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Life Cycle Assessment and Its Application in Wastewater Treatment: A Brief Review

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Abstract: The present study offers a thorough examination of Life Cycle Assessment's (LCA) role in evaluating wastewater treatment systems. Employing a cradle-to-grave methodology, LCA has proven instrumental in revealing the extensive environmental implications of design and operational choices within wastewater treatment facilities. This review's objective is to pinpoint areas where knowledge is lacking, thereby enhancing the use and techniques of LCA in these plants. The paper commences with an overview of LCA and wastewater treatment, proceeding to outline the evolution of research over the two decades preceding this study. A quantitative analysis then follows, detailing the frequency of scholarly articles from 2010 to 2023, identified through searches for "Life Cycle Assessment" in conjunction with "Wastewater Management and Treatment". The discussion concludes by highlighting challenges within the field. Future endeavors should concentrate on the development of holistic upgrade designs and assessment protocols to alleviate environmental and economic pressures. It is imperative that site-specific studies are conducted to assess the repercussions of such upgrades throughout the plants' lifecycles, equipping decision-makers and industry professionals with actionable insights for the sustainable and efficient modernization of wastewater treatment infrastructure.

Keywords: Life Cycle Assessment (LCA), wastewater management, sustainable operations, environmental footprint

1. Introduction

Life Cycle Assessment (LCA) is a methodological approach that measures the environmental impacts across the entire lifespan of a product, service, or process, encompassing every phase from inception to disposal. Originating in the 1960s, LCA has since evolved, giving rise to a multitude of methodologies tailored to various fields of study.

In the field of wastewater treatment (WWT), Life Cycle Assessment (LCA) has been applied since the early 1990s. Since then, a multitude of research studies focusing on the intersection of water treatment and LCA have been published, relying on a diverse array of database resources, clearly defined boundary conditions, and rigorous impact assessment methodologies to interpret and elucidate their findings. In the pursuit of achieving higher levels of environmental sustainability in wastewater treatment processes, LCA has emerged as a valuable tool for uncovering the broader environmental impacts of design and operational decisions [1, 2] .Given the growing interest among utility companies, practitioners, and researchers in utilizing LCA within wastewater treatment systems, it is crucial to systematically review the current research achievements and delineate the key challenges that lie ahead in the coming years. LCA has been widely used to quantify environmental impacts associated with urban water infrastructure, including wastewater treatment plants (WWTPs) [3].As the wastewater management sector shifts its focus from merely eliminating pollutants to embracing resource recovery and circular economy principles, Life Cycle Assessment (LCA) emerges as a crucial tool. It evaluates the environmental sustainability of innovative technologies and processes, while also highlighting the trade-offs across multiple environmental impact categories. LCA, being a quantitative method for environmental assessment, provides valuable support for decision-making. It enables the examination of various operational scenarios during strategic planning phases within the water industry. This approach aids in the transition towards more sustainable and resource-efficient wastewater treatment practices.[1 , 4].

LCA in wastewater systems has evolved significantly over the past two decades. Friedrich et al. provided an early overview of 20 LCA studies on wastewater, while Ahmed introduced framework for conducting LCA in wastewater treatment[5, 6]. Subsequent studies expanded LCA applications, with Chen et al. incorporating it into sustainability assessments of water reuse schemes[7].

This review article systematically reviews the published papers on this topic, deeply analyzes the growth trend of relevant literature, and elaborates on the challenges and future development trends of LCA in the application of wastewater treatment. Furthermore, this study identifies the existing knowledge gaps and aims to provide theoretical support for researchers and practitioners in the field of wastewater treatment and LCA, in order to deepen their understanding and application capabilities of LCA, and thereby promote the achievement of wastewater treatment objectives and the sustainability of wastewater management.

2. Quantitative Environmental Analysis of Wastewater Treatment Facilities

2.1. Municipal Sewage Treatment Facilities

A municipal wastewater management setup typically includes both a sewer network and a wastewater treatment plant (WWTP), which Sikosana et al. categorize as a prevalent example of low-strength waste streams [8]. The sewer systems linked to WWTPs can be either separate or combined. The separate system designates distinct flows/networks for rainwater and for domestic/industrial wastewater, while the combined system utilizes a single pipe for both types of runoff.The WWTP is composed of various stages or units, such as pre-treatment, primary treatment, secondary treatment, sludge management, and, in some cases, tertiary treatment, as depicted in Figure 1. Pre-treatment and primary treatment primarily target the elimination of particulate contaminants, including solids, grit, and grease. Secondary treatment addresses the organic matter, as well as nitrogen and phosphorus compounds present in the sewage, through a combination of biological and chemical processes [9-11]. Tertiary treatment, when implemented, is designed to further eliminate any residual small particles and pathogens in the wastewater.

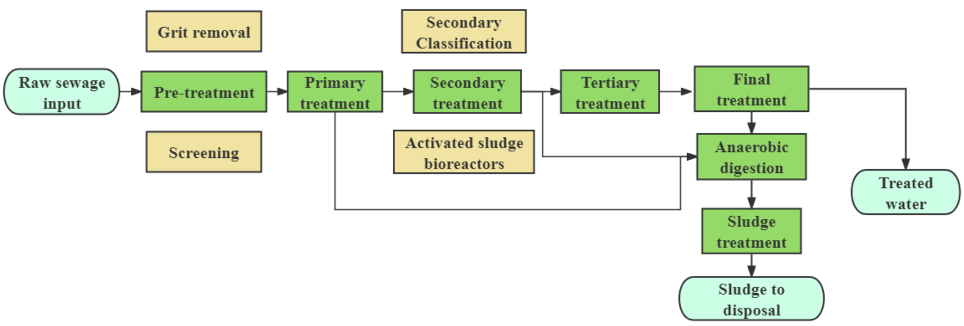

Figure 1: Flow diagram of the WWTP process.

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The final stage in wastewater management is the treatment of excess sludge, which aims to stabilize and reduce its volume through processes like thickening and dewatering. Once treated, the sludge may be disposed of in landfills, utilized in agricultural applications, subjected to incineration, or sent to composting facilities. The construction of a WWTP is a complex endeavor that involves a variety of materials, including concrete, timber, steel, and plastics. It also requires meticulous operational planning and the installation of specialized equipment. The day-to-day functioning of a WWTP necessitates several resources: (i) significant electricity for pumping and aeration processes, (ii) chemical inputs for sludge management and phosphorus elimination, and (iii) the transportation of waste, sludge, and chemicals[12].As a result, the life cycle of a WWTP—encompassing construction, operation, and decommissioning—has considerable environmental implications. These impacts stem from energy use, chemical consumption, sludge production, effluent discharge, and the emission of gases [13].The environmental footprint of WWTPs is thus a critical consideration in the ongoing pursuit of sustainable wastewater management practices.

2.2. State-of-the-Art Methods for Applying LCA in Wastewater Treatment Plants

In the past half-century, there has been a growing global consciousness about environmental protection, particularly concerning water resources. The European Commission Council Directive (1991/271/EEC) on urban wastewater treatment has emphasized that the primary goal of such treatment is to mitigate the environmental impacts caused by the discharge of urban and industrial wastewater. Consequently, numerous wastewater treatment plants (WWTPs) have been designed and managed with the aim of preventing environmental pollution by eliminating a broad spectrum of contaminants from wastewater before it is released back into the environment, thereby restoring the natural quality that has been compromised by human activities or natural processes [14] .

Nevertheless, the treatment process can, to some extent, result in the transference of pollutants to other mediums, such as the emission of greenhouse gases (GHGs) into the atmosphere and the disposal of sludge into the soil. These transfers can lead to detrimental effects on both human health and the environment in different forms [15, 16].Assessing the comprehensive environmental impact of WWTPs is a complex task, necessitating a cradle-to-grave analysis to understand the full consequences of these facilities on the environment. The operational impacts of WWTPs include climate change due to GHG emissions, eutrophication from nutrient discharge into water bodies, and damage to ecosystems from heavy metal emissions. The United Nations' sustainable development goals highlight climate change, eutrophication, and the acidification of water bodies as among the most urgent environmental challenges. Therefore, it is crucial to conduct an environmental impact assessment for specific technologies, products, or processes to identify their environmental footprint and potential strategies for mitigation.

Environmental assessment tools provide accurate information on environmental impacts, aiding in decision-making for the sustainable operation of systems or processes[17]. The environmental impact of a wastewater treatment system can be evaluated using various assessment tools, including Life Cycle Assessment (LCA), economic and exergy analysis, Environmental Impact Assessment (EIA), and Net Environmental Benefit Analysis (NEBA) [15].LCA is a comprehensive method for assessing the environmental impact across all stages of a product's, process's, or service's life cycle, from raw material extraction to final material disposal, adhering to a cradle-to-grave approach [10, 15].

LCA has garnered significant interest from researchers and industry professionals in identifying environmental impacts and evaluating the sustainability of wastewater treatment technologies[13,18,19].LCA offers a structured framework for assessment that includes defining goals and scope, conducting a life cycle inventory, assessing life cycle impacts, and interpreting the results. Additionally, economic analyses can be performed using Cost-Benefit Analysis (CBA), Life

Cycle Costing (LCC), and Techno-Economic Analysis (TEA) [20-22]. These economic evaluations can often be integrated with LCA to provide a comprehensive system-level analysis, supporting the sustainable operation of WWTPs.

3. Statistics and Analysis

Various research papers indicate that Life Cycle Assessment (LCA) has evolved over the past two decades to incorporate more improvements and systematic evaluations. Figure 2 present the statistical results of the annual academic paper publication volume retrieved from the Google Scholar platform, using the keywords "Life Cycle Assessment" and "Wastewater Management and Treatment" for the period from 2010 to 2023.

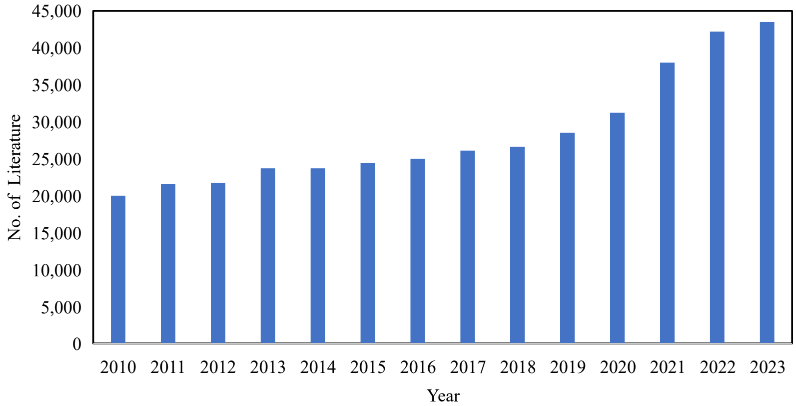

Figure 2: The number of papers searched using "Life Cycle Assessment" and "Wastewater Management and Treatment" per year

4. Evolution and Applications of LCA in Wastewater Management

The application of Life Cycle Assessment (LCA) in the realm of wastewater management has undergone substantial progress, with detailed reviews concentrating on particular facets such as sludge handling and activated sludge processes [23, 24] .Wider viewpoints have been introduced by Loubet et al. and Byrne et al., who scrutinized the use of LCA across the entire urban water management cycle, evaluating methodological tendencies and pinpointing new opportunities for advancement [3, 25]. Heimersson et al. highlighted prevalent practices and identified shortcomings in the quantification of nutrient flows, while Corominas et al. delineated significant challenges in the implementation of LCA within wastewater systems [26, 27]. The discipline's maturation is evident in Lam et al.'s exploration of LCA modifications for assessing nutrient recycling in wastewater, marking a shift from general surveys to more specialized and comprehensive analyses [28].

In recent times, studies have broadened and honed the use of LCA in wastewater management. Ontiveros and Campanella applied LCA to assess the environmental efficacy of three distinct biological nutrient removal processes in Argentina, offering crucial insights for selecting processes in localized settings [29]. Yoshida et al. advanced life cycle inventory techniques by integrating on-site GHG emissions and extended-term emission data from the land application of sewage sludge, thereby enhancing the precision of environmental impact evaluations [30]. Morera et al. concentrated on refining LCA methodology within urban wastewater treatment, underscoring the necessity for thorough construction inventories, including those of sewer networks, and the refinement of these inventories with scale assessments [12]. Current research indicates that LCA in the context of Wastewater Treatment Plants (WWTPs) is primarily directed at assessing the environmental ramifications of various technologies. This encompasses the identification of both innovative and

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traditional emission parameters, the analysis of control strategies to enhance WWTP performance, and the exploration of environmental trade-offs among different process options [19, 31, 32].

5. Challenges

LCA has proven effective for assessing the environmental impact of WWTPs, though its use in this field is still relatively new, particularly in developing countries [33]. Further research is needed to ensure reliable outcomes, as many challenges remain, such as how best to apply LCA to WWTPs for accurate environmental assessments. Upgrading plants to improve nutrient removal and resource recovery is essential, but understanding the environmental trade-offs and economic costs is also crucial, especially regarding nitrogen and phosphorus recovery. While energy and phosphorus recovery can reduce environmental impacts, the added costs, like increased chemical and electricity use, remain uncertain.

The complexity of using LCA in WWTPs stems from the interconnected nature of processes, where one process's effluent becomes another's influent, leading to non-linear resource consumption. Moreover, WWTPs are evolving into multi-functional systems beyond just treating effluent, focusing now on resource recovery, energy management, and removing emerging contaminants. Despite this shift, there is no comprehensive guidance for conducting LCAs in WWTPs [34] . Current ISO standards (14040, 14044) provide only general rules, and the Product Category Rules document for wastewater treatment services expired in 2016, leaving gaps in addressing the diverse challenges of applying LCA to this field [35, 36].

Finally, the limitations of current LCA practices may affect the validity of study outcomes, as future research could introduce new pollutants, impact factors, or environmental dynamics, making some conclusions obsolete [37].

6. Future Directions

Although significant progress has been made in Life Cycle Assessment (LCA) research for wastewater treatment, further advancements are needed to fully harness its potential. To achieve more efficient and sustainable WWTPs, it is essential to evaluate the trade-offs between nutrient removal and resource recovery, ensuring environmental benefits are not outweighed by negative impact. Given the complexity of LCA in wastewater management, a comprehensive approach is necessary. This should include design upgrades and assessments of both environmental and economic burdens, tailored to specific site conditions. Such insights are critical for policymakers and practitioners, especially in developing countries, where research on integrating nutrient removal with resource recovery is still limited.

7. Conclusion

LCA is recognized as an effective methodology for assessing the environmental impact of wastewater treatment plants (WWTPs), yet it remains a relatively novel and challenging approach, particularly in developing countries. While upgrading WWTPs for better nutrient removal and resource recovery is essential, there is a lack of thorough analysis comparing environmental and economic trade-offs. The complexity of WWTPs, with their interdependent processes, makes environmental impact assessments even more difficult. The current shift towards making WWTPs multifunctional, addressing resource recovery and energy management, further complicates assessments. Though ISO standards and product category rules offer some guidance, they are not comprehensive for wastewater treatment’s diverse challenges. Therefore, it is critical to improve design and evaluation methods, identify environmental burden hotspots, and develop strategies that consider the specific conditions of WWTPs in developing countries, balancing technical, environmental, and economic impacts..

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