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The Impact of Urban Wastewater Treatment on Carbon Emissions: Current Status, Challenges, and Future Perspectives

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Abstract

Urban wastewater treatment is crucial for protecting public health and aquatic ecosystems, but its carbon footprint has raised concerns in the context of climate change mitigation. This study provides a comprehensive review of the current status of carbon emissions from urban wastewater treatment, identifies key challenges, and proposes future perspectives for sustainable wastewater management. A systematic literature review was conducted to collect data on the carbon footprints of various wastewater treatment technologies, which were analyzed using a life cycle assessment approach. Scenario analysis was performed to evaluate the mitigation potential of different strategies. The results reveal that the carbon footprints of wastewater treatment plants (WWTPs) vary significantly depending on the treatment technologies employed, with advanced treatment processes generally having higher carbon emissions. Key factors contributing to the carbon footprint include energy consumption, direct greenhouse gas emissions, and embedded emissions from chemical use. The scenario analysis indicates that a combination of energy efficiency measures, renewable energy integration, and process optimization can significantly reduce the carbon emissions from WWTPs. This study highlights the importance of considering carbon emissions in the design and operation of urban wastewater treatment systems and provides valuable insights for developing sustainable

wastewater management strategies that balance environmental protection, public health, and climate change mitigation.

Keywords: Urban wastewater treatment, Carbon emissions, Carbon footprint, Greenhouse gases, Mitigation strategies

Introduction

Urban wastewater treatment is a critical component of modern urban infrastructure, playing a vital role in protecting public health, preserving aquatic ecosystems, and supporting sustainable urban development. With the rapid urbanization and population growth worldwide, the demand for efficient and effective wastewater treatment has never been greater. According to the United Nations World Urbanization Prospects [1], 55% of the global population currently resides in urban areas, and this proportion is projected to reach 68% by 2050. As a result, the volume of urban wastewater generated is increasing at an unprecedented rate, putting immense pressure on the existing wastewater treatment facilities and highlighting the need for sustainable wastewater management practices [2].

However, conventional wastewater treatment processes, while essential for maintaining public health and environmental quality, are energy-intensive and contribute significantly to greenhouse gas (GHG) emissions. Wastewater treatment plants (WWTPs) are recognized as significant point sources of GHG emissions, accounting for approximately 3% of the global energy consumption and 1% to 3% of the total GHG emissions [3,4,5]. The carbon footprint of WWTPs is primarily attributed to energy consumption associated with treatment processes, direct emissions from biological treatment, and embedded emissions from chemical use [6,7,8,9,10].

The increasing awareness of the climate change impact of wastewater treatment has prompted researchers and practitioners to investigate the carbon footprint of various treatment technologies and explore mitigation strategies.

Previous studies have compared the carbon footprints of various wastewater treatment technologies, indicating that advanced processes—such as membrane bioreactors (MBRs) and advanced oxidation processes (AOPs)—typically produce higher carbon emissions than conventional methods. This increase in emissions is largely attributed to the greater energy demands required for the operation and maintenance of these advanced systems [11].

Additional studies have aimed to identify the primary factors contributing to the carbon footprint of wastewater treatment plants (WWTPs) and to assess the effectiveness of various mitigation strategies. Demir et al. (2019) examined the carbon footprint of a large urban WWTP in Sanliurfa, finding that electricity consumption and direct emissions from the biological treatment process were the primary sources of the plant's greenhouse gas (GHG) emissions. The authors also evaluated the potential for biogas recovery and utilization to reduce the WWTP’s carbon footprint [12]. Other studies have explored the effectiveness of these strategies in mitigating GHG emissions by focusing on energy optimization, process improvements, and reduced chemical usage [13,14].

Despite the growing body of research on the carbon footprint of wastewater treatment, there remain significant knowledge gaps in understanding the complex interplay between wastewater treatment, carbon emissions, and sustainable urban development. Most of the existing studies focus on specific treatment technologies or individual WWTPs, lacking a comprehensive and systematic analysis of the current status, challenges, and future perspectives of carbon emissions from urban wastewater treatment at a broader scale.

Moreover, the potential synergies and trade-offs between carbon mitigation strategies and other sustainability objectives, such as water quality improvement, resource recovery, and ecosystem protection, are not well understood. As cities strive to enhance wastewater treatment coverage and quality to meet growing demands and stricter environmental regulations, it is crucial to develop sustainable wastewater management strategies that balance environmental protection, public health, and climate change mitigation.

To address these knowledge gaps, this study aims to provide a comprehensive review of the current status of carbon emissions from urban wastewater treatment, identify the key challenges, and propose future perspectives for sustainable wastewater management. The specific objectives of this study are:1. To assess the current status of carbon emissions from different wastewater treatment technologies based on a systematic literature review.2. To identify the key factors and challenges influencing the carbon footprint of urban WWTPs, including technological, operational, and environmental aspects.3. To evaluate the effectiveness of various carbon mitigation strategies, such as energy optimization, process improvement, renewable energy integration, and resource recovery, and their potential synergies and trade-offs with other sustainability objectives.4. To propose future perspectives and research directions for sustainable wastewater management, considering the emerging trends, technological innovations, and policy developments in the field.

Addressing the carbon footprint of urban wastewater treatment is not only essential for mitigating climate change but also for advancing the broader sustainability agenda. The United Nations' Sustainable Development Goals (SDGs) have highlighted the importance of sustainable wastewater management in achieving multiple development objectives, including ensuring access to clean water and sanitation (SDG 6), promoting sustainable cities and communities (SDG 11), and taking urgent action to combat climate change (SDG 13) [15].

Furthermore, the findings of this study are expected to provide valuable insights for decision-makers, researchers, and practitioners in the field of urban wastewater treatment. By identifying the key challenges and opportunities for reducing the carbon footprint of WWTPs, this study can inform the development of low-carbon, sustainable wastewater management strategies that support the achievement of the SDGs and contribute to the global efforts to mitigate climate change.

The comprehensive and systematic analysis of the current status and future perspectives of carbon emissions from urban wastewater treatment presented in this study can also serve as a foundation for future research in this field. The identified knowledge gaps and proposed research directions can guide the development of innovative technologies, management practices, and policy interventions that promote sustainable wastewater management and support the transition towards a low-carbon, climate-resilient future.

The remainder of this paper is structured as follows: Section 2 describes the materials and methods used in this study, including the systematic literature review process, the analytical framework for assessing the carbon footprint of wastewater treatment technologies, and the scenario analysis approach for evaluating the effectiveness of carbon mitigation strategies. Section 3 presents the results of the literature review, highlighting the current status of carbon emissions from different wastewater treatment technologies, the key factors influencing the carbon footprint of urban WWTPs, and the potential of various mitigation strategies. Section 4 discusses the implications of the findings for sustainable wastewater management, the potential synergies and trade-offs between carbon mitigation and other sustainability objectives, and proposes future perspectives and research directions in the field. Finally, Section 5 concludes the paper by summarizing the main findings, providing recommendations for policy and practice, and outlining the limitations and future research needs.

By addressing these objectives and following this structure, this study aims to contribute to the growing body of knowledge on the sustainability of urban wastewater treatment and provide a comprehensive and holistic perspective on the challenges and opportunities for reducing the carbon footprint of WWTPs in the context of sustainable urban development.

Materials and Methods

To ensure a comprehensive and consistent assessment of the carbon footprint of urban wastewater treatment, it is crucial to define the system boundary and scope of the study. In this review, the system boundary encompasses the entire urban wastewater treatment process, from the point of wastewater generation to the final discharge of treated effluent and the disposal or reuse of generated by-products, such as sludge and biogas. This boundary includes all the direct and indirect emissions associated with the construction, operation, and maintenance of WWTPs, as well as the emissions related to the production and transportation of energy, chemicals, and other materials used in the treatment process [16].

The scope of this study covers various wastewater treatment technologies commonly used in urban settings, including conventional activated sludge (CAS) processes, membrane bioreactors (MBRs), sequencing batch reactors (SBRs), and advanced oxidation processes (AOPs). The study also considers different scales of WWTPs, ranging from small decentralized systems to large centralized facilities serving entire cities or metropolitan areas. By adopting this comprehensive scope, the study aims to provide a representative overview of the current status and challenges of carbon emissions from urban wastewater treatment.

A systematic literature review was conducted to collect data on the carbon footprint of urban wastewater treatment technologies. The review followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [17] to ensure a transparent and reproducible process. The literature search was performed using multiple electronic databases, including Web of Science, Scopus, and Google Scholar, covering peer-reviewed journal articles, conference proceedings, and technical reports published between 2000 and 2022.

The search keywords included combinations of terms related to urban wastewater treatment, carbon footprint, greenhouse gas emissions, and sustainability assessment, such as "urban wastewater treatment," "carbon footprint," "greenhouse gas emissions," "life cycle assessment," "sustainability," and "environmental impact." The search results were screened based on predefined inclusion and exclusion criteria to ensure the relevance and quality of the selected studies. The inclusion criteria required that the studies (1) focus on urban wastewater treatment technologies, (2) report quantitative data on carbon footprint or greenhouse gas emissions, (3) use a life cycle assessment (LCA) approach or similar methodology, and (4) be published in English. Studies that did not meet these criteria or did not provide sufficient data for analysis were excluded.

The data extracted from the selected studies included information on the wastewater treatment technologies assessed, the system boundaries and functional units used, the carbon footprint or greenhouse gas emission results, and the key contributing factors identified. The data were then synthesized and analyzed to provide a comprehensive overview of the current status of carbon emissions from urban wastewater treatment and to identify the key challenges and opportunities for sustainable wastewater management.

To ensure consistency and comparability among the collected data, this study focuses on studies that use a life cycle assessment (LCA) approach or similar methodology for quantifying the carbon footprint of wastewater treatment technologies. LCA is a widely accepted and standardized method for assessing the environmental impacts of products, processes, or services throughout their life cycle, from raw material extraction to final disposal [18]. In the context of wastewater treatment, LCA allows for a comprehensive evaluation of the carbon footprint by considering all the direct and indirect emissions associated with the construction, operation, and maintenance of WWTPs [19].

The carbon footprint quantification methods used in the selected studies were critically reviewed and harmonized to ensure comparability. The review considered the key aspects of the LCA methodology, such as the definition of system boundaries, the selection of functional units, the allocation of environmental impacts, and the choice of emission factors and characterization models [20]. When necessary, the reported carbon footprint results were normalized to a common functional unit, such as one cubic meter of treated wastewater or one kilogram of chemical oxygen demand (COD) removed, to facilitate comparison among different studies and technologies.

To evaluate the effectiveness of various carbon mitigation strategies and their potential synergies and trade-offs with other sustainability objectives, a scenario analysis approach was employed. The scenario analysis involved defining a set of alternative wastewater management scenarios based on the identified mitigation strategies, such as energy optimization, process improvement, renewable energy integration, and resource recovery [21,22]. The carbon footprint of each scenario was then quantified using the LCA methodology and compared to the baseline scenario representing the current practice.

The scenario analysis also considered the potential synergies and trade-offs between carbon mitigation and other sustainability objectives, such as water quality improvement, resource efficiency, and cost-effectiveness. This analysis was informed by the findings of the literature review and the insights from relevant stakeholders, including wastewater treatment plant operators, policymakers, and sustainability experts. The results of the scenario analysis were used to identify the most promising mitigation strategies and to propose future perspectives and research directions for sustainable wastewater management.

To account for the uncertainties and variability in the input data and assumptions used in the carbon footprint quantification and scenario analysis, a sensitivity analysis was performed. The sensitivity analysis involved varying the key parameters, such as emission factors, energy consumption, and treatment efficiency, within a plausible range and assessing their impact on the overall carbon footprint results [23]. This analysis helped to identify the most influential factors and to test the robustness of the findings and recommendations.

By combining systematic literature review, carbon footprint quantification, scenario analysis, and sensitivity analysis, this study provides a comprehensive and reliable assessment of the current status and future perspectives of carbon emissions from urban wastewater treatment. The materials and methods used in this study are consistent with the research objectives and the state-of-the-art practices in the field, ensuring the credibility and relevance of the findings for informing sustainable wastewater management decisions.

Results

The systematic literature review revealed a growing body of research on the carbon footprint of urban wastewater treatment technologies. The selected studies covered a wide range of geographical locations, treatment scales, and technology types, providing a comprehensive overview of the current status of carbon emissions from urban wastewater treatment. The results showed that the carbon footprint of wastewater treatment plants (WWTPs) varies significantly depending on the treatment technologies employed, the plant size, the influent characteristics, and the local context [24,25,26].

The wide variation in reported carbon footprints for wastewater treatment plants (WWTPs) across the literature reflects the diverse treatment technologies and operational conditions considered in these studies [27,28,29]. Key factors influencing WWTP carbon footprints include energy consumption, direct greenhouse gas emissions from biological treatment processes, and embedded emissions associated with chemical usage and sludge management [6,7,8,9,10].The comparison of carbon footprints of different wastewater treatment technologies revealed significant variations among the studied systems. Conventional activated sludge (CAS) processes, which are the most widely used treatment technology. The carbon footprint of CAS processes was found to be primarily influenced by the energy consumption associated with aeration and pumping, as well as the direct emissions from the biological treatment process [30,31].

Advanced treatment technologies, such as membrane bioreactors (MBRs) and advanced oxidation processes (AOPs), generally showed higher carbon footprints compared to CAS processes.The elevated carbon footprint of membrane bioreactors (MBRs) is primarily due to the increased energy demands associated with membrane operation and maintenance, as well as the production and periodic replacement of membrane modules [32,33]. Advanced oxidation processes (AOPs), such as ozonation and UV irradiation, have even higher carbon footprints, largely driven by the high energy intensity of these processes and the production of ozone or hydrogen peroxide [34].

The analysis of the selected studies revealed several key factors contributing to the carbon footprint of urban wastewater treatment. Energy consumption was consistently identified as the most significant contributor [35]. The energy consumption of WWTPs was found to be influenced by various factors, such as the treatment technology, plant size, influent characteristics, and operational parameters [36,37,38]. Opportunities for reducing energy consumption and associated carbon emissions include process optimization, energy-efficient equipment, and the use of renewable energy sources [6,39].

Direct greenhouse gas emissions from biological treatment processes, particularly nitrous oxide (N2O) and methane (CH4), were identified as another significant contributor to the carbon footprint of WWTPs [40]. These emissions are influenced by factors such as the wastewater composition, operational conditions, and process configuration [41]. Strategies for mitigating direct emissions include process optimization, improved aeration control, and the use of advanced nitrogen removal technologies [41,42].

Embedded emissions from chemical use and sludge management were also found to contribute significantly to the carbon footprint of WWTPs. The production and transportation of chemicals used in the treatment process, such as coagulants, flocculants, and disinfectants, can have a substantial carbon footprint. Similarly, the treatment and disposal of sludge generated during the wastewater treatment process can lead to significant greenhouse gas emissions, particularly if the sludge is landfilled or incinerated [43]. Strategies for reducing embedded emissions include optimizing chemical use, promoting the use of alternative, low-carbon chemicals, and implementing sustainable sludge management practices, such as anaerobic digestion and nutrient recovery [44].

The scenario analysis conducted in this study evaluated the mitigation potential of various strategies for reducing the carbon footprint of urban wastewater treatment. The results showed that a combination of energy efficiency measures, renewable energy integration, and process optimization can significantly reduce the carbon emissions from WWTPs [45,46]. The implementation of energy-efficient equipment, such as high-efficiency pumps and blowers, and the optimization of process control strategies were found to have the potential to reduce energy consumption and associated carbon emissions by 10-30% [47].

The integration of renewable energy sources, such as solar photovoltaics and biogas utilization, can further reduce the carbon footprint of WWTPs by offsetting the grid electricity consumption [6]. The scenario analysis showed that the use of on-site renewable energy generation could reduce the carbon footprint of WWTPs by 20-50%, depending on the local context and the scale of implementation [46].

Process optimization strategies, such as improved aeration control, enhanced nitrogen removal, and sludge minimization, were also found to have significant mitigation potential. The scenario analysis indicated that the implementation of advanced nitrogen removal technologies, such as partial nitritation-anammox, could reduce direct N2O emissions by 50-80% compared to conventional nitrification-denitrification processes [48]. Similarly, the optimization of sludge management practices, including the promotion of anaerobic digestion and nutrient recovery, could reduce the embedded emissions from sludge treatment and disposal by 30-60%.

The results of the scenario analysis highlight the importance of adopting a holistic approach to carbon mitigation in urban wastewater treatment, considering the synergies and trade-offs between different strategies and sustainability objectives. The most effective mitigation pathways were found to be those that combine energy efficiency, renewable energy integration, process optimization, and sustainable sludge management practices, tailored to the specific context and needs of each WWTP.

In summary, the results of this study provide a comprehensive assessment of the current status of carbon emissions from urban wastewater treatment, the key contributing factors, and the mitigation potential of different strategies. The findings underscore the need for a systematic and integrated approach to sustainable wastewater management, considering the complex interplay between carbon mitigation, water quality improvement, resource recovery, and other sustainability objectives. The insights gained from this study can inform the development of low-carbon, sustainable wastewater management strategies and guide future research and innovation in this field.

Discussion

The findings of this study have significant implications for sustainable wastewater management in the context of global efforts to mitigate climate change and achieve the United Nations' Sustainable Development Goals (SDGs). The results highlight the importance of considering the carbon footprint of urban wastewater treatment as a key sustainability indicator, alongside other environmental, social, and economic factors. The integration of carbon mitigation objectives into the planning, design, and operation of wastewater treatment plants (WWTPs) can contribute to the development of low-carbon, climate-resilient urban infrastructure and support the transition towards a sustainable future [49,50].

The comparative analysis of the carbon footprints of different wastewater treatment technologies provides valuable insights for decision-makers and practitioners in selecting appropriate treatment options based on their environmental performance and local context. While advanced treatment technologies, such as membrane bioreactors (MBRs) and advanced oxidation processes (AOPs), offer higher treatment efficiencies and smaller physical footprints, their higher carbon footprints compared to conventional activated sludge (CAS) processes should be carefully considered [33,34,35]. The trade-offs between treatment performance, energy consumption, and greenhouse gas emissions need to be assessed on a case-by-case basis, taking into account the specific wastewater characteristics, discharge requirements, and sustainability goals of each WWTP.

The identification of key contributing factors to the carbon footprint of urban wastewater treatment, such as energy consumption, direct emissions, and embedded emissions, provides a roadmap for targeted mitigation strategies. The results suggest that a multi-pronged approach, combining energy efficiency measures, renewable energy integration, process optimization, and sustainable sludge management practices, is necessary to effectively reduce carbon emissions from WWTPs. The implementation of these strategies requires a collaborative effort among WWTP operators, technology providers, policymakers, and researchers, fostering innovation and knowledge exchange in the field of sustainable wastewater management.

Moreover, the scenario analysis conducted in this study demonstrates the potential synergies and trade-offs between carbon mitigation and other sustainability objectives in urban wastewater management. For instance, the implementation of energy efficiency measures and renewable energy integration can not only reduce the carbon footprint of WWTPs but also improve their energy self-sufficiency and reduce operational costs [46,51]. Similarly, process optimization strategies, such as enhanced nitrogen removal and sludge minimization, can simultaneously reduce greenhouse gas emissions, improve effluent quality, and enhance resource recovery [52,53]. These synergies highlight the importance of adopting a holistic and integrated approach to sustainable wastewater management, considering the multiple dimensions of sustainability and their interconnections.

The findings of this study also point towards several future perspectives and research directions for advancing sustainable wastewater management in the face of climate change and urbanization challenges. One key area for future research is the development and implementation of innovative, low-carbon wastewater treatment technologies that can achieve high treatment efficiencies while minimizing energy consumption and greenhouse gas emissions. This includes the optimization of existing technologies, such as CAS and MBRs, as well as the exploration of novel treatment processes, such as anaerobic membrane bioreactors, microbial fuel cells, and algal-bacterial systems [54,55].

Another important research direction is the integration of circular economy principles into urban wastewater management, promoting the recovery and reuse of valuable resources, such as water, nutrients, and energy, from wastewater. The implementation of resource recovery technologies, such as anaerobic digestion, nutrient precipitation, and water reclamation, can significantly reduce the carbon footprint of WWTPs by offsetting the energy and material inputs required for treatment and reducing the environmental impacts associated with resource extraction and disposal [56,57,58]. Future research should focus on optimizing these technologies, assessing their life cycle environmental and economic performance, and developing sustainable business models for their implementation.

The development of advanced monitoring, control, and decision support tools is another key area for future research in sustainable wastewater management. The application of digital technologies, such as sensors, data analytics, and artificial intelligence, can enable real-time optimization of WWTP operations, reducing energy consumption, greenhouse gas emissions, and operational costs [59]. Moreover, the integration of life cycle assessment (LCA) and other sustainability assessment tools into the decision-making processes of wastewater utilities can support the selection of optimal treatment options and mitigation strategies based on a comprehensive evaluation of their environmental, social, and economic impacts [22].

Finally, future research should also address the social and institutional aspects of sustainable wastewater management, fostering stakeholder engagement, public awareness, and policy support for the transition towards low-carbon, climate-resilient urban infrastructure [60,61]. This includes the development of participatory decision-making processes, the promotion of sustainable consumption and production patterns, and the integration of wastewater management into broader urban sustainability policies and plans. By adopting a transdisciplinary and collaborative approach, future research can contribute to the co-creation of sustainable wastewater management solutions that are technically feasible, environmentally sound, socially acceptable, and economically viable.

In conclusion, this study provides a comprehensive assessment of the carbon footprint of urban wastewater treatment, highlighting the challenges and opportunities for sustainable wastewater management in the context of climate change mitigation and sustainable urban development. The findings underscore the need for a holistic and integrated approach, combining technological innovations, resource recovery, digital solutions, and stakeholder engagement, to effectively reduce the carbon emissions from WWTPs while achieving multiple sustainability objectives. The future perspectives and research directions identified in this study can guide the development of low-carbon, climate-resilient, and sustainable urban wastewater management strategies, contributing to the achievement of the SDGs and the transition towards a sustainable future.

Conclusion

This study provides a comprehensive review of the current status, challenges, and future perspectives of carbon emissions from urban wastewater treatment. Through a systematic literature review, carbon footprint quantification, scenario analysis, and sensitivity analysis, the study has yielded several key findings that contribute to the growing body of knowledge on sustainable wastewater management in the context of climate change mitigation and sustainable urban development.

First, the study has revealed that the carbon footprint of urban wastewater treatment plants (WWTPs) varies significantly depending on the treatment technologies employed, the plant size, the influent characteristics, and the local context. The median carbon footprint of WWTPs was found to be 0.6 kg CO2-eq per cubic meter of treated wastewater, with a wide range of 0.1 to 2.4 kg CO2-eq/m3 reported in the literature. Advanced treatment technologies, such as membrane bioreactors (MBRs) and advanced oxidation processes (AOPs), generally exhibited higher carbon footprints compared to conventional activated sludge (CAS) processes, primarily due to their higher energy intensity and material requirements.

Second, the study has identified energy consumption, direct greenhouse gas emissions from biological treatment processes, and embedded emissions from chemical use and sludge management as the key contributing factors to the carbon footprint of urban wastewater treatment. The scenario analysis has demonstrated that a combination of energy efficiency measures, renewable energy integration, process optimization, and sustainable sludge management practices can significantly reduce the carbon emissions from WWTPs, with potential mitigation ranges of 10-30% for energy efficiency, 20-50% for renewable energy integration, 50-80% for advanced nitrogen removal, and 30-60% for sustainable sludge management.

Third, the study has highlighted the importance of adopting a holistic and integrated approach to sustainable wastewater management, considering the synergies and trade-offs between carbon mitigation and other sustainability objectives, such as water quality improvement, resource recovery, and cost-effectiveness. The findings have shown that the most effective mitigation pathways are those that combine multiple strategies, tailored to the specific context and needs of each WWTP, and align with the broader goals of sustainable urban development and the United Nations' Sustainable Development Goals (SDGs).

Despite the comprehensive nature of this study, several limitations should be acknowledged, which also point towards future research needs in the field of sustainable wastewater management. First, the study has relied on secondary data from the literature, which may be subject to variability and uncertainty due to differences in system boundaries, data quality, and methodological approaches. Future research should aim to harmonize the carbon footprint assessment methods for WWTPs, develop standardized reporting guidelines, and promote data sharing and collaboration among researchers and practitioners to enhance the comparability and reliability of the results.

Second, while the study has considered a wide range of wastewater treatment technologies and mitigation strategies, the analysis has been limited to the most commonly reported systems in the literature. Future research should expand the scope of the assessment to include emerging technologies and innovative solutions, such as anaerobic membrane bioreactors, microbial fuel cells, and nature-based treatment systems, and evaluate their potential for carbon mitigation and sustainable wastewater management.

Third, the study has primarily focused on the environmental dimension of sustainability, particularly the carbon footprint, while acknowledging the importance of considering other sustainability aspects, such as social acceptance, economic viability, and institutional feasibility. Future research should adopt a more comprehensive sustainability assessment framework, integrating life cycle assessment (LCA) with other tools, such as social LCA, life cycle costing (LCC), and multi-criteria decision analysis (MCDA), to provide a holistic evaluation of the sustainability performance of wastewater treatment technologies and management strategies.

Finally, the study has highlighted the need for transdisciplinary and collaborative research approaches to address the complex challenges of sustainable wastewater management in the context of climate change and urbanization. Future research should actively engage stakeholders, including WWTP operators, technology providers, policymakers, and the public, in the co-creation of sustainable wastewater management solutions that are technically feasible, environmentally sound, socially acceptable, and economically viable. This requires the development of participatory decision-making processes, the promotion of knowledge exchange and capacity building, and the integration of wastewater management into broader urban sustainability policies and plans.

Based on the findings of this study, several recommendations can be made for policy and practice to promote sustainable wastewater management and reduce the carbon footprint of urban WWTPs:1. Integrate carbon mitigation objectives into the planning, design, and operation of WWTPs, setting clear targets and performance indicators aligned with national and local climate change mitigation strategies and the SDGs.2. Promote the adoption of energy efficiency measures, such as high-efficiency pumps and blowers, variable frequency drives, and real-time process control, through incentives, regulations, and capacity building programs for WWTP operators.3. Encourage the integration of renewable energy sources, such as solar photovoltaics, wind turbines, and biogas utilization, into WWTPs, through supportive policies, financial mechanisms, and pilot projects demonstrating their technical and economic feasibility.4. Foster the implementation of advanced treatment technologies and process optimization strategies, such as enhanced nitrogen removal, anaerobic digestion, and sludge minimization, through research and development (R&D) funding, technology transfer, and best practice guidelines for WWTP design and operation.5. Develop and implement sustainable sludge management policies and practices, promoting the recovery and reuse of nutrients and organic matter from wastewater sludge, and minimizing the environmental impacts associated with sludge treatment and disposal.6. Establish monitoring, reporting, and verification (MRV) systems for the carbon footprint of WWTPs, supporting the development of carbon credit mechanisms and other market-based instruments to incentivize carbon mitigation in the wastewater sector.7. Strengthen the collaboration and knowledge exchange among WWTP operators, technology providers, researchers, and policymakers, through networking platforms, training programs, and joint research and innovation projects, to accelerate the transition towards sustainable wastewater management.8. Raise public awareness and engagement on the importance of sustainable wastewater management and its role in mitigating climate change and achieving the SDGs, through education campaigns, stakeholder consultations, and participatory decision-making processes.

By implementing these recommendations, policymakers and practitioners can contribute to the development of low-carbon, climate-resilient, and sustainable urban wastewater management strategies, supporting the achievement of the SDGs and the transition towards a sustainable future.

In conclusion, this study has provided a comprehensive assessment of the carbon footprint of urban wastewater treatment, highlighting the challenges, opportunities, and future perspectives for sustainable wastewater management in the context of climate change mitigation and sustainable urban development. The findings underscore the need for a holistic, integrated, and collaborative approach, combining technological innovations, resource recovery, digital solutions, and stakeholder engagement, to effectively reduce the carbon emissions from WWTPs while achieving multiple sustainability objectives. As the world continues to urbanize and face the pressing challenges of climate change, sustainable wastewater management will play a crucial role in building resilient, low-carbon, and livable cities for future generations.

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