Emerging Technologies in WWTP Control Systems for Sustainable Water Management

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Abstract: The integration of emerging technologies in Wastewater Treatment Plants (WWTPs) provides a transformative approach to enhancing operational efficiencies, finding sustainability, and fulfilling regulatory compliance. Traditional control methods-including manual operations and PID controllers-are limited in their ability to grapple with the dynamic complexities of wastewater treatment. Control technologies such as Artificial Intelligence (AI), Machine Learning (ML), SCADA, and IoT-enabled sensors are capable of real-time monitoring, predictive analytics, and automated control mechanisms to bolster performance, reduce energy consumption, and enhance resource efficiency. These smart systems allow for anomaly detection, optimization of processes, and decision-making adaptations to promote stable and efficient sewage treatment. However, the difficulties of the broad adoption of these technologies include the costs of implementation, the complexity of integration, cybersecurity issues, and the possibility of the additional requirements for skilled staff. Other environmental issues, such as microplastic particulate pollution, high-energy consumption, or contamination from PFAS, may motivate yet other avenues of research into more advanced filtration and resource recovery approaches. Coping with these problems calls for collaborative efforts from policymakers, industry leaders, and researchers to develop cost-effective, scalable, and sustainable approaches. Through automation, AI-driven analytics, and circular economy dimensions, WWTPs can establish long-term resilience, regulatory compliance, and environmental responsibility via cleaner water discharges and sustainable resource management.

Keywords: Wastewater Treatment Plants (WWTPs), Proportional-Integral-Derivative control (PID), Supervisory Control and Data Acquisition (SCADA), Artificial Intelligence (AI), Machine Learning (ML), blockchain, cyberattacks, biochemical oxygen demand (BOD).

I. INTRODUCTION

Wastewater Treatment Plants (WWTPs) serve as the first line of defence for public health and the environment against the discharge of its effluent containing contaminants from municipal, industrial, and agricultural sewage into natural water bodies. These plants utilize various treatment processes based on physical-, chemical-, and biological-based operations to bring the effluent within the legal limits while minimizing its harmful effects on the natural environment [1]. The operation of the WWTP is considerably influenced by the controlling systems, which regulate some of the main operational areas, including flow control, aeration, chemical dosing, and sludge management. Advanced control systems, including Supervisory Control and Data Acquisition (SCADA), IOT-enabled sensors, and AI-driven predictive analytics, improve process efficiency, minimize energy consumption, and enhance treatment performance [2]. Strong control mechanisms must be in place to ensure WWTPs operate effectively and sustainably, taking into account the increasing demands of water quality and guidelines of environmental regulations. The processes that WWTPs usually aim to monitor and control are aeration, sedimentation, and chemical dosing through highly complex control systems. Methods of control used so far include manual operations, feedback control, and Proportional-Integral-Derivative control (PID). Manual control depends heavily on the operator's experience and thus requires intense monitoring and frequent tweaks. Feedback control employs monitoring sensors to measure process variables, and responses are made appropriately [3].

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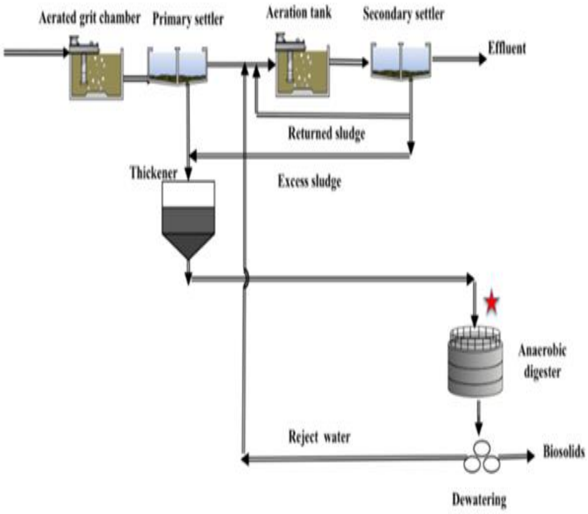

Figure 1 Schematic diagram of the full-scale wastewater treatment plant and the sampling point [4]

The figure 1 represents the process flow of a typical wastewater treatment plant (WWTP). The waste enters a grit chamber where most of the large, heavy inorganic particles settle down. Next come the primary settling tanks where solids settle and form primary sludge. Clarified water flows into aeration tanks, where microorganisms break down the organic pollutants [4]. These are followed by secondary settling tanks where biomass (activated sludge) is separated from water. Part of this sludge is returned to the aeration tank and the excess sludge is thickened and forwarded to an anaerobic digester (shown as a red star) for biogas production via breakdown. The remaining sludge is dewatered to produce bio solids while reject water may be recycled. Finally, treated water will be discharged as effluent that is compliant with environmental quality standards. The combined systems of physical, biological, and resource recovery strategies achieve efficient wastewater treatment. PID controllers make corrections automatically according to real-time feedback, ensuring stabilizing control of processes. However, even though these traditional strategies have become established practice, they have not fully catered for the combined complexity and dynamism involved with wastewater-treatment processes. Traditional control methodologies with their limitations are affecting the efficiency and sustainability of WWTPs. Manual intervention tends to be slow and error-prone, which tends to lead to inefficiencies in necessary process adjustments. In PID controllers, feedback mechanisms react to some of the deviations in set points but lack the predictive ability to mitigate the impact of fluctuating characteristics in the wastewater [5]. Moreover, most traditional systems tend to waste a lot of energy, with aeration and chemical dosing being considerable points of concern, leading to a rise in operational costs.

They also fail to analyse sudden changes in influent quality, which leads to inconsistent treatment performance. The sustainability of WWTPs that implement some kind of traditional control poses challenges [6]. High energy use remains an obnoxious sore haunts and which stands out as a major challenge as aeration systems represent a great extent of energy usage and are mostly inefficient under conventional control. Inefficient dosing of chemicals and aeration causes wasteful consumption of other resources, an upward push of operational costs, and a dire impact on the environment. Other dimensions of WWTP operational inefficiency that have arisen include obligate inconsistency of effluent quality due to process variability, a constant thorn in the subpar performance standards to conform to the prevailing regulatory discharge standards [7]. The more traditional control methods of WWTPs have for long been the basis for wastewater management; however, these approaches are increasingly inadequate to enable all elements of WWTP efficiency and sustainability. Advanced technologies such as artificial intelligence, model predictive control, and real-time data analytics present exciting opportunities to improve on WWTP performance. These intelligent control strategies allow WWTPs to make conservation of energy much more effective, keep their effluent quality more uniform, and maximize resource utilization. The advent of smarter control systems will be a compelling requirement to ensure sustainable and cost-effective treatment of wastewater.

II. EMERGING TECHNOLOGIES IN WWTP CONTROL SYSTEMS

Control systems used in wastewater treatment plants (WWTPs) are becoming modernized so as to reduce the limitations of traditional methods. Central in this movement are advanced sensors and Internet of Things (IOT) devices that will make WWTP operations more intelligent, efficient, and sustainable. The technologies provide better monitoring, analysis, and optimization of the myriad processes involved in the treatment of wastewater [8]. Advanced sensors can, therefore, detect a lot of physical, chemical, and biological parameters, including dissolved oxygen, pH, degree of nutrient loading, and specific pollutant levels. These sensors, once integrated in IoT systems, continuously collect and relay real-time data to centralized or cloud platforms. It allows remote monitoring of facility performance and data-driven decisions based upon accurate and real-time information by plant operators [9]. IOT-based systems also can automate control actions that would have otherwise been of a manual nature, thus promoting efficiency in the operation of process systems.

A. Advanced Sensors and IOT Integration

With real-time capabilities, modern technologies for wastewater treatment offer several benefits. Unlike conventional methodologies that almost always depend on manual water sample collection and analysis, a real-time monitoring system offers immediate recognition of deviations or disturbances in critical parameters of the treatment process. This provides the opportunity for rapid corrective action to keep the treatment process stable and, therefore, more efficient and reliable [10]. High-tech sensors constantly collect data that can help develop a predictive maintenance plan. With predictive maintenance, plants can detect the existence of a problem before it leads to a complete failure of the equipment; thus, ensuring continuous operation of the plant reduces unplanned interruptions, saving time and money. Transitioning from reactive management to proactive management offers insights toward a new horizon in ensuring the optimal operation of WWTPs. Smart sensors, using advanced algorithms and machine learning technologies, have been a game changer in pollutant detection and treatment optimization [11]. These sensors identify specific contaminants and measure their concentrations, making possible modifications to the treatment process based on real-time data. Smart systems in aeration would regulate the oxygen supply depending on real-time dissolved oxygen levels, reducing energy consumption while maintaining treatment efficiency. Similarly, chemical dosing can take place based on precise actual pollutant concentrations, thereby minimizing wastage and environmental impact. The introduction of the aforementioned intelligent technologies enables WWTPs to operate more efficiently, sustainably, and adaptively; this represents a great leap toward a smart and effective wastewater treatment management system capable of dealing with the challenges of modern water treatment.

B. Supervisory Control and Data Acquisition (SCADA) Systems

Supervisory Controls and Data Acquisition (SCADA) systems perform regulating and monitoring functions of operations taking place in a wastewater treatment plant (WWTP). SCADA systems are made up of not only hardware but software components that provide procedures for remote acquisition, control, and real-time monitoring from diverse plant processes. With the aid of sensors, a controller, and a communication network, SCADA employs a unified user interface for monitoring key processes such as aeration, chemical dosing, and sludge management [12]. SCADA systems perform simple automation, like monitoring, control, and automation for certain repetitive tasks, and performance monitoring, where they are accessed from a centre at an unknown location. SCADA allows continuing monitoring and reporting by achieving operational efficiencies, reducing response times to disturbance in process disturbances, and being able to meet the required regulatory standards.

The studies cantered on SCADA system implementation in such WWTPs show the transformation SCADA produced there first, a WWTP applying SCADA for aeration control is reported to have achieved notable energy savings as it is dynamically responding to sensors [13]. A second case utilized SCADA systems to optimize sludge processing with a resultant lowering in the use of chemicals and operational costs while improving effluent quality. In addition, SCADA's ability to make forecasts about upcoming equipment failures and alarms through trend analysis has reduced unplanned downtimes within many of the facilities. These examples show how SCADA systems enjoy greater reliability, sustainability, and cost-effectiveness in contributing to modern wastewater management.

C. Artificial Intelligence (AI) and Machine Learning (ML) Applications

AI and machine learning are impacting wastewater treatment plants through advanced data-driven process optimization and decision-making. AI-driven predictive analytics build a deep learning model that employs historical and real-time data to forecast process outcomes for milling out more optimized operational parameters. For example, predictive models can estimate influent flow rates, pollutant loads, or energy demands that allow operators to adjust processes proactively, such as aeration, sludge handling, or chemical dosing, to avoid operating at suboptimal efficiency [14]. The proactive nature of this approach reduces energy consumption, generates less chemical waste, and stabilizes effluent quality while minimizing overall operational costs. AI systems, moreover, could also simulate alternative treatment scenarios and sophistically recommend the best corresponding treatment strategies put in place to maximize plant performance, in turn, providing a more adaptive and sustainable option for wastewater management. Machine learning, as a subset of AI applicable to this transformation, is increasingly being applied to detect patterns and anomalies from huge volumes of operational data collected by sensors. ML algorithms can scan for some early signs of an equipment malfunction, process deviation, or unusual influent condition, and send alerts ahead of time to prevent failure or disruption [15]. Further, those sentient systems can operationally renegotiate themselves for optimum plant operation by, for instance, dynamically varying aeration rates or sludge return rates on the basis of unit strategy of characteristics in a changing wastewater context. Through advanced predictive capabilities, automation of complex decision-making, and improved situational awareness, AI and machine learning will provide WWTPs with operational resilience while also enhancing their efficiency, sustainability, and adaptability in the face of ever increasing environmental and regulatory challenges.

D. Big Data and Cloud-Based Monitoring

Big Data and cloud monitoring-integration are changing how wastewater treatment works. Real-time monitoring will be possible thanks to advances in Big Data technology and provides additional tools to increase operational efficiency. Nowadays, it is feasible for WWTPs to take the huge operational data from sensors, equipment, and historical records for simulations and analysis in Big Data analytics. Data analytics help discover trends during the treatment of wastewater, process optimization, and disclosure of inefficiencies that would otherwise proceed unnoticed [16]. For example, data analytics could discover patterns of energy consumption, warn plant operators about software peaks in demand periods, or identify an inefficient aeration system or a faulty dosing system. The operators will be equipped with the tools that allow them to leverage insights from Big Data, helping them make data-driven decisions consequently, lower costs, improve resource utilization, and achieve even better performance. Cloud is augmenting the functionality of Big Data by enabling real-time monitoring and control of processes in wastewater treatment plants from nearly any location. A cloud-based computer system uses secure servers to upload data from sensors and devices continuously while allowing operators to evaluate and analyse real-time information via web-based dashboards or mobile apps [17]. The real-time connectivity offers quicker responses to process disturbances, such as predictive maintenance or operation management from a distance. Cloud platforms enhance all functions with scalability and computational power, making it easy to implement a range of advanced technologies from machine learning to IOT devices. Symbolically, Big Data analytics- and Cloud- combined provide a comprehensive modern advanced overview for wastewater treatment plants and their wastewater management challenges.

E. Blockchain for Wastewater Data Security

Blockchain plays a prominent role in secured and decentralized data management, enabling transformative advantages for industries, ranging from wastewater treatment to environmental monitoring. At its core, a blockchain is a distributed ledger system that guarantees data integrity, security, and transparency through a decentralized network of nodes. Unlike traditional centralized systems, it removes the defect of an authority, allowing data to be recorded in unalterable blocks cryptographically linked [18]. Such decentralization, thus, decides that the data shall not be altered, deleted, or re-engineered without consent from the others present in the network, making it a highly secure solution for critical and sensitive information management. In wastewater data treatment plants and similar applications, blockchain stores sensitive operational data like sensor data readings, parameters for the process, and compliance records, which become an irrefutable audit trail for regulatory and operational Transparency. Blockchain further enhances trust in sharing information among several parties, including regulatory bodies, plant operators, and service providers, since it accounts for all transactions and interaction in an unchangeable format. It also allows final authorization to verify real-time data, an option that assures that only accurate and authorized data is used [19]. In addition, smart contracts, or self-executing protocols that are integrated within blockchain, could help automate various processes, e.g., planning necessary equipment maintenance or sending pollutants threshold notifications; hence, such approaches maintain real-time execution with minimum manual intervention. By employing blockchain, WWTPs and other industries can assure that their data management functions are secure, transparent, and decentralized, thus paving the way for stronger operational accountability, increased collaboration, and enhanced resistance to cyberattacks or data breaches.

III. SUSTAINABILITY ASPECTS OF EMERGING CONTROL TECHNOLOGIES

Emerging control technologies in wastewater treatment plants (WWTPs) must therefore be researched for sustainability aspects, as they are linking certain environmental, economic, and social challenges with advanced control systems. Their incorporation in most state-of-the-art control systems has made remarkable strides for WWTPs in terms of energy conservation because real-time data are used to adjust treatment processes such as aeration and chemical dosing [20]. This reduces resource wastage and operating costs while falling within effluent quality demanded by regulatory authorities. Predictive maintenance and smart sensors enhance the longevity of equipment and minimize pollutant discharges, which would otherwise occur through frequent replacements and prolonged downtimes. The amalgamation of these technologies also adheres to circular economy ideas on resource retrieval-such as energy gain from anaerobic digestion or nutrient retrieval from sludge [21]. Emerging control technologies, by encouraging effective resource use, pollution reduction, and cost-effectiveness, provide long-term sustainability to WWTP operations in line with global goals for environmental protection and resource conservation.

A. Reducing energy consumption and operational costs

Energy Consumption is one of the largest operational expenses in the wastewater treatment plants (WWTPs), with aeration, pumping, and chemical dosing representing a significant part of energy consumption in WWTPs. The new emerging technologies such as AI-driven process optimization, real-time monitoring, and cutting-edge control systems will significantly reduce the energy demand by dynamically adjusting operational parameters in real time based on demand [22]. For instance, the smart aeration control systems will supply the optimum oxygen to the biological treatment processes and would thus avoid excessive energy use-efficient treatment. Also, predictive maintenance supported by machine learning detection of the inefficiencies prevents the cascade of costly breakdowns while reducing the expense on maintenance. With the merging of these energy-efficient systems, these treatment plants could significantly lower their operational costs while improving sustainability.

B. Enhancing Treatment Efficiency and Effluent Quality

Since the introduction of modern control technologies, wastewater treatment efficiency has improved through precise process control and reduced treatment performance variability. IoT-enabled sensors collect real-time data, which enables continuous monitoring of the parameters like pH, nutrient levels, and dissolved oxygen for the operator in making data-driven decisions to optimize treatment efficiency. Provided with such algorithms, the use of AI and machine learning can analyse huge datasets to predict and prevent a process disturbance so that the effluent meets regulatory discharge standards [23]. With advanced technologies improving treatment efficiency, water quality, it also minimizes the amount of chemical dosing, thus further reducing environmental impact.

C. Minimizing Greenhouse Gas Emissions from WWTPs

WWTPs play a major role in GHG emissions namely CH_4 and N_2O, which arise from biological treatment and sludge handling. Advanced process control strategies mitigate such emissions by optimizing aeration, reducing excessive organic matter breakdown, and enhancing sludge management. For example, an AI-based system can provide precise control of the oxygen fed into the aeration tank, preventing excessive GHG emissions, especially nitrous oxide, while ensuring that microbial efficiency is maintained [24]. Also, by employing improved anaerobic digestion techniques for sludge treatment, they enhance biogas production, thereby reducing methane emission whilst providing a renewable energy source for internal use in the facility. Such means help WWTPs to significantly reduce their carbon footprint through efforts to mitigate climate change.

D. Resource Recovery and Circular Economy Approaches

An important aspect of modern wastewater treatment is the growing trend towards resource recovery and circular economy approaches, in which wastewater is considered a valuable resource rather than a waste product. New technologies aid in the recovery of nutrients from the water, particularly nitrogen and phosphorus that could be utilized to produce fertilizers in sustainable agriculture. Biogas generated from anaerobic digestion of the sludge can be used for energy generation, thereby minimizing the burden on fossil fuels. Some advanced filtration and membrane technologies provide an opportunity to reuse water for industrial, agricultural, and even potable applications, therefore reducing freshwater demands [25]. With circular economy thinking, WWTPs can transition into a sustainable model where waste is almost eliminated, resources are recovered, and environmental impacts are greatly reduced.

IV. CHALLENGES OF EMERGING TECHNOLOGIES

Emerging technologies offer significant benefits for wastewater treatment plant (WWTP) operation; they nevertheless face various challenges to implementation. The first is the high cost and infrastructure requirements of deployment. Advanced control techniques-whether for AI optimization, IoT monitoring, or blockchain-secure data-collect high investments in hardware, software, or technical expertise. Some WWTPs, especially in developing regions, might find it challenging to upgrade old systems to incorporate these latest technologies. In addition, the integration of these systems often requires some modifications in the existing infrastructure, which can be both complicated and time-consuming.

Another large challenge is the demand for data management accompanied by cybersecurity concerns. As WWTPs get more reliant on real-time monitoring, cloud computing, and AI-based analytics, they produce vast amounts of data which need to be carefully stored, processed, and mined. Ensuring data integrity and making certain that confidential operational information is safe from cyber-attacks guarantees system reliability. There are risks of hacking, breaching of information, or system failure regarding cloud-based monitoring platforms-a potential threat to both plant security and its operational stability. Setting up robust cybersecurity frameworks and employing block-chain-based decentralized security framework will provide an answer.

Technical complexity and workforce adaptability also hamper the adoption of emerging technologies. Many WWTPs have used traditional control systems, while other technological advances-such as automation, AI, and machine-learning processes-would require specialized expertise. Without trained personnel to work with AI-based decision-making systems and the interpretation required, efficient installation may be weakened. Also, plant operators and technicians may need rigorous training to utilize new digital tools and smart control systems. This challenge involves workforce development and the fostering of a culture of continuous learning in the industry.

WWTPs are among the main sources of microplastic pollution; thus, a better understanding of microplastics behaviour during treatment processes is in dire need. In a review which involved 38 WWTPs in 11 countries, it was shown that influent microplastic concentrations varied between 0.28 and 3.14×10^4 particles per liter, and discharged effluents were determined to contain microplastic levels from 0.01 to 2.97×10^2 particles per liter. Between 4.40×10^3 and 2.40×10^5 particles per kilogram were retained by sludge, while WWTPs on an approximate basis released 5.00×10^5 to 1.39×10^{10} microplastic particles on a daily basis. The filter-based treatments exert the greatest removal efficiency during primary settling, where fibers and large microplastics with sizes ranging between 0.5 mm and 5 mm are also separated, while smaller particles (probably <0.5 mm in diameter) end up captured in activated sludge by bacteria [26]. Overall, microplastic pollution from WWTPs is a reason for concern; more effort in research needs investigation toward

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their transformation, toxicity, as well as long-term environmental impact. The number of wastewater treatment plants WWTPs is on the increase and power-intensive treatment technologies are getting adopted, thereby increasing energy consumption, further complicated by climate change impacts; the present study discusses the latest available energy efficiency research regarding municipal WWTPs, analysing the different treatment phases, and other influential factors including plant size, load factor, and dilution factor. Anaerobic-anoxic-oxic systems are the best at high-pollutant-removal areas with moderate energy consumption (0.267 kWh/m^3) and practically equal to the conventional activated sludge process (0.269 kWh/m^3), while greater energy is required by membrane bioreactors-adopted for wastewater reuse (0.33 kWh/m^3). Other energy-efficiency improvements can be made via automation, inverters, and flexible operational strategy [27]. Therefore, a holistic multi-criteria approach for the more advantageous energy performance of WWTPs is suggested, integrating several input and output factors to this end.

Existing study highlights the importance of improving energy efficiency in wastewater treatment plants (WWTPs) in light of growing populations, increasing energy prices, and more stringent effluent discharge regulations. The energy used in these plants significantly affects their economic viability and the performance of smart grids, yet there is still a lack of comprehensive studies on achieving energy self-sufficiency and optimizing costs [28]. Areas that require attention include the development of better pumping systems, advanced motor technologies, and robust control systems to manage the complexities and uncertainties inherent in WWTP operations. The quality of effluent is influenced by levels of biochemical oxygen demand (BOD) and total Kjeldahl nitrogen (TKN), underscoring the necessity for effective treatment processes. This study aims to review previous research, identify current challenges, and explore future directions in WWTP control technologies, with the goal of steering studies and industry professionals toward sustainable and cost-effective solutions that optimize energy use.

Poly- and perfluoroalkyl substances (PFAS) refer to a large group of over 4,000 synthetic chemicals that are commonly found in various industrial and consumer products. The study focused on their global distribution and behavior in wastewater treatment plants (WWTPs). Most monitoring studies have been carried out in China (30%), Europe (30%), and North America (16%), while data from developing regions is still scarce. PFAS, which include both short and long-chain perfluoroalkyl acids (PFAAs), are often found in influents (up to 1,000 ng/L) and effluents (ranging from 15 to over 1,500 ng/L), with conventional WWTPs showing low removal efficiencies [29]. The main process that transforms PFAS precursors into PFAAs is biodegradation. Advanced treatment methods, such as ion exchange resins, electrochemical degradation, and nanofiltration, can achieve higher removal rates (approximately 95–100%), but they encounter challenges when it comes to large-scale application. Combining different treatments, like using nanofiltration followed by biochar or activated carbon adsorption, appears promising but needs more validation for practical use. The study focuses on the methods used for sampling, preparing samples, and identifying microplastics in wastewater treatment plants. The presence and accumulation of microplastics in the environment raise significant environmental and ecological issues. Wastewater treatment plants contribute to the spread of microplastics, creating further risks that must be addressed. Consequently, a major challenge lies in comprehending the fate and prevalence of microplastics within these facilities and the capacity to detect them at every stage of the treatment process [30]. This study aims to enhance our understanding of how microplastics behave and occur in wastewater treatment plants. Additionally, it is structured to provide a comprehensive overview of the various techniques available for detecting microplastics, from sampling to identification.

Table 1 Comparative Analysis of WWTP Treatment Efficiency and Sustainable Practices

Aspect	**Key Findings**	**Effective Treatment Methods**	**Challenges**
Microplastic Pollution in WWTPs	Microplastic levels in influent: 0.28 - 3.14 × 10^4 particles/L; Effluent: 0.01 - 2.97 × 10^2 particles/L; Sludge: 4.40 × 10^3 - 2.40 × 10^5 particles/kg; WWTPs release 5.00 × 10^5 - 1.39 × 10^{10} particles daily.	Filter-based treatments show the best removal efficiency; Primary settling removes large microplastics (0.5-5 mm); Smaller particles (<0.5 mm) captured in activated sludge.	Further research needed on microplastic transformation, toxicity, and long-term environmental impact.
Energy Efficiency in WWTPs	Anaerobic-anoxic-oxic systems consume 0.267 kWh/mÂ^3, similar to conventional activated sludge (0.269 kWh/mÂ^3); Membrane bioreactors for reuse require higher energy (0.33 kWh/mÂ^3); Automation and	Anaerobic-anoxic-oxic systems for high-pollutant removal; Energy efficiency improvements via automation, inverters, and flexible strategies.	Impact of climate change on WWTP energy use; Need for sustainable energy integration in treatment plants.

	operational flexibility improve efficiency.		
Challenges in WWTP Energy Optimization	Energy use affects plant economy and smart grid performance; Limited research on energy self-sufficiency; Key focus areas include optimized pumping systems, advanced motor technologies, and robust control systems.	Holistic multi-criteria approach integrating multiple inputs and outputs; Smart control technologies and adaptive operational strategies.	Limited comprehensive studies on achieving energy self-sufficiency; Uncertainties in optimizing operational costs and system efficiencies.
PFAS Contamination in WWTPs	PFAS levels: Influent up to 1,000 ng/L, Effluent 15 - 1,500 ng/L; Low removal efficiency in conventional WWTPs; Advanced treatments like ion exchange resins, electrochemical degradation, and nanofiltration show ~95â€“100% removal.	Nanofiltration followed by biochar/activated carbon adsorption promising; Ion exchange resins and electrochemical degradation effective but face scaling challenges.	Lack of data on PFAS in developing countries; Large-scale applicability of advanced removal technologies remains unverified.

V. CONCLUSION

The use of emerging technologies in wastewater treatment facilities (WWTPs) offers a transformative opportunity to optimize operational efficiency, bring sustainable approaches, and satisfy the regulatory requirements for cleaner water discharge with optimal resource utilization. Traditional control methods with manual mechanics and PID controllers have long been the standard; however, they were faced with substantial limitations in controlling the dynamic and complicated processes associated with wastewater treatment. Sophisticated control models, such as AI, ML, SCADA, and IoT-enabled sensors, offer real-time monitoring, predictive analytics, and grand control mechanisms to minimize energy consumption, improve treatment performance, and mitigate operational inefficiencies. Basic AI and ML are algorithms used to scour data sets for anomalous trends, relating them to directly control mechanisms that facilitate adaptable process adjustments for enhanced operational stability and reduced waste. IoT sensor technology enables remote telemetry monitoring of operational parameters. SCADA systems enable remote monitoring and automation with very little manual intervention and improvements in response time to processes' disturbances, and IoT-enabled sensors continually collect and transmit real-time data, ensuring that critical parameters such as pH, dissolved oxygen, and pollutant levels stay balanced, thus decreasing energy waste and optimizing the treatment. These advancements have, however, not been widely adopted partly because of the high costs of initial investment, integration difficulties with existing infrastructure, and the need for skilled personnel to operate or maintain these advanced systems. Threats to cybersecurity and issues of data management are critical as wastewater treatment plants (WWTPs) increasingly become reliant on cloud-based monitoring and digital automation, which require proper cybersecurity mechanisms and decentralized mechanisms of data management like blockchain technologies in safeguarding operational integrity and preventing unauthorized access. Furthermore, continuing environmental problems, such as micro-plastic pollution, excessive energy consumption, and possible contamination of the water sources by Poly- and Perfluoroalkyl Substances (PFAS), warrant further research and innovation in treatment methodologies. Microplastics represent enormous ecological and health threats; thus, advanced filtration, bioremediation, and monitoring may play a role in enhancing their removal efficiency, while the operation of the WWTP requires energy-intensive technologies' integration, including anaerobic digestion for biogas production, renewable energy adoption, and smart grid adaptability to lessen carbon footprints and reduce operational costs. In connection with that, developing cost-effective and scalable solutions on WWTP's performance and environmental sustainability can be achieved as a collaborative effort among various stakeholders, including policymakers, industry leaders, researchers, and regulatory bodies. It will be the regulatory framework transition toward smart wastewater management that would in particular require incentives and also developments in innovation areas around resource recovery technologies, including nutrient extraction, biogas production, and water reuse applications, reinforcing the principles of circular economy and curbing waste generation and improving the efficiency of resource utilization. Future initiatives should focus on integrating automation, energy efficiency, pollutant removal and cost-effectiveness to form holistic, multicriteria assessment models that will inform sustainable WWTP operations towards long-term process resiliency, compliance with regulatory requirements, and an expanded commitment to environmental stewardship. Trained for technology advances and sustainable management strategies can help WWTPs secure a significant positive step towards water resource protection and public health that, when coupled, form a cleaner and more sustainable future for generations to come.

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