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Current Status of Research on Carbon Emissions and Combined Benefits in Wastewater Treatment

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Abstract

According to the United Nations, the global carbon footprint of the water treatment industry, including wastewater treatment, accounts for approximately 2% of global carbon emissions. As a result, it is becoming increasingly critical to reduce carbon emissions from the wastewater treatment sector. Wastewater treatment plants (WWTPs) currently exist in two forms: above-ground and underground. With the development of urbanization, increased population density, and land constraints, the trend is gradually shifting towards underground WWTPs. But there are many challenges. The investment costs during the construction phase, building materials, and energy requirements are much higher for underground sewage treatment plants compared to above-ground ones. Additionally, during the operation phase, energy consumption is higher and there are high risk factors to consider. The aforementioned elements will undeniably affect the complete life span of carbon emissions from sewage treatment facilities. Additionally, the advantages, both environmentally and economically, of subterranean WWTPs do not necessarily surpass those of above-ground WWTPs. At present, the lack of a systematic approach towards accounting and assessing the carbon footprint of underground WWTPs is a significant issue. This not only prevents an accurate understanding of the environmental impact of such facilities but also hinders efforts to reduce their carbon emissions. Moreover, the absence of a comprehensive review of the benefits of these facilities further compounds this problem. Therefore, a thorough analysis of the carbon, environmental, and economic aspects of underground WWTPs is necessary to reveal the true relationship between their comprehensive benefits, carbon emissions, and energy consumption.

Keywords: Wastewater treatment plant; carbon footprint; underground; combined benefits.

1. Introduction

High temperatures are a direct result of the global climate crisis. As global temperatures continue to rise, extreme weather events like heat waves and dramatic changes in precipitation patterns are becoming more frequent. These events can lead to natural disasters such as sea level rise, droughts, and forest fires, with serious socio-economic and developmental consequences. It is estimated that the global economy could incur a cost of US$178 trillion per year as a result of these impacts (Spotlight Resources). Global warming, a phenomenon that is currently affecting our planet, is primarily caused by the massive amount of greenhouse gases. According to the WMO report, concentrations of CO_2 and temperature have been continuously increasing since 1850. In 2020, atmospheric CO_2 concentrations of 414.24 ppm were recorded at several stations around the world, which represents a 30% increase from the pre-industrial level of 280 ppm. In the same period, the global average temperature has risen by approximately 1°C (IPCC, 2022; UNFCCC, 2018). The reality of global climate change is indisputable and has become a shared crisis for the survival and progress of humanity.

In various regions around the world, wastewater treatment plants in northern Italy emit between 0.04 to 0.20 t CO_2-eq/PE per year (Mojtaba, 2022). Laura et al. (2018) estimated the carbon emissions from artificial wetlands treating winery wastewater in Spain to be 1.2 kg CO_2-eq per m^3. Gu estimated that the carbon emissions from power consumption of nine different WWTPs in southern China to be 0.23 kg CO_2 per m^3. It is worth noting that the carbon emissions from water treatment industries, including wastewater treatment, make up roughly 2% of the world's total carbon emissions, according to UN statistics cited by Chunli in 2021(Chunli, 2021). This emphasizes the importance of taking a holistic approach to reducing carbon emissions, not only in the water treatment industry but also in other sectors that contribute to climate change. There are two main types of greenhouse gas emissions associated with wastewater treatment: direct and indirect. As noted by the Intergovernmental Panel on Climate Change (IPCC) in 2006, the two most significant direct GHG emissions from these processes are CH_4 and N_2O. These gases are produced as byproducts of various biological and chemical reactions that occur during wastewater treatment, the amount of CO_2 generated from the degradation of organic matter or endogenous metabolism of sewage sludge is not included in this category. These organic emissions are considered to be biological sources that do not contribute to the increase in the relative concentration of CO_2 in the atmosphere and are therefore not counted as carbon emissions (IPCC, 2006). However, certain daily products such as toiletries, cosmetics, and medicines are now synthesized from carbon sources extracted from mineral deposits such as oil and coal by humans. During the treatment process, these products enter wastewater and emit CO_2, known as fossil carbon (FC), which can significantly contribute to the atmospheric carbon cycle and cause warming (Law et al., 2013). According to the research findings, the proportion of fossil carbon in raw sewage ranged from 2.1% to 27.9%, in secondary effluent from 7.4% to 48.5%, in biogas from 0.6% to 2.7%, and in digested sludge from 10.2% to 15.5% (Tseng et al., 2016; Nara et al., 2010; Gwen et al., 2010; Griffith et al., 2009). N_2O emissions mainly occur during the biological denitrification process of wastewater treatment, whereas CH_4 emissions occur in significant quantities during effluent transfer and anaerobic treatment processes (Guisasola et al., 2008). The atmospheric greenhouse effect contribution per unit weight of N_2O and CH_4 emissions is 298 and 25 times greater than the Global Warming Potential (GWP) over 100 years, respectively. These two gases have a significant impact on global warming, with Massara et al. (2018) reporting that N_2O emissions alone can affect carbon emissions from wastewater treatment plants by 60-75%. As such, even minor emissions require a comprehensive evaluation. Indirect emissions resulting from the use of energy, chemicals, and other resources are also a significant concern. For example, in China, WWTPs consume about 4-6% of the country's total energy consumption, while in the United States, it accounts for approximately 3-4% (National Renewable Energy Lab, 2012; Simon-Várhelyi et al., 2020). These findings emphasize the need for more sustainable and efficient approaches to wastewater treatment that minimize the environmental impact and reduce the overall energy consumption of these critical facilities.

With economic growth, urbanization, and increased population density, human demand for water resources has escalated. This has resulted in an increase in the volume of urban wastewater as well. Consequently, urban wastewater treatment plants play a critical role in reducing pollutant emissions, recycling resources, and enhancing the ecological environment. However, high-density urban areas have limited land availability, making traditional above-ground wastewater treatment plants expensive. These facilities are typically surrounded by commercial and residential areas, causing negative impacts on the environment, such as noise and unpleasant odors (Wang et al., 2018). In contrast, underground wastewater treatment plants have a small footprint, generate minimal secondary pollution, and do not affect the surrounding environment. Compared to above-ground sewage treatment plants, underground sewage plants require additional requirements for excavation of pits and construction of large underground frame structures during the construction phase, requiring far more building materials and energy consumption than above-ground sewage treatment plants, and are more difficult; during the operation phase, lighting systems, deodorisation systems, and sludge off-loading all have increased energy consumption (Yang, 2021; Wang et al., 2018; Wang et al., 2018;Hou, 2017;), and Hao et al. (2021) found that the full life-cycle cost of a domestic fully underground WWTP is approximately 1.31 times that of an above-ground WWTP, while Wang (2019) reported that the combined environmental impact index of underground WWTPs is 3.0% higher than that of above-ground ones. However, there is currently no systematic accounting or assessment of the carbon emissions of underground WWTPs, and there is also a lack of systematic reviews of comprehensive benefit analysis studies. To accurately understand the relationship between the comprehensive benefits of underground WWTPs and carbon emissions and energy consumption, a comprehensive evaluation and analysis of the carbon emissions, environmental effects, and economic considerations associated with underground WWTPs is imperative.

2. Research related to carbon emissions and energy consumption in wastewater treatment

Experts and scholars from around the world have conducted extensive research on carbon emissions and energy consumption in the field of wastewater treatment. With 136 countries worldwide having set targets for carbon neutrality, including China's aim to reach carbon neutrality by 2060, the wastewater treatment sector has also made significant progress in adopting technologies that reduce carbon emissions, such as renewable energy sources, and conducting energy efficiency studies on wastewater treatment plant equipment to reduce energy consumption.

Mojtaba and Antonio found that electricity consumption of energy grids powering plants had a significant impact on CFP, with Danish WWTPs having higher CFP due to their higher electricity consumption (16-28%) than Swedish WWTPs (2%). This is because Sweden has a smaller CFP potential in their electricity mix (Mojtaba et al., 2020; Antonio et al., 2019), highlighting the need for renewable energy sources. Laura et al. (2018) and Garfi et al.(2017) compared the carbon footprint of an artificial wetland scenario, a high proportion of algal ponds and an activated sludge system by accounting for the higher GHG emissions from chemical products and power consumption in the activated sludge scenario.

Zhang et al. (2017) determined the carbon emissions of different biological treatment processes at Xi'an No. 4 Wastewater Treatment Plant, which had 45.9% direct emissions and 53.8% indirect emissions, with energy consumption being the focus of emission reduction; Several researchers have studied the carbon emissions of various combinations of wastewater and sludge treatment technologies using an emission factor approach. They concluded that anaerobic co-digestion of kitchen waste and sludge can be carbon neutral with carbon emissions of -9223 kg CO_2-eq/d, and that the most effective way to recover energy and reduce carbon emissions is to use chemically enhanced primary treatment and anaerobic digestion of sludge, which can reduce greenhouse gases by 70% (Wu,et al.,2022;Zhuang,et al.,2020). However, it has been shown that the current options for using anaerobic digestion to minimize sludge and generate energy are challenging to evaluate when considering wastewater treatment on a system-wide scale. Direct incineration of sludge has been found to have lower energy deficits and input-output costs compared to conventional anaerobic digestion, which typically requires pretreatment through thermal hydrolysis (Xiaodi et al., 2020). The study on the Kakolanmäki WWTP in Finland discovered that the plant achieved carbon neutrality primarily through the recovery of heat and its contribution to the carbon sink from the TSE heat pump station, rather than from the energy recovery of the wastewater treatment process (Xiaodi et al., 2021). In comparison to above-ground facilities, underground wastewater treatment plants consume more energy than they should. However, China's wastewater treatment plants built to high standards are now equipped with hardware that is no less advanced than those found in foreign countries. Ban et al. (2022) designed and developed a horizontal piston flow ductless ventilation technology. It requires less engineering, has low noise, small investment, small installed power, low operational energy consumption, and convenient construction. Hou (2017) introduced a next-generation FBBR process suitable for underground wastewater treatment plants. The process omits the secondary sedimentation tank from the biochemical treatment unit, has a higher treatment load compared to the AAO process, and proposed an innovative lighting system combining natural and indirect lighting, which was shown to reduce power consumption by 41.7% in engineering practice.

From the above studies, it is evident that the primary emphasis of present research is on carbon emissions in conventional wastewater treatment. There is a greater emphasis on analyzing the impact of different emission factors, carbon reduction technologies, energy consumption, and energy recovery on achieving carbon neutrality.

3. Research related to urban underground sewage treatment

Developed countries such as Finland, Japan, Sweden, and Norway have been able to construct underground WWTP is notable for its ongoing efforts to enhance the energy efficiency of its underground WWTP. By doing so, it has successfully improved the local water environment, conserved land resources, and reduced the number of WWTPs needed. The Gèolide WWTP, located in the center of Marseille, France, treats sewage from the city and 16 surrounding areas annually, providing significant ecological benefits to the region. (WATER NEWS EUROPE, 2016). Daseung et al. (2019) quantified the GHE of subsurface WWTPs except for the demolition phase, using the life cycle assessment (LCA) method and the emission factor method. And the main contributors were the energy consumption of the bioreactor and aeration and ventilation, which were 81.0%.

Initially, research on wastewater treatment plants focused mainly on their engineering construction and design characteristics. This involved summarizing practical experience and exploring development trends. However, with the construction of practical projects and advancements in technology, scholars began to increasingly emphasize research on the adaptability, safety, economy, and ecology of underground wastewater treatment plants. Hou Feng and Niu Xin have addressed several problems related to the construction of underground sewage plants, such as high investment costs, imperfect standards and norms, and limited above-ground usage. They propose to optimize the treatment process and reduce the CFP of underground WWTPs. By integrating the functions of urban forest parks, sports and fitness, leisure and entertainment, science education, and technology research and development, an ecological complex can be created, enabling above-ground and underground material circulation, energy use, and information transfer. Wang et al. (2018) and Hou (2017) used the double-difference distribution method to study the impact of above-ground sewage treatment plants on land values in Beijing. They found that conventional above-ground sewage treatment plants suppressed the rise in residential prices nearby, resulting in significant economic losses. The closer the residences were to the sewage plant, the stronger the environmental disincentive. However, the underground sewage treatment plant drove up the value of the surrounding land by 12.235 billion yuan, 11.4 times its total investment. Based on an underground wastewater treatment plant in Shaanxi, Wang Rui compared various sludge treatment technologies from a techno-economic standpoint and concluded that the bioleaching dry sludge treatment technology is more suitable for local underground subsurface WWTPs (Wang et al., 2018). Zheng et al. (2019) conducted an economic analysis of the construction phase of an underground sewage treatment plant in Yueyang City, Hunan Province. The project cost indicator was 5,862.15 RMB/m^3, and the total investment indicator was 7,008.89 RMB/m^3. Although the indicator was about 2,000 RMB/m^3 higher than that of a conventional above-ground sewage treatment plant, it saved a significant amount of land resources, preserving 0.00246 hectares of engineering area and resulting in substantial land benefits.

Although there have been individual studies on the effects of underground sewage treatment plant operation on the surrounding population, landscape design within the plant, and carbon emissions, comprehensive research on the overall impact of these plants is lacking. With the rising global ecological problems and land resource scarcity, there has been a recent emergence of studies exploring the environmental and economic aspects of underground WWTPs.

4. Environmentally and economically relevant research in the field of wastewater treatment

Buonocore et al. (2018) conducted a study on the environmental impact of five improvement options using the LCA method. They relied on a wastewater treatment plant located in southern Italy. The study revealed that reusing effluent water for plant production or adopting residual sludge incineration for electricity generation significantly reduced eutrophication potential and human toxicity potential. Sadegh et al. (2019) assessed the environmental and economic aspects of various treatment strategies for two wastewater treatment plants in the city of Mashhad using energy value and LCA methods. The LCA option was found to reduce energy consumption by 10%, thereby achieving sustainability. The results of the energy value analysis indicate that constructing two wastewater treatment plants is the most sustainable option, but this difference is attributed to the fact that the energy value analysis doesn't account for operational costs and environmental degradation. From 2016 to 2019, Santos et al. (2021) employed financial metrics to evaluate the economic viability of 222 WWTPs in the Pyrenees. The study results indicated that the viability of resource recovery technologies heavily relies on economic feasibility; Fallahiarezoudar used a window-based data envelopment analysis model to evaluate the ecological efficiency of five WWTPs in Malaysia. The model utilized labor costs, operating costs, utility costs, and chemical consumption costs as inputs, while pollutant removal rates and greenhouse gas emissions were used as desired and undesired outputs, respectively. The analysis revealed a direct relationship between the amount of pollution removed and the cost (Fallahiarezoudar et al.,2022); Numerous research endeavors have sought to evaluate the financial worth of detrimental environmental impacts that stem from greenhouse gas emissions through the use of CO_2 shadow prices. Ramon implements stochastic frontier analysis methodologies to gauge the incremental expense of decreasing GHG emissions within the water and wastewater industry. His analysis found a CO_2 shadow price of £0.181/kg CO_2 eq for ten water and wastewater companies in the UK over 2010-2019.María used a directional distance function to estimate the CO_2 shadow price for 25 wastewater treatment plants, which represented 17.7% of the price of treated water (María et al., 2012; María et al., 2015).

A comprehensive analysis of the benefits in the wastewater treatment field involves various methods, such as whole life cycle assessment, energy value analysis, and eco-efficiency. Studies that quantify the benefits of environmental externalities of wastewater treatment include evaluating its environmental performance throughout the entire life cycle and using shadow price methods to measure the external benefits of wastewater treatment. The application of this method in the wastewater treatment industry originated from foreign research and has become widely used since its proposal. Additionally, this method has some applicability in studies related to the cost of reducing pollutants.

5. Conclusion

With global environmental issues such as the greenhouse effect becoming increasingly prominent, it is important to explore the construction of underground WWTPs. This exploration should involve not only an economic cost analysis but also a comprehensive environmental impact assessment, particularly in terms of accounting for their carbon emission systems. There is no systematic study of the carbon emissions and energy consumption of underground WWTPs, and it is necessary to account for the carbon emissions of each treatment unit at all stages, as well as to analyse the relationship between carbon emissions and energy consumption according to the special characteristics of underground WWTPs in terms of increased energy consumption during the construction and operation phases, and to make a scenario analysis with reference to different resource and energy recovery options for above-ground WWTPs, so that the carbon reduction of underground sewage treatment plants can be made. This will serve as a reference for reducing carbon emissions in underground wastewater treatment plants and supplementing greenhouse gases in the wastewater treatment sector. It quantifies carbon emissions at each stage, promoting the industry's green and low-carbon transformation.

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