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Review

INTEGRATION OF MEMBRANE TECHNOLOGY AND INTELLIGENT AUTOMATION IN URBAN WASTEWATER TREATMENT: A CONCEPTUAL CRITICAL REVIEW

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ABSTRACT

Integration of Membrane Technology and Intelligent Automation in Urban Wastewater Treatment: A Conceptual Critical Review. *Increasing urbanization and urban population growth have intensified pressure on wastewater treatment systems, necessitating the development of more efficient, adaptive, and sustainable technologies. Conventional systems still face limitations in handling the complexity of wastewater characteristics and in meeting increasingly stringent effluent quality standards. This study aims to review the advancement of membrane technologies and intelligent automation, as well as to develop an integrative conceptual framework for urban wastewater treatment. The method employed is a critical literature review of 39 relevant scientific articles published between 2021 and 2025 and indexed in reputable databases. The results indicate that membrane technologies, such as microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactors, can significantly improve contaminant separation efficiency and produce high-quality effluent. Meanwhile, intelligent automation systems based on the Internet of Things (IoT) and artificial intelligence enable real-time, adaptive, and data-driven monitoring and process control, thereby enhancing operational efficiency and system reliability. The proposed integration has the potential to improve system responsiveness, energy efficiency, and sustainability, although its effectiveness remains conceptual. However, challenges such as membrane fouling, high energy consumption, and limitations in cost, infrastructure, and human resource capacity remain barriers to implementation. This study proposes an integrative conceptual framework that combines physical, biological, and digital technologies as a foundation for developing modern, adaptive, and sustainable urban wastewater treatment systems.*

INTRODUCTION

Urban population growth and rapid urbanization have significantly increased the pressure on wastewater management systems[1]. Domestic, industrial, and commercial activities generate large volumes of wastewater with increasingly complex characteristics, thereby requiring treatment systems that are adaptive, efficient, and sustainable [2]. Poorly managed wastewater has the potential to contaminate water bodies, trigger eutrophication, and increase health risks due to exposure to pathogenic microorganisms and hazardous compounds [3,4]. In addition, conventional treatment processes contribute to greenhouse gas emissions, particularly N_2O [5,6].

Wastewater treatment is still largely dominated by conventional biological and physico-chemical technologies, such as activated sludge, stabilization ponds, and coagulation–flocculation [7]. However, these systems have limitations in optimally removing dissolved contaminants, micropollutants, and nutrients [8,9]. Moreover, their performance is sensitive to fluctuations in pollutant loads, requires extensive land areas, and involves high energy consumption, particularly in aeration processes, which constitute a major component of operational costs [10,11]. These challenges are further intensified by increasingly stringent effluent quality standards and the growing demand for wastewater reuse.

In recent decades, membrane technology has emerged as a leading solution in urban wastewater treatment. This technology includes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), which are capable of separating biological and chemical contaminants with high efficiency [12–14]. In addition to producing high-quality effluent, membrane technology can also be integrated with biological processes through membrane bioreactors (MBRs), thereby improving treatment efficiency and supporting wastewater reuse systems [15–17]. Furthermore, advancements in membrane material innovation and surface engineering continue to be developed to mitigate fouling while enhancing the sustainability and operational efficiency of membrane systems [18,19].

In line with these developments, digital transformation has accelerated the implementation of the Internet of Things (IoT), smart sensors, and Artificial Intelligence (AI) in wastewater management [20]. IoT-based systems enable real-time water quality monitoring through sensors that measure parameters such as pH, COD, TSS, and temperature, with the collected data transmitted to digital platforms for automated analysis [3,21]. The integration of AI and machine learning supports process optimization, including aeration control, membrane pressure regulation, and chemical dosing, thereby improving energy efficiency, reducing operational costs, and maintaining system performance stability [10,22]. In addition, AI-based predictive models are capable of detecting membrane fouling and predicting system performance in real time [23].

Although the advancement of membrane technology and intelligent automation demonstrates significant potential for urban wastewater treatment, studies integrating membrane technology, the Internet of Things (IoT), and Artificial Intelligence (AI) within a unified system framework remain relatively limited. Most existing studies tend to examine membrane technology and automation systems separately, resulting in a lack of comprehensive understanding regarding the synergistic relationship between physical and digital technologies in enhancing treatment performance. In fact, the integration of these three components has strong potential to improve treatment efficiency, system adaptability, dynamic fouling control, as well as energy and operational cost optimization [24,25]. Moreover, data-driven integrated systems are capable of responding to influent fluctuations in real time through automated control, thereby supporting the development of more efficient and sustainable smart wastewater systems [20]. Therefore, a conceptual synthesis is needed to integrate membrane technology, IoT, and AI while also identifying future directions for the development of intelligent wastewater treatment systems.

Based on this background, this study aims to review the development of membrane technologies and intelligent automation systems in urban wastewater treatment, as well as to identify the potential for integrating these two approaches. Furthermore, this study proposes an integrative conceptual framework as its main scientific contribution, combining physical, biological, and digital technologies into a single wastewater treatment system that is adaptive, efficient, and sustainable.

MATERIALS AND RESEARCH METHODS

This study employs a Critical Literature Review (CLR) approach combined with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method to analyze the development of membrane technologies and automation systems in urban wastewater treatment. The CLR approach was used to critically evaluate methodological quality, technological performance, limitations, and research gaps. Study quality assessment was conducted based on methodological relevance, consistency of findings, system efficiency, operational reliability, and technological scalability. In addition, a comparative critical synthesis was applied to identify patterns, differences, and inconsistencies across studies, while PRISMA ensured that the literature search and selection process was conducted systematically and transparently [26,27].

Literature Search Strategy
The literature was collected from reputable scientific databases, namely Scopus, ScienceDirect, SpringerLink, MDPI and Google Scholar. The search employed a combination of keywords, including "urban wastewater treatment," "membrane technology," "membrane bioreactor (MBR)," "reverse osmosis," "Internet of Things (IoT)," "artificial intelligence (AI)," and "smart wastewater system," using Boolean operators (AND, OR). The articles were limited to the period 2021-2025 to ensure novelty and relevance.

Literature Selection
The literature selection followed the PRISMA stages, namely identification, screening, and eligibility. During the screening stage, articles were selected based on titles and abstracts, while the eligibility stage involved full-text assessment to ensure topic relevance and methodological quality. The inclusion criteria were: (1) peer-reviewed journal articles, (2) studies focusing on membrane technology and/or automation systems in urban wastewater treatment, and (3) studies employing experimental, modeling, or conceptual approaches. The exclusion criteria included articles that were not relevant, lacked clear methodology, or were not scientifically indexed.

Data Extraction and Classification
The selected articles were extracted into a literature matrix that included authors, year, methods, type of technology, key findings, and research limitations. Subsequently, the literature was classified into five main themes: (1) membrane technology performance, (2) IoT-based monitoring systems, (3) application of AI, (4) system integration, and (5) implementation challenges.

Critical Analysis and Synthesis
The analysis was conducted using thematic and comparative approaches on the selected articles. Each study was evaluated based on efficiency, reliability, scalability, and operational limitations. Cross-study comparisons were used to identify patterns, differences, and inconsistencies in research findings, with a focus on issues such as membrane fouling, energy consumption, system complexity, and data integration.

Identification of Research Gaps
The analysis revealed several research gaps, including: (1) limited integration of membrane technology and intelligent automation, (2) a lack of full-scale implementation, (3) the absence of integrated performance evaluation standards, and (4) challenges related to energy efficiency and fouling control. These findings highlight the need for more holistic and multidisciplinary approaches.

Conceptual Framework Development

Based on the results of the literature synthesis, an integrative conceptual framework was developed that combines membrane technology, biological processes, physico-chemical treatments, and digital systems based on IoT and AI in urban wastewater treatment. This framework emphasizes a data-driven approach through real-time monitoring, intelligent decision-making, and adaptive and sustainable system operation.

PRISMA Flow Diagram

The literature selection process is illustrated in the PRISMA Flow Diagram (Figure 1), which presents the flow of information through the stages of identification, screening, eligibility assessment, and inclusion.

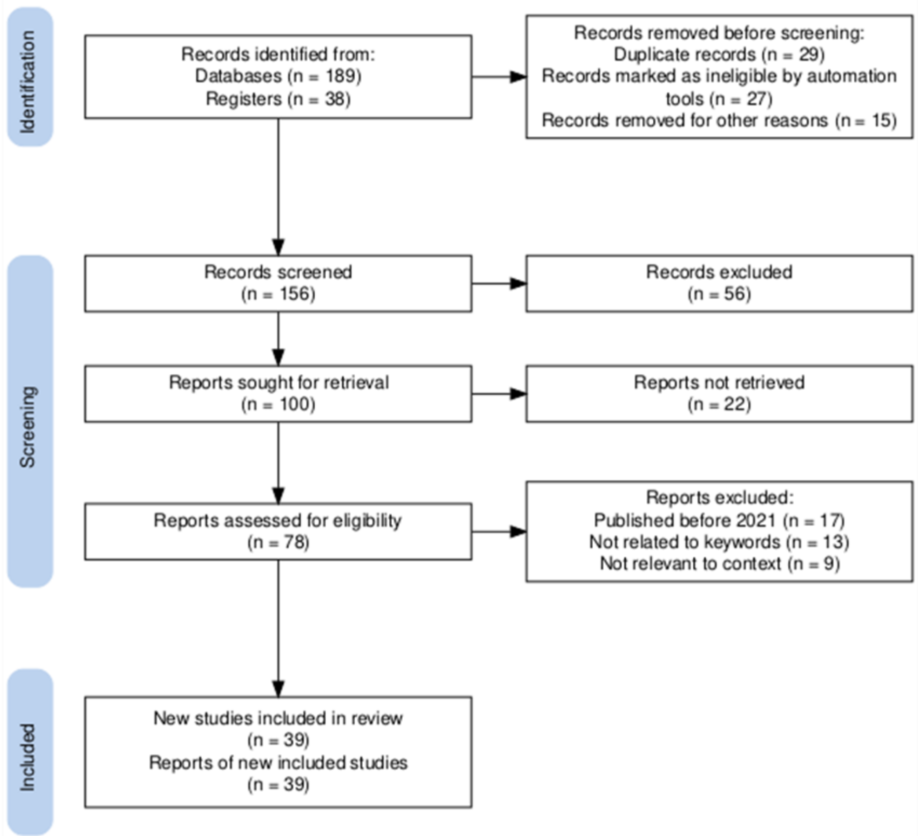

Figure 1. The PRISMA Diagram for Article Selection

RESEARCH RESULTS AND DISCUSSION

Trends in Membrane Technology for Wastewater Treatment

The analysis of 39 studies indicates that membrane technology has become one of the most dominant approaches in urban wastewater treatment, particularly in response to increasing demands for effluent quality and process efficiency. Technologies such as MF, UF, NF, RO, and MBR are widely applied due to their ability to selectively separate both biological and chemical contaminants [12,14]. In general, membrane-based systems are capable of achieving high efficiency in the removal of suspended solids, microorganisms, and organic and inorganic compounds, thereby producing treated water that meets increasingly stringent environmental standards [8].

The development of membrane technology also indicates a shift toward more sustainable material innovations and system designs. Membrane modification using natural and recycled materials has been proven to enhance antifouling properties, permeability, and membrane lifespan, while simultaneously reducing operational costs and environmental impacts [17,19].

In addition, the development of nanomaterial-based and composite membranes further improves separation selectivity and resistance to extreme operating conditions (13,28). Furthermore, technological innovations such as electrified membranes membranes that utilize electric fields to enhance separation efficiency while reducing fouling demonstrate promising potential in improving water treatment system performance [(29)]. These advancements highlight the significant potential for improving water treatment performance in a more efficient and sustainable manner.
Each membrane technology has distinct advantages and limitations. MF and UF are effective in removing suspended solids, bacteria, and macromolecules with relatively low energy consumption, but they are less efficient in eliminating dissolved ions and small organic compounds. NF demonstrates better performance in removing multivalent ions, heavy metals, and certain organic micropollutants while operating at lower pressure than RO. In contrast, RO provides the highest separation efficiency, producing high-quality effluent by removing dissolved salts, pharmaceutical compounds, and microscopic contaminants. However, RO requires high energy consumption and operating pressure and generates concentrated brine, which remains a major environmental challenge [(12,30)]. Meanwhile, electrochemical membrane technologies such as electrodialysis and electrified membranes offer advantages in selective ion separation and fouling control, although they still face challenges related to cost and system complexity [(29)]. Therefore, the selection of membrane technology should be tailored to wastewater characteristics, effluent quality targets, energy efficiency, and resource recovery potential.
The development of membrane technologies is increasingly moving toward more complex applications, such as specific ion separation, treatment of high-strength wastewater, and resource recovery [(31)]. Reverse osmosis and nanofiltration are effective in removing heavy metals, dissolved salts, and micropollutants, including pharmaceutical compounds, thereby producing high-quality effluent [(12,30)]. However, concentrate (brine) management remains a major challenge due to its potential environmental impacts. In addition, electrowinning enables the efficient extraction of valuable metals [(32)]. To address this complexity, integrated membrane, physico-chemical, and biological approaches are developed to improve efficiency, minimize secondary waste, and support circular economy principles in wastewater management.
The integration of membrane technology with biological processes, particularly in MBR systems, has shown significant improvements in wastewater treatment performance [(15,16,33)]. MBR systems are capable of enhancing the removal efficiency of organic matter, nutrients, and micropollutants, while producing high-quality effluent with reduced land requirements [(9,15)]. Furthermore, combining MBR with advanced technologies such as membrane distillation has been demonstrated to improve energy efficiency and water quality to meet reuse standards [(6,34)].
Thus, the main challenges in membrane technology are still related to fouling, energy consumption, and relatively high initial investment costs. Fouling, caused by the accumulation of organic matter and microorganisms, can reduce membrane performance, thereby requiring effective control strategies through material modification and operational optimization [(19,35)]. Therefore, integration with intelligent control systems is increasingly being developed as a solution to improve system efficiency and sustainability.
Synthesis of Study Results Based on Technology Categories
To obtain a more systematic understanding, the results of the analysis of 39 studies were grouped into four main categories: (1) membrane technology performance, (2) IoT-based monitoring systems, (3) application of AI, and (4) system integration.
Based on Table 1, the synthesis of 39 studies indicates that membrane technology remains the dominant approach in urban wastewater treatment. Approximately ten studies emphasize the performance of membrane processes such as MF, UF, NF, RO, and MBR, which have been proven effective in removing biological and chemical contaminants and improving

effluent quality. However, challenges such as fouling and energy consumption remain major issues in their implementation.

Table 1. Synthesis of Wastewater Treatment Studies Based on Technology Categories

No	Category	Technology / Method	Key Findings	Key Advantages/Operational Challenges	Ref.
1	Membrane	Ultrafiltration (UF)	Effective in removing TSS and microorganisms	Low energy consumption, but less effective for dissolved ions	(14)
2	Membrane	Membrane modification	Enhances membrane performance	Improves antifouling, but costs remain high	(19)
3	Membrane	Nanofiltration (NF)	Removal of heavy metals and organic compounds	High selectivity with moderate operating pressure	(8)
4	Membrane	MBR + MD	Improves water quality for reuse	High treatment efficiency, but prone to fouling	(34)
5	Membrane	Reverse Osmosis (RO)	Micropollutant removal	Produces high-quality effluent but consumes high energy	(30)
6	Membrane	NF/RO hybrid	Ion separation selectivity	Efficient hybrid system, but operational complexity is higher	(31)
7	Membrane	Adsorption–membrane hybrid	Removal of emerging contaminants	Highly effective for micropollutant removal	(9)
8	Membrane	Forward Osmosis	Low energy consumption	Low operating pressure,	(16)
9	Membrane	Ceramic membrane	Low fouling and high stability	High initial investment	(15)
10	Membrane	Electrified membrane	Enhanced separation efficiency	Reduces fouling, but requires complex control systems	(29)
11	Membrane	Anti-fouling membrane	Reduces fouling using nanomaterials	Extends membrane lifespan	(35)
12	Membrane	Advanced membrane	Sustainable membrane technology	High efficiency	(13)
13	Membrane	Lithium extraction membrane	Selective ion separation from brine	Promising for resource recovery	(17)
14	Membrane	Nanofiltration enhancement	Improved membrane performance	Increased selectivity and permeability	(28)
15	Membrane	Nanoengineered membrane	Surface engineering for high efficiency	Improved fouling resistance	(33)
16	Membrane	Antifouling nanomateri	Advanced fouling prevention	Enhances operational stability	(18)
17	Membrane	Heavy metal removal membrane	Industrial wastewater treatment	Effective for heavy metal ion removal	(12)
18	IoT	IoT monitoring system	Real-time water quality monitoring	Rapid response to water quality changes	(20)
19	IoT	Smart aeration control	Energy efficiency in aeration processes	Reduces aeration energy consumption	(10)
20	IoT	Real-time monitoring system	IoT-based industrial wastewater monitoring	Continuous monitoring, but requires stable networks	(21)
21	IoT	Digital monitoring	Improves operational efficiency	More effective process automation	(1)
22	IoT	Online monitoring	Reduces human error	Improves monitoring accuracy	(11)
23	IoT	Remote monitoring	Enables remote system monitoring	High flexibility	(2)
24	AI	Machine learning	Water quality prediction	More accurate prediction	(37)
25	AI	AI trend analysis	Trends in AI use in WWTPs	Supports treatment optimization	(23)
26	AI	AI application	Enhances treatment efficiency	Reduces operational costs	(25)
27	AI	Automated ML	Automated ML systems for optimization	More adaptive and rapidly developed models	(38)
28	AI	AI-based control	Adaptive system control	Improves process stability	(22)
29	AI	Data-driven system	Data-driven decision-making	Supports predictive maintenance	(39)
30	Integration	Process emission analysis (N_2O)	Greenhouse gas emissions influenced by process conditions	Supports emission reduction strategies	(5)
31	Integration	Circular WWTP	Integration toward net-zero systems	Supports circular economy implementation	(24)
32	Integration	Hybrid treatment	Technology combination	Improves treatment efficiency	(7)
33	Integration	Sustainable treatment	Emission reduction and energy efficiency	Enhances system sustainability	(6)
34	Integration	Electrowinning	Metal recovery from wastewater	Promising for resource recovery	(32)
35	Integration	LCA membrane system	Life cycle assessment of membrane technology	Provides comprehensive environmental evaluation	(40)
36	Integration	Wastewater epidemiology	Waste-based monitoring systems	Supports public health surveillance	(3)
37	Integration	Electrocoagulation + WWTP	Enhances existing WWTP performance	Effective for complex wastewater treatment	(36)
38	Integration	Agroecosystem approach	Integrated sustainability approach	Supports resource efficiency	(41)
39	Integration	Environmental impact system	Influence of environmental factors on systems	Supports sustainability assessment	(4)

The development of IoT-based monitoring systems shows significant progress in supporting real-time control of wastewater treatment processes [20,21]. This technology enables continuous water quality monitoring and enhances operational efficiency through more responsive and data-driven systems [1,2]. In addition, AI plays a strategic role in process optimization, water quality prediction, and adaptive control, particularly in improving energy efficiency and reducing membrane fouling [23,36,37].

The integration of membrane technology, IoT, and AI results in wastewater treatment systems that are efficient, adaptive, and sustainable, and represents a key direction for the development of smart wastewater treatment systems to support sustainable urban water management.

Integration of Membrane Technology, Automation Systems, and IoT in Wastewater Treatment

The development of urban wastewater treatment technologies is currently shifting from conventional systems toward more integrated, intelligent, and sustainable approaches [20,21]. The integration of membrane technology with IoT and AI-based automation systems has emerged as an innovative approach capable of enhancing efficiency, process stability, and treated water quality [8,24,39]. This combination enables the development of wastewater treatment systems that are adaptive to changes in wastewater characteristics and increasingly stringent environmental quality standards [6,41].

Membrane technologies, such as MF, UF, NF, RO, and MBR, have been proven to possess high capability in removing biological, chemical, and micropollutants [14,17]. These systems are able to produce higher-quality effluent compared to conventional methods, making them widely used in water reuse applications [12,15,33]. In this context, integration with automation systems and IoT becomes a key solution to improve the performance and reliability of membrane technology. Sensors integrated within the system enable real-time monitoring of critical parameters, such as transmembrane pressure (TMP), flow rate, pH, COD, and Total Suspended Solids (TSS) (1,2). These data are then used to automatically regulate operating conditions through control systems such as Supervisory Control and Data Acquisition (SCADA), thereby maintaining process stability and preventing performance degradation of the membrane [22,25].

One of the main advantages of this integration is its ability to control membrane fouling, which is a major challenge in membrane technology [18,19]. Fouling can lead to reduced permeability, increased energy consumption, and higher operational costs [10,35]. With IoT-based monitoring systems and AI-driven data analysis, fouling can be detected at an early stage and controlled through adjustments in operational parameters, such as backwashing, pressure, and chemical dosing [23,37]. The use of innovative membrane materials, such as nanomaterials and antifouling membranes, can also be combined with intelligent control systems to extend membrane lifespan [18,19].

Furthermore, the integration of AI and machine learning (ML) enables more adaptive and complex optimization of wastewater treatment processes. AI-based predictive models can forecast system performance, optimize operating conditions, and dynamically reduce energy and chemical consumption by utilizing both historical and real-time data. The application of AI has been shown to improve operational efficiency, reduce maintenance costs, and minimize failure risks through predictive maintenance and fault detection [23,39]. In addition, automated machine learning (AutoML) accelerates the development of models that are more adaptive and tailored to wastewater characteristics, thereby enhancing system flexibility in responding to variations in pollutant loads [38].

The integration of membrane technology and automation enhances energy efficiency and the sustainability of wastewater treatment systems [41]. Real-time control based on sensors and intelligent systems can optimize energy usage in energy-intensive units such as pumps, aeration, and membrane pressure. Studies show that sensor-based control reduces energy consumption without compromising performance, while AI-based approaches optimize energy distribution and minimize waste [10,15]. This optimization also contributes to reducing greenhouse gas emissions through improved aeration efficiency and lower electricity consumption [6].

In the context of sustainability, the integration of these technologies supports circular economy principles through water and resource recovery via membrane processes and enhanced efficiency through automation. This fosters the development of smart wastewater treatment plants (Smart WWTPs) that integrate operational efficiency, environmental sustainability, and optimal resource utilization [24,33].

Although the integration of IoT and AI offers various advantages in wastewater treatment, its implementation still faces several technical and non-technical challenges [21,24]. Digital infrastructure readiness remains one of the major constraints, particularly in regions lacking stable data communication systems and sensor networks [1,22]. In addition, the initial investment required for sensors, automation devices, SCADA systems, and AI-based computing infrastructure is relatively high, which may increase implementation and operational costs [8,25]. Sensor maintenance also represents a significant challenge because corrosive and fluctuating wastewater conditions can reduce sensor accuracy and shorten device lifespan [2,18]. Furthermore, IoT-based system integration increases cybersecurity risks, including data breaches, cyberattacks, and failures in automated control systems that may affect the operational stability of wastewater treatment facilities [1,20]. Another challenge is the limited availability of human resources with expertise in data analysis, AI system operation, and digital technology maintenance [37,39]. Therefore, the implementation of smart technologies in wastewater treatment requires adequate infrastructure support, robust data security strategies, regular maintenance programs, and capacity building for human resources to ensure optimal and sustainable system performance.

Conceptual Framework for the Integration of Membrane Technology and IoT-Based Automation Systems in Urban Wastewater Treatment

This study proposes an integrative conceptual framework that combines membrane technology with IoT and AI-based automation systems in urban wastewater treatment. The framework is developed to address research gaps indicating that most studies still examine membrane technologies and automation systems separately, resulting in suboptimal, less adaptive, and less sustainable treatment systems [8,17,25]. This integrative approach is essential to cope with the complexity of urban wastewater, driven by urbanization, variability in pollutant loads, and increasingly stringent effluent standards [1,2].

As illustrated in Figure 2, the conceptual framework consists of four main modules: wastewater input and characterization, membrane-based treatment, IoT-AI-based monitoring and automation, and output and sustainability. The integration of these modules forms a smart wastewater system that is adaptive, energy-efficient, and environmentally friendly. Wastewater characterization identifies key parameters such as BOD, COD, TSS, nutrients, and physicochemical properties, which determine the design and performance of membrane processes that are sensitive to variations in organic and solid loads [12,19,36]. Pre-treatment removes coarse solids, reduces initial loads, and stabilizes influent conditions to minimize membrane fouling [33,35].

The main treatment unit integrates membrane processes (MF, UF, NF, RO) with biological processes and physico-chemical methods (coagulation, adsorption, and advanced oxidation) to enhance the removal efficiency of contaminants, nutrients, heavy metals, and micropollutants, producing high-quality effluent suitable for reuse [8,9,30]. Membrane material innovations, including nanomaterials and antifouling technologies, improve selectivity, permeability, and energy efficiency. For example, the incorporation of activated carbon nanoparticles into NF-PES (polyethersulfone) membranes enhances lignin separation and antifouling properties [13,18,33].

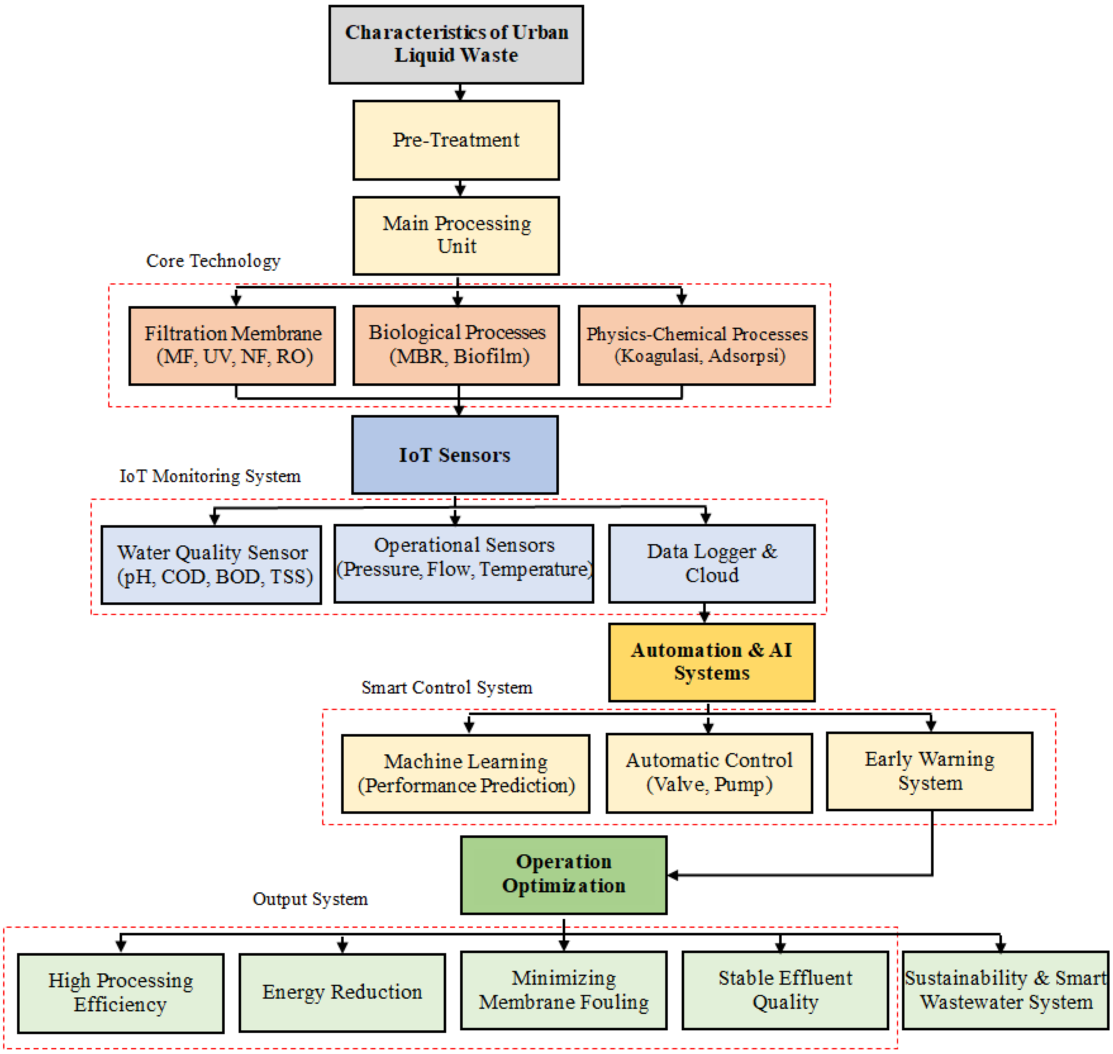

Figure 2. Conceptual Framework for the Integration of Membrane Systems, IoT, and Automation in Urban Wastewater Treatment

The IoT-AI-based monitoring and automation module is a key component in enhancing system intelligence (39). The monitoring system enables real-time measurement of water quality parameters and operational conditions, such as pH, COD, BOD, TSS, pressure, temperature, and flow rate. The collected data are transmitted to cloud-based platforms for further analysis, thereby supporting operational transparency and data-driven decision-making (20,21).

AI-based automation systems utilize these data to predict system performance, detect disturbances such as membrane fouling at an early stage, and optimize operations through automated control of pumps, valves, and aeration systems. This approach enables predictive maintenance, reduces energy consumption, and improves process stability (10,23,37). Integration with control systems such as SCADA and predictive models further enhances operational efficiency and overall system reliability (22,25). The output stage produces stable effluent, high energy efficiency, and minimal membrane fouling, while also supporting the circular economy through water reuse, resource recovery, and the reduction of greenhouse gas emissions. LCA analyses indicate that the integration of membrane technology and intelligent systems improves environmental efficiency and supports net-zero emission targets (6,24,40).

Thus, the proposed conceptual framework integrates sensor-based wastewater characterization, technology selection, real-time IoT–AI control, and sustainability-based output evaluation, creating a system that is predictive, proactive, and adaptive. It supports the transformation of urban wastewater management toward smart and sustainable systems, while providing a foundation for future development of intelligent wastewater treatment technologies. Nevertheless, this framework remains an initial conceptual model and still requires further empirical validation through experimental studies, field implementation, and simulation-based evaluation to assess its effectiveness, reliability, and applicability under various wastewater characteristics and operational conditions.

Implications and Future Research

The integration of membrane technology, automation, and IoT promotes the development of more adaptive, efficient, and sustainable smart wastewater systems, including enhanced removal of BOD, COD, TSS, and nutrients, as well as improved effluent quality stabilization through real-time responses. AI also plays an important role in process optimization, energy efficiency, and improving system reliability.

However, the implementation of these technologies still faces various practical challenges, particularly in developing countries and existing wastewater treatment facilities. High investment costs for membrane technologies, IoT sensors, SCADA systems, and AI infrastructure remain major barriers. In addition, limited digital infrastructure, system integration complexity, data security and cybersecurity risks, and limited human resources for operating and maintaining smart systems affect implementation effectiveness. Membrane fouling, energy consumption, and long-term operational costs also remain critical challenges for full-scale applications.

Research gaps also remain significant because most studies are still focused on laboratory and pilot scales, while full-scale evaluations, sustainability assessments, and economic feasibility studies are still limited. Therefore, future research should focus on the development of energy-efficient membrane-AI hybrid systems, sustainable antifouling materials, and the integration of digital technologies such as digital twin for real-time optimization to support intelligent and sustainable wastewater treatment systems.

CONCLUSIONS AND RECOMMENDATIONS

This study indicates that the integration of membrane technology and intelligent automation has the potential to improve the performance of urban wastewater treatment systems. Membrane technology can produce higher-quality effluent through effective contaminant separation processes, while IoT- and AI-based automation may enhance operational efficiency by enabling more stable, adaptive, and data-driven process control. In combination, these approaches conceptually lead to a more responsive system capable of handling fluctuations in influent characteristics, while also potentially improving reliability and energy efficiency in treatment plant operations.

From a conceptual perspective, the proposed framework suggests that data-driven approaches can serve as a foundation for real-time system optimization. However, these findings remain conceptual and require further validation through implementation-based studies and field-scale applications to confirm their effectiveness under real operational conditions. Challenges such as membrane fouling, relatively high energy demand, and limitations in investment capacity and human resources also need to be carefully addressed in practical deployment. Therefore, further development is needed to produce more efficient, cost-effective, and adaptive technologies to support intelligent and sustainable wastewater treatment systems in the future.

ETHICAL APPROVAL
This study did not require formal ethical approval as it did not involve human subjects or sensitive personal data. The research was conducted as a literature review.

CONFLICT OF INTEREST
The authors declare no conflict of interest

AUTHOR CONTRIBUTIONS
DB: critical review of the manuscript, data analysis, manuscript writing, data collection and documentation. Authors read and approved the final manuscript.

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