconomic aspects [1].

Environmental sanitation is essential for public health, water resource preservation, and ecosystem balance. However, traditional water and wastewater management methods, based on conventional processes, are proving insufficient in the face of population growth, rapid

urbanization, and climate change [6]. In this scenario, integrating Industry 4.0 with environmental sanitation emerges as an alternative to making the sector more efficient, resilient, and sustainable.

Industry 4.0, with technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, blockchain, and advanced manufacturing, is redefining management practices, including sewage treatment and monitoring. An example of this application is the use of IoT-based effluent monitoring systems and sensors, where real-time data tracking provides significant improvements in the management and performance of treatment plants, reducing losses and making the process safer and more efficient.

The implementation of sensors and predictive modeling based on data analysis enable a more precise and adaptive approach to water quality control and treatment plant operations, enabling rapid action to mitigate environmental damage and reduce operating costs.

Thus, this paper considers that the Fourth Industrial Revolution, associated with sanitation, is likely to transform the sector through new technologies, contributing to achieving SDG 6 by expanding access to safe water, reducing water pollution, and increasing the effectiveness of treatment systems [2]. In this context, an analysis was carried out on how Industry 4.0 can optimize sewage network monitoring and effluent treatment. To this end, we conducted a systematic literature review, gathering approximately ten studies that exemplify real-world applications of Fourth Industrial Revolution technologies in the sector, mapping the sensors and digital platforms used

2. METHODOLOGY

This study is characterized as qualitative research, with a descriptive approach, with the main objective of analyzing and synthesizing advances in the application of Industry 4.0 technologies in environmental sanitation.

This research began with the adoption of the scientific String search strategy for articles to be analyzed. The String search strategy was used in the Scopus database, combining keywords to identify recent and relevant articles on Industry 4.0 in sanitation. Table 1 presents the keyword combinations used, and the number of articles found.

Table 1 - Combination of keywords for article selection.

Keyword combinations	Number of articles
Sewer AND system AND control	3
Remote sensing in wastewater systems	5
Predictive analytics in wastewater networks	3
IoT sensors in sewer systems	4
Smart AND sewer AND systems AND iot	2
Sewer AND systems AND IoT	6
"Smart sewer systems"	2
“Smart manufacturing” AND “Wastewater treatment”	1
"Efficiency improvement" AND "Sewer systems"	1
"Smart manufacturing" AND "Wastewater treatment"	1
"Sensor network" AND "Wastewater	2

treatment"	
"IOT" AND "Wastewater treatment"	7

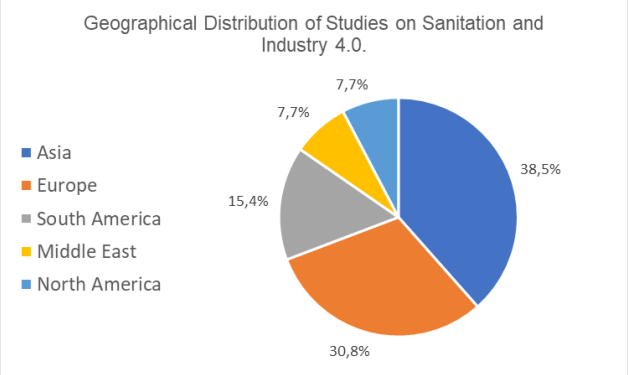
The search was limited to open publications published in the last five years (2019-2024) to ensure the most recent research incorporating Industry 4.0 technologies and studies into environmental sanitation and presenting empirical results and technical analyses or models applicable to the environmental sanitation sector. The articles found were subsequently organized into a database for subsequent analysis.

In the initial selection phase, approximately seventy articles were identified based on relevant keywords, encompassing the application of Industry 4.0 both in water treatment and in wastewater treatment plants. Following a thorough review and the refinement of the central themes, thirty-seven articles were retained, specifically addressing the implementation of emerging technologies in wastewater treatment. Ultimately, after comprehensive analysis and research on the subject, ten articles were highlighted for their strong alignment with the objectives of this study, as they presented real-world applications, pilot projects, simulations, or practical models involving the use of Fourth Industrial Revolution technologies for the treatment, analysis, management, and monitoring of sewage networks.

3. RESULTS

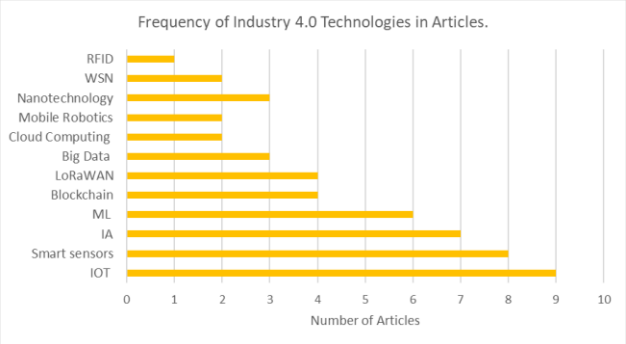
Based on the research carried out, it was observed that most applications and studies are developed in Asia and Europe, with countries such as China, India and Germany standing out, which lead initiatives aimed at modernizing sanitation based on innovative technological solutions [1; 4].

Graph 01 - Geographical Distribution of Studies on Sanitation and Industry 4.0.



Technological advances presented in the studies include the Internet of Things (IoT) for data collection and transmission, the use of multiparametric sensors (level, pH, turbidity, dissolved oxygen), and the application of Artificial Intelligence (AI) alongside Machine Learning (ML) for predictive analysis and automated decision-making [3;5]. Graph 2 shows the technologies presented and the number of articles that provide this information.

Graph 02 - Frequency of Industry 4.0 Technologies in Articles.



Sensors play a fundamental role in the sewage monitoring systems analyzed, as they are essential components of the Internet of Things (IoT), capable of collecting data and detecting system problems, in addition to capturing information. Some models are being tested to detect manholes and pipe blockages, and to operate with lower energy consumption [4; 6].

IoT transforms real-time data monitoring and efficient wastewater management by connecting sensors, controllers, and cloud platforms [1]. Wireless communication technologies are essential, enabling the transmission of sensor data to servers or cloud platforms. LoRaWAN is also used in this process, standing out for its long range and low power consumption, ideal for remote areas and challenging environments [6].

Some specific sewage treatments, such as membrane bioreactors (MBRs), which offer high efficiency, permeate quality, and compaction, in addition to occupying a reduced area, have been integrated with the IoT, enabling dynamic monitoring and stable and efficient operation [2]. Another treatment used is nanocomposite membranes (NFMs), which have greater porosity to water and solute rejection compared to TFC membranes, and whose manufacturing can be optimized with Artificial Intelligence and Industry 4.0 [8].

Case studies with the APAH, HADA, and SPUDD systems demonstrate the effectiveness of emerging technologies in environmental sanitation, as they use sensors, AI, and low-energy networks to monitor sewage systems in real time and perform automated interventions in critical situations. Chavhan et al. [1] point to improvements in the performance of treatment plants, with reduced losses, increased safety, better use of natural resources, and process stabilization. Drenoyanis et al. [5] highlighted that radar sensors integrated with LoRaWAN networks for monitoring pumping stations generated operational and economic gains, in addition to reducing maintenance costs by replacing manual inspections with remote monitoring, increasing safety by avoiding interventions in unhealthy environments.

Another example is the implementation, in Malang (Indonesia), of an effluent monitoring system in a WWTP, using sensors to measure pH, temperature, turbidity and dissolved oxygen, allowing data storage and real-time operation [1]. Utepov et al. [7] presented a system to detect opening of manholes, critical liquid levels and siltation, with successful integration to prevent flooding, sewage accumulation, lid thefts and obstructions.

Table 2, which is presented in Annex A of this study, shows a relationship between the applied technologies and their contributions to sanitation for each author of the articles selected for this systematic review, as well as the objectives of the studies. Through this table, it is possible to identify the most studied applications by the authors and what can be optimized and added in relation to environmental sanitation. An example of this is the Internet of Things, where nine out of ten studies present applications using this technology for the improvement, automation of processes, and early detection of problems that may occur in sewage networks.

These cases reinforce the viability of smarter and more sustainable sewage management models, improving early detection of problems such as blockages, leaks, and contamination. Anticipating these failures prevents environmental damage by preventing waste from reaching water bodies, preserving water quality [4] and supporting SDG 6, which promotes the efficient management and proper treatment of wastewater [2].

4. CONCLUSION

Based on the analysis of the selected articles, it was possible to conclude that technologies associated with Industry 4.0, such as the Internet of Things (IoT), smart sensors, and Artificial Intelligence (AI), have great potential to transform the environmental sanitation sector. The main contribution of these technologies lies in the possibility of continuous, automated, and efficient monitoring of sewage networks. In this context, IoT allows real-time monitoring of the network operation, faster failure identification, and proactive action. AI and Machine Learning (ML)-based systems enable the analysis of large volumes of data, failure prediction, and the optimization of operational processes, contributing to cost reduction and increased environmental safety.

Thus, the present study brings several analyses regarding the implementation of Industry 4.0 for environmental sanitation and its benefits. However, there is still a need for the creation and adaptation of standards and public policies that promote the standardization of monitoring systems, ensuring the security, expansion, and integration of the proposed solutions

In addition, it is possible to carry out a monitoring prototype in Brazil in regions that still do not have access to effluent collection and treatment and thus develop a network and sewage treatment plants together with new technologies so that it is possible to analyze the implementation stages and the benefits of the technologies in the process and ensure safety, efficiency, and improvement of the population's quality of life.

References

[1] CHAVHAN, Nishant; BHATTAD, Resham; KHOT, Suyash et al. APAH: An autonomous IoT driven real-time monitoring system for industrial wastewater. Digital Chemical Engineering, Amsterdam: Elsevier, v. 14, p. 100217, 2025.

[2] SAADATINAVAZ, Fateme; ALOMARI, Mohammed; ALI, Muhammad et al. Striking a

balance: decentralized and centralized wastewater treatment systems for advancing Sustainable Development Goal 6. Advanced Energy and Sustainability Research, Weinheim: Wiley-VCH, 2024. DOI: https://doi.org/10.1002/aesr.202400097.

[3] ALPROL, Ahmed E.; MANSOUR, Abdallah T.; IBRAHIM, Marwa EED; ASHOUR, Mohamed. Artificial intelligence technologies revolutionize wastewater treatment: current trends and future prospects. Water, Basel: MDPI, v. 16, p. 314, 2024.

[4] SOLANO, Fernando; KRAUSE, Steffen; WÖLLGENS, Christoph. An Internet-of-Things enabled smart system for wastewater monitoring. IEEE Access, Piscataway: IEEE, v. 10, p. 4666–4685, 2022.

[5] DRENOYANIS, Adam; RAAD, Raad; WADY, Ivan; KROGH, Carmel. Implementation of an IoT based radar sensor network for wastewater management. Sensors, Basel: MDPI, v. 19, p. 254, 2019.

[6] UTEPOV, Yelbek; ZHUMANOV, Yerlan; ALIMZHANOV, Yerbolat et al. Potential application of an automatic sewer monitoring system based on sensors. International Journal of GEOMATE, Tokyo: Geomate International Society, v. 25, no. 107, p. 45–52, 2023a.

[7] UTEPOV, Y.; DZHUNUSSOV, Y.; KULBAYEV, B.; KULMAGANBETOVA, A. et al. Prototyping an integrated IoT-based real-time sewer monitoring system using low-power sensors. Eastern-European Journal of Enterprise Technologies, [Sl]: Private Company Technology Center, v. 3, no. 5 (123), p. 5–9, 2023b.

[8] UWAMUNGU, J. Y.; KUMAR, P.; ALKHAYYAT, A. et al. Future of water/wastewater treatment and management by Industry 4.0 integrated nanocomposite manufacturing. Journal of Nanomaterials, [London]: Hindawi, v. 2022, Art. ID 5316228, p. 1–11, 2022.

ANNEX A

Table 02 - Data obtained from the literature review regarding Industry 4.0 and ICT technologies applied to environmental sanitation

Authors (Year)	Applied ICTs	Contributions to sanitation
Alprol *et al* (2024)	IoT, AI, ML, sensors and cloud computing	Real-time monitoring, process optimization and automation, quality prediction and modeling, early problem detection, increased efficiency and cost reduction.
Alzahrani *et al* (2023)	IoT, wireless sensor network, blockchain, anomaly detection algorithms, GPS-based remote sensing and simulation analysis.	Improved management, extraction of refinements and pollutants, real-time monitoring, anomaly detection and cost reduction
Chavhan *et al* (2025)	IOT, ML, Multiparametric Sensors, Cloud Platform and Android Mobile App.	Real-time monitoring of treatment processes, contamination prevention, automatic valve control, real-time alerts and post-treatment water quality improvements.
Drenoyanis *et al* (2019)	IoT, radar sensors, Low Power Wide Area Networks (LPWAN), microcontrollers, mobile applications and cloud platforms.	Early detection of network problems, prevention and reduction of sewage overflow, improvement of operational efficiency and cost reduction
Makowska *et al* (2024)	Structural and existing equipment modernization.	Increased capacity of WWTPs and the introduction of modern, more efficient treatment equipment.
Saadatinavaz *et al* (2024)	Specific treatment technologies and collection and transportation systems.	Modular DWTS designs for water reuse, quantitative CAPEX/OPEX assessments for sewer networks, and facilitates decision-making to achieve a comprehensive sanitation network.
Solano *et al* (2022)	IOT, wireless sensor and actuator network, multi-parameter sensors, distributed real-time anomaly detection and localization (HADA)	Real-time monitoring, location of illegal industrial discharges and monitoring within main sewer lines.

	algorithm, source determination algorithms, simulation software and tracking robot.	
Utepov *et al* (2023a)	Sensors, multifunctional device, wireless interfaces (WI-FI, LoRAWAN) and microcontrollers	Efficient management of sewage systems, real-time monitoring, automatic detection of manhole openings and critical liquid and siltation levels, cost optimization and alerts for overflow, clogging and vandalism.
Utepov *et al* (2023b)	IOT, sensors, wireless technologies (LoRaWAN - SX1278, WiFi - ESP8266, GSM/GPRS - SIM800L), data collection station, wireless sensor device and algorithm for sewage problem detection integrated with GIS.	Real-time, low-cost monitoring, early detection, rapid response, automated corrective actions, alerts and notifications, and improved operational efficiency and cost reduction.
Uwamungu *et al* (2022)	Cyber-physical models, IoT, AI, Big Data analytics, ML, Deep Learning, Artificial Neural Networks (ANNs), Nanocomposites	Innovative treatment technologies, effective pollutant removal processes, AI/ML-powered performance optimization and prediction, cost reduction, and operational efficiency.