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Study on the Impact of Mechanical Equipment Efficiency on Energy Consumption and Carbon Emissions in Wastewater Treatment Plants

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دراسة تأثير كفاءة المعدات الميكانيكية على استهلاك الطاقة والانبعاثات الكربونية في محطات معالجة مياه الصرف الصحي

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Abstract:

Wastewater treatment plants (WWTPs) are widely recognized as energy-intensive facilities that consume a substantial share of municipal electricity, with mechanical equipment—such as pumps, blowers, and mixers—accounting for the majority of this demand. This intensive energy consumption translates directly into indirect carbon emissions, while biological treatment processes concurrently generate direct greenhouse gas emissions, notably methane and nitrous oxide. This paper presents a comprehensive review of the relationship between mechanical equipment efficiency, energy consumption, and carbon footprints within WWTPs. The analysis examines the energy profiles of primary mechanical systems, revealing that aeration and pumping units constitute the largest energy consumers. Furthermore, the biological treatment stage is identified as the primary contributor to overall carbon emissions. The study explores optimization pathways, including high-efficiency motor adoption, variable frequency drives, advanced control algorithms, and artificial intelligence-based frameworks. Evidence from recent literature indicates that targeted equipment upgrades and intelligent management can achieve significant energy savings, reinforcing that mechanical optimization is a cost-effective strategy for advancing carbon neutrality in wastewater management.

Keywords: Wastewater treatment plants; Mechanical equipment efficiency; Energy consumption; Carbon emissions; Pumping systems; Aeration systems; Greenhouse gases; Energy optimization.

الملخص
تُصنف محطات معالجة مياه الصرف الصحي على نطاق واسع كمنشآت كثيفة استهلاك الطاقة، حيث تستحوذ على حصة معتبرة من الكهرباء البلدية، وتتسبب المعدات الميكانيكية مثل المضخات، والموافق الهوائية، والخلاطات في الجزء الأكبر من هذا الطلب. يترجم استهلاك الطاقة هذا بشكل مباشر إلى انبعاثات كربونية غير مباشرة، بينما تولد عمليات المعالجة البيولوجية في نفس الوقت انبعاثات مباشرة لغازات الدفيئة، لا سيما غاز الميثان وأكسيد النيتروز. تقدم هذه الورقة مراجعة شاملة للعلاقة بين كفاءة المعدات الميكانيكية، واستهلاك الطاقة، والبصمة الكربونية في محطات معالجة مياه الصرف الصحي. يدرس التحليل استهلاك الطاقة للأنظمة الميكانيكية الرئيسية، مبينًا أن وحدات التهوية والضخ تمثل المستهلك الأكبر للطاقة. علاوة على ذلك، تم تحديد مرحلة المعالجة البيولوجية باعتبارها المساهم الأساسي في إجمالي الانبعاثات الكربونية. تستكشف الدراسة مسارات التحسين، والتي تشمل اعتماد المحركات عالية الكفاءة، ومحركات التردد المتغير، وخوارزميات التحكم المتقدمة، والأطر المستندة إلى الذكاء الاصطناعي. تشير الأدلة المستمدة من الأدبيات الحديثة إلى أن ترقيات المعدات المستهدفة والإدارة الذكية يمكن أن تحقق وفرا كبيرا في الطاقة، مما يؤكد أن التحسين الميكانيكي يمثل استراتيجية مجدية من حيث التكلفة لتعزيز الحياد الكربوني في إدارة مياه الصرف الصحي.

الكلمات المفتاحية: محطات معالجة مياه الصرف الصحي؛ كفاءة المعدات الميكانيكية؛ استهلاك الطاقة؛ الانبعاثات الكربونية؛ أنظمة الضخ؛ أنظمة التهوية؛ غازات الدفيئة؛ تحسين الطاقة.

1. Introduction

Wastewater treatment plants (WWTPs) serve as critical infrastructure for protecting public health and aquatic ecosystems by removing contaminants from municipal and industrial wastewater. However, these facilities are traditionally known as energy-intensive operations, where substantial energy consumption not only results in higher operational costs but also contributes significantly to indirect carbon emissions. The wastewater treatment sector accounts for approximately 1–2% of society-wide total carbon emissions, with emissions divided into direct discharges of gases such as CO_2, CH_4, and N_2O during treatment processes, and indirect carbon emissions caused by equipment operation and energy consumption.

The global imperative to achieve carbon neutrality has intensified research efforts to reduce energy consumption and carbon emissions in wastewater treatment. Energy consumption typically accounts for 40% of the operating costs of WWTPs, making energy efficiency improvements both an environmental and economic priority. Mechanical equipment—including pumps, blowers, aerators, mixers, and sludge processing machinery—represents the primary energy-consuming components within WWTPs. The efficiency of this equipment directly influences both the quantity of electricity consumed and the associated indirect carbon emissions.

This manuscript provides a comprehensive analysis of the relationship between mechanical equipment efficiency, energy consumption, and carbon emissions in wastewater treatment plants. The study synthesizes recent research findings and technological developments to establish a framework for understanding how equipment efficiency improvements can contribute to carbon reduction goals. The specific objectives include:

(1) characterizing energy consumption patterns across different mechanical systems in WWTPs.

(2) quantifying the carbon emission implications of equipment energy use.

(3) examining emerging technologies and strategies for improving mechanical equipment efficiency.

(4) presenting case studies demonstrating successful efficiency improvement implementations.

2. Energy Consumption in Wastewater Treatment Plants

2.1 Overview of Energy Consumption Patterns

WWTPs are recognized as energy-intensive industries, particularly those employing anaerobic–anoxic–oxic (A_2O) technology. The energy consumption of sewage treatment encompasses multiple processes, with aeration energy consumption and pumping energy consumption representing the two largest components. The specific energy consumption of WWTPs typically ranges from 0.21–0.34 kWh/m^3 of treated wastewater, influenced by various internal and external factors including treatment technologies, plant scale, and operational strategies.

The main sources of energy consumption within WWTPs have been systematically identified in recent reviews, with key influencing factors including treatment technologies, plant scale, and operational strategies. Based on this foundation, three main pathways toward energy neutrality have been identified: (1) energy conservation, (2) energy recovery, and (3) utilization of external renewable energy sources.

2.2 Equipment-Level Energy Consumption Breakdown

At the equipment level, energy consumption patterns vary significantly across different treatment stages and technologies. Aeration systems consistently emerge as the dominant energy consumer, with aerators accounting for 72.68% of energy consumption in many configurations. Mixers follow at approximately 12.95%, with pumps contributing around 10.59%. Other equipment, including clarifier bridges and ancillary systems, account for the remaining energy use.

A study of an industrial zone WWTP in Vietnam revealed that wastewater pumps, blowers, mixers, and sludge pumps consume a substantial 77.6% of total electricity consumption, with an average specific energy consumption of 0.93 kWh/m^3 of treated wastewater—15–20% higher than international benchmarks for similar-scale facilities. This finding highlights the significant opportunities for energy efficiency improvements through mechanical equipment optimization.

3. Major Mechanical Equipment Systems and Their Efficiency Impact

3.1 Pumping Systems

Pumping systems represent one of the most critical mechanical components in WWTPs, serving multiple functions including raw sewage lifting, recirculation, sludge transfer, and final effluent discharge. It has been estimated that pumping systems account for 15–70% of total WWTP electricity consumption, depending on plant configuration and hydraulic design.

The energy efficiency of pumping systems is influenced by numerous factors including pump type, motor efficiency, operating point relative to best efficiency point, system head characteristics, and control strategies. Variable frequency drives (VFDs) have emerged as a key technology for improving pumping system efficiency by adjusting pump parameters according to changing flow conditions. However, the full potential of VFDs is not realized without sophisticated control algorithms.

Recent research has demonstrated the substantial energy savings achievable through pumping system optimization. A deep learning approach combining ResNet, self-attention mechanisms, and Grey Wolf Optimizer developed for wastewater pumping energy optimization achieved 10–30% energy savings compared to traditional PID control, outperforming genetic algorithms (12–18%) and LSTM-based approaches (18–25%). The optimization framework employs key design variables including the ratio of static head to best efficiency point head, demonstrating that higher values substantially improve energy efficiency while enhancing prediction capabilities.

The pretreatment stage presents particularly significant opportunities for pumping system optimization. Research on carbon emission accounting in municipal WWTPs has revealed that

80.4% of carbon emissions in the pretreatment stage originate from the electricity consumption of sewage lifting pump stations (0.030 kg CO_2eq/m^3). This finding underscores the importance of efficient pump selection and operation in reducing the carbon footprint of wastewater treatment.

3.2 Aeration Systems

Aeration systems are universally recognized as the most energy-intensive process in wastewater treatment. Aeration represents approximately 51–70% of the total energy required in a WWTP, with some studies indicating that the aeration process accounts for 65–70% of overall energy consumption. Aeration energy consumption refers to the energy consumed by aerating the aerobic tank when treating biochemical oxygen demand (BOD) matter in sewage, a process affected by various factors including organic matter concentration, dissolved oxygen requirements, and equipment efficiency.

The efficiency of aeration systems is determined by several factors including blower type, diffuser design, oxygen transfer efficiency, and control system sophistication. Conventional air diffuser systems have been shown to consume significantly more energy than innovative alternatives. A novel aeration device based on Bernoulli's principle, the Jetventrumixer (JVM), demonstrated a dramatic 52.1% reduction in energy consumption while maintaining high removal efficiency and nitrification efficiency compared to conventional systems.

Turbo blowers and other advanced aeration technologies are reshaping the future of wastewater treatment, helping plants cut energy consumption, reduce costs, and improve operational efficiency. A recent blower system retrofit at a WWTP produced a noticeable uptick in energy efficiency, with the G5plus series enabling an efficiency gain of approximately 21% for the aeration of wastewater tanks. Efficient rotary screw blowers and optimized aeration have demonstrated savings of up to 35% in comparison to conventional blower systems.

Intermittent aeration strategies have also shown promise for reducing energy consumption and greenhouse gas emissions. Studies comparing conventional activated sludge with oxic-settling-anaerobic processes employing intermittent aeration have demonstrated that operational strategies can significantly influence both treatment efficiency and energy consumption. Seasonal variation in hydraulic flow and load has a significant effect on aeration energy requirements, highlighting the importance of adaptive control strategies.

3.3 Mixing Equipment

Mixers in aeration and sludge tanks can account for up to 10–20% of a WWTP's overall energy use. While mixing energy consumption is smaller than aeration, it remains a substantial component of total energy use and presents significant optimization opportunities.

By selecting energy-efficient mixers, operators can reduce energy consumption attributed to mixing by as much as 50%. Advanced mixer technologies including permanent magnet motors have demonstrated significant energy savings. Sulzer's XRW 400 submersible mixers with permanent magnet motors, installed in denitrification tanks, have been shown to cut energy costs by up to EUR 45,000.

Energy-efficient mixing can also indirectly reduce the far larger aeration energy consumption by improving process efficiency. This synergistic effect underscores the importance of considering mixing system optimization as part of a holistic approach to WWTP energy management.

3.4 Sludge Treatment Equipment

Sludge treatment represents another significant energy consumer in WWTPs, with mechanical dewatering equipment including centrifuges, belt presses, and filter presses consuming substantial electricity. Energy consumption per tonne of dry solids processed increases when sludge is poorly conditioned, as the equipment runs longer or at higher intensity to achieve target throughput.

Research on decanter centrifuge energy modeling has identified opportunities for energy optimization through braking recovery systems during the sludge dewatering process. The morphological characteristics of activated sludge significantly impact the energy requirements for centrifugal dewatering, with sludge characteristics affecting both the operating conditions and energy consumption for achieving desired dewatering levels.

Carbon emissions during the sludge treatment stage are concentrated in residual sludge lifting (0.0086 kg CO_2eq/m^3) and sludge dewatering/pressing (0.0088 kg CO_2eq/m^3). These findings highlight the importance of optimizing sludge handling equipment to reduce both energy consumption and carbon emissions.

4. Carbon Emissions from Wastewater Treatment

4.1 Sources and Magnitude of Carbon Emissions

Wastewater treatment plants are recognized as significant sources of greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These emissions contribute substantially to global climate change, with methane and nitrous oxide exhibiting particularly high global warming potentials. Methane traps 27–29.8 times more heat than CO_2, while N_2O has an exceptionally high Global Warming Potential of 273.

Global estimates indicate that CH_4 and N_2O emissions from wastewater treatment amount to 378 and 79.7 million tons of CO_2-equivalent annually. Approximately 9% of global methane and 3% of nitrous oxide emissions originate from wastewater treatment activities. In China, CO_2 emissions from wastewater treatment surged from 13.34 million tons in 2005 to 53 million tons in 2019.

Direct emissions include CO_2 produced during biological breakdown of organic matter through microbial respiration, CH_4 released from anaerobic sludge digestion and septic tanks, and N_2O generated during nitrogen removal processes under low dissolved oxygen conditions. Indirect CO_2 emissions from electricity and fuel consumption contribute an additional 17% to the sector's GHG footprint.

4.2 Process-Level Carbon Footprint

A life-cycle carbon footprint model encompassing pretreatment, biological treatment (A_2O process), and sludge treatment stages has revealed that the biological treatment stage contributes 68.14% of total carbon emissions. N_2O, due to its high global warming potential, is the primary source of direct emissions at 0.333 kg CO_2eq/m^3.

In the pretreatment stage, 80.4% of carbon emissions originate from the electricity consumption of sewage lifting pump stations (0.030 kg CO_2eq/m^3). During sludge treatment, carbon emissions are concentrated in residual sludge lifting (0.0086 kg CO_2eq/m^3) and sludge dewatering/pressing (0.0088 kg CO_2eq/m^3).

4.3 Relationship Between Equipment Efficiency and Carbon Emissions

The relationship between mechanical equipment efficiency and carbon emissions is direct and quantifiable. Each unit of electricity consumed by mechanical equipment results in indirect CO_2 emissions proportional to the carbon intensity of the electricity grid. Improving equipment efficiency reduces electricity consumption and consequently reduces indirect carbon emissions.

For aeration systems, which represent the largest energy consumer, efficiency improvements have substantial carbon reduction potential. The implementation of precise aeration control systems and high-efficiency blowers can reduce energy consumption by 20–35%, with corresponding reductions in indirect carbon emissions. Similarly, pumping system optimization through VFD implementation and advanced control algorithms can achieve 10–30% energy savings.

5. Energy Efficiency Optimization Strategies

5.1 High-Efficiency Equipment Selection

The selection of high-efficiency mechanical equipment represents the most fundamental strategy for reducing energy consumption and carbon emissions. High-efficiency motors, including IE3 and IE4 class motors, have demonstrated significant energy savings in pumping and mixing applications. The adoption of energy-efficient mixers has been shown to reduce mixing energy consumption by up to 50%.

For aeration systems, the selection of efficient air blowers is of paramount importance for energy conservation, as up to 50% of the operating cost in a WWTP is attributed to airflow generation. Turbo blowers and efficient rotary screw blowers offer substantial efficiency advantages over conventional systems.

5.2 Variable Frequency Drives and Advanced Control

Variable frequency drives have emerged as a key technology for improving mechanical equipment efficiency by enabling precise matching of equipment output to process requirements. VFD-controlled blowers can adjust airflow based on dissolved oxygen levels, maintaining ideal treatment conditions while minimizing energy consumption. VFD implementation for pumps, blowers, and agitators represents one of the most cost-effective energy-saving measures.

Advanced control systems incorporating machine learning and artificial intelligence have demonstrated significant potential for energy optimization. Machine learning-driven process parameter optimization minimizes direct and indirect carbon emissions by reducing energy-intensive operations. Machine learning facilitates sludge management through energy-efficient dewatering and resource recovery strategies, demonstrating both environmental compatibility and economic viability.

5.3 Process Optimization and Control Strategies

Simulation-based optimization has proven effective for reducing energy consumption in WWTPs. A study implementing aeration control in the WEST software platform achieved a 26% reduction in energy consumption within a month of implementation on a processing line, while maintaining treatment effectiveness and producing excellent effluent quality. The control approach achieved significant reductions including 93% for oxygen demand, 98% for suspended solids, 20% for total phosphorus, and 98% for ammonium levels.

Intelligent control and process optimization have demonstrated energy savings of 13.1% and electricity cost reductions of 41.4% through integrated approaches combining multiple optimization strategies. Fuzzy control combined with machine learning for WWTP operations has achieved a 19.8% cost reduction.

5.4 Equipment Retrofit and Replacement

Equipment that has reached the end of its mechanical life typically exhibits decreased energy efficiency during operation and requires frequent maintenance. Replacing such equipment with modern, high-efficiency alternatives can yield substantial energy savings. A mechanical infrastructure renewal project achieved 50% energy savings through the replacement of pumps and mixers.

Targeted retrofits of specific mechanical systems have demonstrated significant improvements. A blower system retrofit achieved a 21% efficiency gain. The installation of high-efficiency blowers, variable speed drives, mass airflow meters, and automated controls has been shown to reduce energy usage across multiple systems.

6. Case Studies

6.1 Aeration System Optimization

The implementation of precise aeration control systems has demonstrated substantial energy savings in full-scale applications. The Jetventrumixer (JVM), a novel aeration device based on

Bernoulli's principle, achieved a 52.1% reduction in energy consumption while maintaining high removal efficiency. This innovation demonstrates the potential for disruptive technologies to dramatically improve aeration efficiency.

Aeration control strategy implementation in a large WWTP in Saida, Algeria, using simulation modeling, achieved a 26% reduction in energy consumption within one month. The approach successfully maintained treatment effectiveness while reducing oxygen demand by 93% and suspended solids by 98%.

6.2 Pumping System Upgrades

A deep learning approach for wastewater pumping energy optimization achieved 10–30% energy savings compared to traditional control methods. The optimization framework demonstrated that higher values of the ratio of static head to best efficiency point head substantially improve energy efficiency while enhancing prediction capabilities ($R^2 = 0.9957$).

The use of IE3 energy-efficient motors in pump installations has assisted in reducing energy consumption to about 1.3 kW per kilogram COD treated, from a level of over 1.9 kW previously. This represents a significant improvement in energy intensity for organic matter removal.

6.3 Integrated Mechanical Equipment Upgrades

A comprehensive mechanical infrastructure renewal project achieved 50% energy savings through the replacement of pumps and mixers that had reached the end of their mechanical life. The project demonstrated that systematic equipment replacement based on lifecycle analysis can yield substantial energy and cost savings.

A pilot study aimed at improving energy efficiency through upgrading mechanical equipment and electrical controls in one treatment line, while maintaining existing equipment in a reference line, enabled direct comparison of energy consumption and effluent quality between the lines. Such comparative studies provide valuable evidence for the effectiveness of equipment upgrades.

7. Discussion

7.1 The Interconnected Nature of Equipment Efficiency and Carbon Emissions

The analysis presented in this manuscript demonstrates that mechanical equipment efficiency is fundamentally interconnected with both energy consumption and carbon emissions in WWTPs. The direct relationship between electricity consumption and indirect carbon emissions means that every efficiency improvement translates into measurable carbon reduction. For aeration systems, which represent the largest energy consumer, efficiency improvements have the greatest potential for carbon reduction.

The biological treatment stage, which contributes 68.14% of total carbon emissions, relies heavily on mechanical equipment including aerators, mixers, and recirculation pumps. Optimizing the efficiency of these mechanical systems directly reduces both the energy consumption and the associated carbon emissions of the most emissions-intensive treatment stage.

7.2 Emerging Technologies and Future Directions

Machine learning and artificial intelligence are emerging as transformative tools for achieving carbon reduction in WWTPs. Machine learning-driven process parameter optimization minimizes direct and indirect carbon emissions by reducing energy-intensive operations, while greenhouse gas emission prediction modeling provides critical datasets for process effectiveness evaluation.

The integration of machine learning across wastewater, sludge, and gas systems establishes machine learning as a transformative tool enabling WWTPs to synchronize treatment efficiency enhancement, energy conservation, and carbon neutrality. Future research should focus on validating machine learning-based optimization strategies under varying conditions and exploring optimized approaches for energy-neutral wastewater management.

Technologies such as Anammox, biogas recovery, photovoltaic systems, and microbial fuel cells offer promising pathways for operational efficiency and long-term sustainability. The transition from energy efficiency to climate neutrality requires both lower energy consumption and a transition towards renewable energy sources.

7.3 Policy Implications and Practical Recommendations

The findings of this review have important implications for policy and practice. Energy costs typically represent 60–80% of a water treatment facility's operational expenses, making energy efficiency a critical concern. Policymakers should consider incentives for equipment upgrades and the adoption of energy-efficient technologies.

Practical recommendations for WWTP operators include: (1) conducting comprehensive energy audits to identify efficiency improvement opportunities; (2) prioritizing the replacement of end-of-life equipment with high-efficiency alternatives; (3) implementing variable frequency drives and advanced control systems; (4) adopting machine learning-based optimization where feasible; and (5) considering renewable energy integration to further reduce carbon footprints.

8. Conclusion

This manuscript has provided a comprehensive analysis of the impact of mechanical equipment efficiency on energy consumption and carbon emissions in wastewater treatment plants. The key conclusions are as follows:

1. Mechanical equipment—particularly pumps, blowers, aerators, and mixers—accounts for the majority of energy consumption in WWTPs, with aeration systems alone consuming 45–75% of total plant energy.
2. The biological treatment stage contributes approximately 68% of total carbon emissions, with N_2O emerging as the primary direct emission source due to its high global warming potential.
3. Pumping system optimization through variable frequency drives and advanced control algorithms can achieve 10–30% energy savings, while aeration system improvements can yield 20–52% reductions in energy consumption.
4. High-efficiency equipment selection, equipment retrofit and replacement, and intelligent control systems represent the most effective strategies for improving mechanical equipment efficiency.
5. Machine learning and artificial intelligence are emerging as transformative tools for optimizing equipment operation and reducing carbon emissions.
6. Case studies demonstrate that targeted mechanical equipment upgrades can achieve energy savings of 20–50% across various systems, with corresponding reductions in carbon emissions.

The path toward carbon-neutral wastewater treatment requires a multi-faceted approach combining energy conservation, energy recovery, and renewable energy utilization. Improving mechanical equipment efficiency represents one of the most immediate and cost-effective strategies for reducing both operational costs and carbon footprints. As the global community intensifies efforts to achieve carbon neutrality, the optimization of mechanical equipment in WWTPs will play an increasingly critical role in sustainable wastewater management.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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