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Aerobic treatment feasibility for young and old landfill leachates using the aerated lagoon method

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ABSTRACT

This study evaluated the feasibility of using the aerated lagoon method as a pre-treatment stage for young and old landfill leachates within a comprehensive multi-stage treatment system. Experimental results demonstrated that the method alone is insufficient to achieve final purification standards. However, its application as a pre-treatment step offers significant advantages, including cost-effectiveness and accessibility. The aerated lagoon method achieved notable reductions in contaminant concentrations, including ammonium nitrogen (70% for old leachates and 99% for young leachates), COD (31% for old leachates and 26% for young leachates), and phosphates (93% for old leachates and 81% for young leachates). These reductions effectively alleviate the load on subsequent treatment stages, such as reverse osmosis, municipal wastewater treatment plants, or constructed wetlands. The findings highlight the potential of the aerated lagoon method to serve as an economical and efficient pre-treatment strategy in landfill leachate management systems.

Keywords: aerated lagoon, aerobic treatment, hydraulic retention time, landfill leachate, treatment kinetics.

INTRODUCTION

The current phase of environmental technology development emphasizes a return to modified natural processes for treating environmental components, minimizing the introduction of substances or energy foreign to ecosystems. These processes mimic natural self-recovery mechanisms but are implemented more intensively due to their specific organization. Particular attention is given to biological treatment processes (Malovanyy et al., 2021), the use in treatment technologies of natural sorbents (Kochubei et al., 2020), and sorbents produced from organic waste (Ptashnyk et al., 2020; Soloviy et al., 2020). The application of treatment by-products, such as sewage sludge from wastewater treatment plants (Tymchuk et al., 2020, 2021a, 2021b), for reclamation purposes, as well as the use of modified waste (Kurylets et al., 2022; Malovanyy et al., 2020; Vasiichuk et al., 2022), is particularly promising. Additionally, the utilization of technogenic areas for energy production has proven to be effective (Shapoval et al., 2019, 2021; Zhelykh et al., 2021). This approach can also be effectively applied to the treatment of landfill leachates from municipal solid waste (MSW) landfills.

Landfill leachate forms due to waste decomposition in landfills and contains a complex mixture of organic and inorganic pollutants. This composition makes its treatment a significant challenge. Current research aims to develop more efficient and sustainable technologies to mitigate its environmental impact. There are several approaches to the treatment of MSW leachate. Anjum et al. (2023) demonstrated the potential of pre-treating leachate before anaerobic digestion to increase biogas production. They highlighted the technical and economic feasibility of this approach, focusing on trends and economic assessments of modern pre-treatment technologies. Additionally, they noted that biological methods, such as anaerobic and aerobic treatment, remain central technologies but require the support of other methods for more comprehensive leachate treatment. Similar conclusions are found in many recent studies (Dhamsaniya et al., 2023; Luo et al., 2020; Samadi, Asgari, et al., 2024; Samadi, Leili, et al., 2024). An interesting study by Wei et al. (2021) investigated the combined use of pre-microaeration with the IC-AO_2 process for treating fresh leachate. This work showed that this combination significantly reduces pollution levels and improves overall leachate treatment efficiency.

A significant body of research is dedicated to biological treatment methods for MSW leachate (Britz, 2020; Koc-Jurczyk and Jurczyk, 2020). Britz (2020) reviews the main methods of landfill leachate treatment, emphasizing microbiological processes. The results of biological leachate treatment are presented in the studies by Aboudi et al. (2023) and da Silva et al. (2022), indicating the potential of aerobic methods in the first case and the prospects of using aerobic granular activated sludge technology in the second. The conclusions in these studies highlighted that these technologies can provide enhanced treatment efficiency through better utilization of organic matter and reduced leachate toxicity. Based on the review, aerobic treatment as a pre-treatment appears to be promising, with its efficiency largely depending on the age of the leachate. The general trend is that as the leachate ages, the content of organic pollutants, expressed through biochemical oxygen demand (BOD) and chemical oxygen demand (COD), gradually decreases. However, with increasing leachate age, the BOD/COD ratio drops sharply, while the concentration of ammonium nitrogen (NH_4–N) and leachate pH rise. These changes in leachate composition are explained by anaerobic biochemical processes occurring within the landfill body, coinciding with landfill gas production.

Leachate aging leads to its natural stabilization, reducing its biodegradability and, consequently, the effectiveness of biological treatment, especially in terms of COD and NH_4–N. This effect can be attributed to the increased presence of humic substances, which are resistant to biological degradation, and the simultaneous rise in ammonium nitrogen, which is toxic to microorganisms. Comparisons of the pollution parameters of leachates of different ages are provided in studies (Alvarez-Vazquez et al., 2004; Hussein et al., 2019; Kulikowska and Klimiuk, 2008; Malovanyy et al., 2022, 2023; Renou et al., 2008; Wang et al., 2018). It should be noted that the values of these parameters vary significantly among different researchers. Therefore, in authors' view, the decisive criterion for classifying leachates into one of these two categories is the assessment of biodegradability (oxidation potential). This can be determined by analyzing kinetic curves.

The levels of BOD, COD (Figure 1a), and ammonium nitrogen (Figure 1b) in leachate from the same landfill can change significantly throughout the year. This variation is caused by different degrees of dilution by surface runoff. In such situations, the BOD/COD ratio is the most reliable indicator of leachate age and the degree of anaerobic biodegradation, as it remains unaffected by dilution.

While existing studies have explored aerobic pre-treatment of landfill leachates using aerated lagoons, several gaps remain. Limited research has focused on comparing the treatment kinetics of young and old leachates in aerated lagoons, specifically for indicators such as ammonium nitrogen, COD, and phosphates. This comparison is particularly relevant for the effective implementation of the controlled lagoon method at Ukrainian MSW landfills, given the prevalence of very old leachates, some exceeding 40–50 years of age. This study aimed to evaluate the feasibility of using aerobic treatment via the aerated lagoon technology as a pre-treatment method for leachates of different ages. The leachates analyzed were sourced from the Lviv MSW landfill (old leachates) and the Chervonohrad MSW landfill (young leachates) in the Lviv region, Ukraine.

MATERIALS AND METHODS

The Lviv (Hrybovychi) MSW landfill is located 2 km from the northern border of the city of Lviv. The landfill began operations in 1958, and its area, according to various sources, ranges from 33.3 ha to 45.3 ha, with the height of accumulated

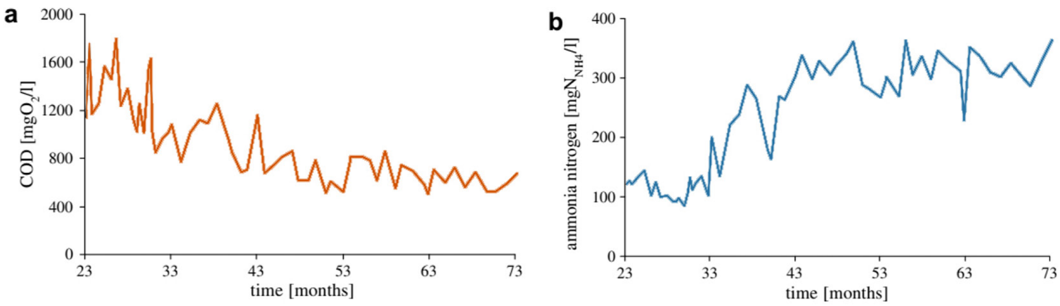

Figure 1. Temporal changes in COD (a) and ammonium nitrogen content (b) in leachate from the Wysieka landfill, Warmian-Masurian Voivodeship, Poland [24]

waste reaching a maximum of 45 meters. The landfill contains approximately 12–15 million tons of waste. For several years, the leachate formed at the Lviv MSW landfill was discharged near the base of the landfill, then flowed down drainage ditches and into retention ponds, which posed an additional environmental threat due to secondary contamination of the surrounding area.

Currently, the Lviv MSW landfill no longer operates as a landfill after the tragedy of the fire and landslide of waste in 2016, reclamation activities have been underway at the site. The treatment of accumulated leachate in the collection reservoirs is nearing completion, using a preliminary chemical treatment unit, a reverse osmosis system, and final treatment at the city's wastewater treatment plants. Newly formed leachates are collected in newly constructed reservoirs equipped with anti-filtration screens (Figure 2).

The Chervonohrad MSW landfill is located 1.0 km south of the town of Chervonohrad, Lviv region, on the right bank of the Solokiya River, a left tributary of the Western Bug River. The total land area under the landfill is 7.2 ha, while the

Figure 2. New leachate collection reservoirs at the Lviv MSW landfill

actual waste body occupies 4.61 ha. In plan view, the MSW landfill has the shape of a parallelogram, with a length of approximately 220 m and a maximum width of 130–140 m. The surface of the waste mass in the southern part is flat, while the northern part is slightly elevated (by 1.5–2.0 m) and covered with a layer of inert material. The thickness of the waste body varies from 6.0 m to 12.0 m. The estimated amount of accumulated waste is 350 thousand tons. Drainage and leachate collection at the Chervonohrad MSW landfill have been carried out in accordance with regulatory documents. Leachate is conveyed by two drainage collectors to a reinforced concrete reservoir, which is a leachate collection tank (Figure 3). Currently, there is no system in place for leachate treatment before its discharge into the sewer system at the Chervonohrad MSW landfill.

Since the authors were interested only in the parameters that change during aerobic treatment (ammonium nitrogen, COD, P_2O_5), Table 1 presents the comparison of these parameters in the leachates sampled for the study from the Lviv and Chervonohrad MSW landfills. Since the leachates from both studied landfills have different initial parameters, for the accuracy of comparison of treatment effectiveness, the data on the relative change of the parameters of the leachates were compared in percentage terms, calculated as follows:

$$V(K) = \frac{K_t}{K_0} \times 100\% \quad (1)$$

where: $V(K)$ is the relative change of parameter K; K_0 and K_t are the initial and current values of parameter K.

Figure 4b shows a photo of the experimental setup, while Figure 4a presents the schematic diagram of the investigated setup. An equal amount of leachate (12.5 liters) previously collected from

Figure 3. General view of the leachate collection tank at the Chervonohrad MSW landfill

the reservoirs at the landfills was poured into four containers. The first two containers contained leachate from the Lviv MSW landfill, while the other two contained leachate from the Chervonohrad MSW landfill. The conditions in buckets 1 and 2 as well as buckets 3 and 4 were identical. This was done to obtain a larger number of parallel results for the studied process for one type of leachate. The leachates in the containers were aerated with a total airflow rate of 2.5 L/min, as indicated by data from the RDS-6 rheometer. This aeration rate was determined based on the preliminary optimization experiments, which are presented in the article by Malovanyy et al. (2023). The specific aeration intensity by volume in all four containers was the same and amounted to 0.05 min^{-1} or 3.0 h^{-1}.

Samples were taken from each container for two days to measure the values of ammonium nitrogen, phosphates, and chemical oxygen demand (COD). In the conducted study, the analytical approach for determining chemical parameters followed the guidelines outlined in the Standard Methods for the Examination of Water and Wastewater (American Public Health Association et al., 2017). Given the initial color of the leachate (black), dilutions of the collected samples were performed for the experiments. For the photometric determination of ammonium nitrogen and phosphates, the leachate samples were diluted by factors of 1000 and 500, respectively, while COD was determined on a 10-fold diluted sample. These dilutions were necessary due to the high concentrations of the target pollutants in the leachates, which would otherwise exceed the optimal range for accurate measurement. To mitigate the potential impact of high dilution factors on detection limits or accuracy, the measurement process was carefully controlled. Each sampling and subsequent analysis were repeated twice, and the average value of these two measurements was taken as the final result, provided that the standard deviation did not exceed 10% of the average value. In the cases where this threshold was surpassed, a third sample was collected and analyzed until repeatability within a 10%

Table 1. Average values of pollution parameters of the tested leachates

Pollution parameter and measurement unit	Lviv MSW landfill (old leachate)	Chervonohrad MSW landfill (young leachate)
Ammonium nitrogen (mg×L^{-1})	932	1258
COD (mg×L^{-1})	4489	5158
BOD_5 /COD	0.168	0.481
P_2O_5 (mg×L^{-1})	5114	4250
pH	9.06	9.51

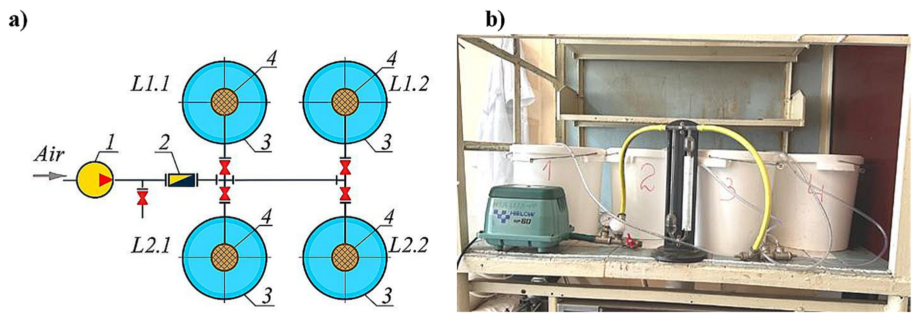

Figure 4. Schematic diagram (a) and experimental setup (b) for studying the effectiveness of aerobic treatment of leachates: 1 – air pump; 2 – rheometer; 3 – containers; 4 – aerators

standard deviation was consistently achieved. This approach ensures the reliability of the results despite the high dilution factors.

RESULTS AND DISCUSSION

Based on the research results, dependencies of the relative concentration changes of ammonium ions and the relative changes in COD for the studied leachates have been constructed.

In Figure 5, the relative change in ammonium ion concentration in the leachates from the Lviv and Chervonohrad landfills is presented. As can be seen from Figure 5, the dynamics of the change in ammonium nitrogen concentration in the leachate decrease during aeration. However, the dynamics of its change significantly differ for young and old leachates. For old leachates, the change dynamics can be approximated by a linear dependence (the correlation coefficient is $R^2 = 0.9926$). The potential for leachate treatment from ammonium nitrogen under aerated lagoon conditions is limited – in laboratory studies, it was possible to purify the leachate from ammonium nitrogen by 70% over 14 days. In authors' opinion, further continuation of the process is unreasonable due to increased energy costs. Final polishing should be carried out in the second stage of the comprehensive technology.

For young leachates, the decrease in ammonium nitrogen concentration can be described by a polynomial relationship. Over a period of 14 days of aeration, the leachate was nearly completely purified of ammonium nitrogen. The t-test results for the comparison between young and old leachate characteristics are as follows: t-statistic is 2.19; p-value is equal to 0.046. Since the p-value is less than 0.05, it can be concluded that the differences between these two samples are statistically significant at the 5% significance level. In authors' opinion, these differences in the dynamics of leachate purification from ammonium nitrogen can be explained by the different forms of bonding of ammonium ions in complex compounds – products of the biological decomposition of the organic fraction of municipal solid waste in young and old leachates. In old leachates, these bonds are more complex, and not all of them can be oxidized during aeration. Typically, a portion of the ammonium nitrogen, especially at the beginning of the aeration purification process, volatilizes from the leachate into the atmospheric air. It is difficult to estimate the amount of volatilized ammonia, but it can be assumed that a significantly larger amount of ammonia volatilizes from young leachates compared to old ones. This is precisely what explains the deviation from linearity in the curve of relative change in ammonium ion concentration in the leachates from the Chervonohrad landfill (Figure 5). Ammonia volatilization, while beneficial for reducing ammonium nitrogen in leachate, can contribute to air pollution if not managed properly. Future studies should bridge this gap by incorporating measurements of ammonia emissions and assessing mitigation strategies, such as gas scrubbing or biofiltration, to minimize environmental risks.

In Figure 6, the relative change in COD values in the leachates from the Lviv and Chervonohrad

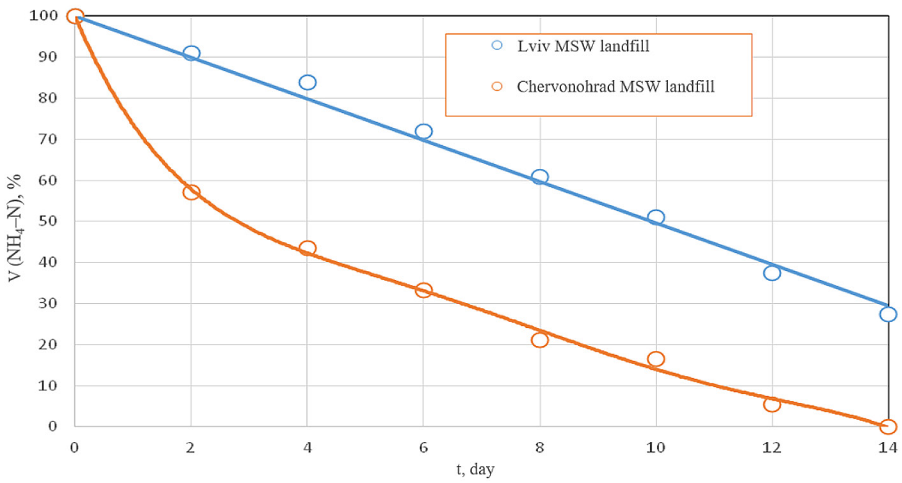

Figure 5. Relative change in ammonium ion concentration in the leachates from the Lviv and Chervonohrad MSW landfills during aeration

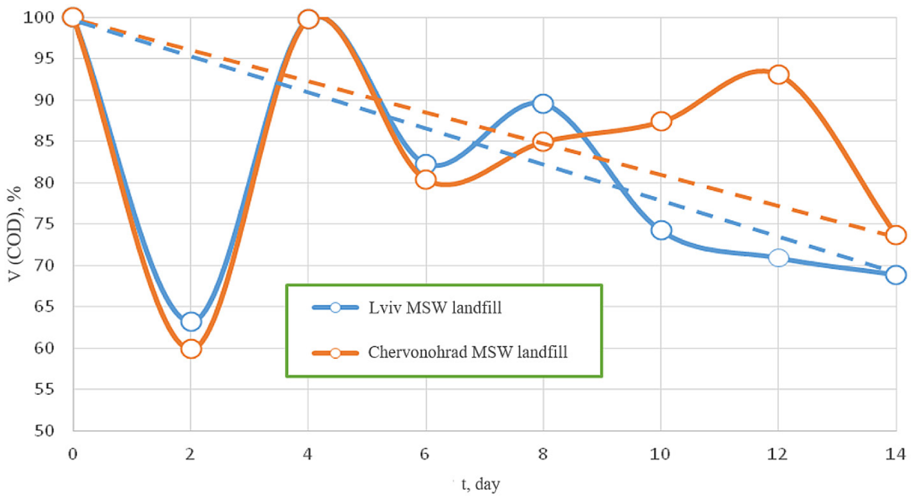

Figure 6. Relative change in the COD values in the leachates from the Lviv and Chervonohrad MSW landfills during the aeration process

landfills is presented. The t-test for the COD values between the Lviv and Chervonohrad leachates yielded a p-value of 0.587, which is significantly greater than 0.05. This indicates that there is no statistically significant difference in the relative COD changes between the two groups at the conventional significance level.

The somewhat unusual shape of the kinetic curves necessitated multiple repetitions of the experiments; however, in all cases, a kinetic curve in the form of fluctuations that diminished over time was obtained. In authors' opinion, this may be related to the mutual transitions during the purification of complex organic compounds into forms that are not detected by the selected analytical method. These transitions occurred throughout the entire oxidation period. The observed COD fluctuations are consistent with dynamic biodegradation and transformation processes known to occur in aerobic treatment systems, where complex organic mixtures undergo sequential breakdown, mineralization, and formation of intermediate products. Therefore, the most accurate approach would be to evaluate the change in the dynamics of COD reduction based on the initial and final values of this parameter. As shown in Figure 5, during the 14-day period of constant aeration, a reduction in COD values of approximately 30% was achieved for both types of leachates studied.

In Figure 7, the relative change in the concentration of phosphates in the leachates from the Lviv and Chervonohrad landfills during the aeration oxidation process is presented.

As can be seen from Figure 7, the kinetic dependencies of P_2O_5 changes during aeration in both types of leachates have a similar character, and three phases of the process can be distinguished: a decrease in concentration of 20–40%, a certain stabilization period of P_2O_5 concentration (which lasted 4 days for the studied leachates), and a subsequent period of further decrease in P_2O_5 concentration, achieving 80–90% treatment effect.

Based on the conducted studies, recommendations for establishing stages of preliminary aerobic treatment of leachates were formulated. For small daily leachate flows (small MSW landfills), it is advisable to use concrete collectors – sumps for preliminary aerobic treatment of leachate, and for significant flows - waterproof geotechnical structures, namely aerated lagoons.

The bottom and side walls of the aerated lagoon should be covered with two layers of a waterproof membrane. The maximum working volume of the aerated lagoon should be determined by the maximum daily leachate flow and the hydraulic retention time (HRT) of the leachate in the structure, which should be within 10−20 days, depending on the quality composition of the specific leachate. Jet-type aerators or mechanical aerators are recommended for leachate aeration in aerated lagoons. The use of pneumatic aeration systems requires additional justification and verification regarding the reliability of prolonged operation of aeration elements in a specific leachate.

Future studies could focus on the pilot-scale implementation of aerated lagoon technology to better assess its scalability and practicality in real-world conditions, particularly in managing seasonal fluctuations in leachate composition. Optimizing aeration parameters, such as aeration intensity

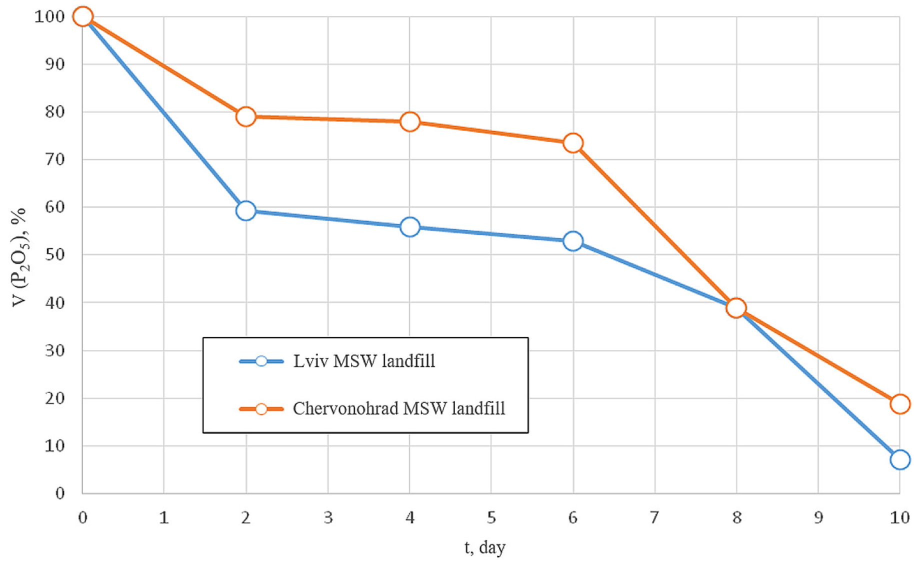

Figure 7. Relative change in the concentration of phosphates in the leachates from the Lviv and Chervonohrad landfills during the aeration process

and HRT, experimenting with intermittent periodic aeration, could enhance the efficiency of the treatment process. Additionally, replacing pneumatic aeration with jet aerators in pilot-scale systems might offer advantages in terms of sustainability, energy efficiency, and aeration uniformity. Furthermore, combining the aerated lagoon method with other biological or chemical treatment stages could yield synergistic effects. For instance, coupling the aerated lagoon with physicochemical methods, such as various modifications of Fenton's method augmented by coagulation and flocculation, holds promise for improving overall treatment efficiency and addressing a broader spectrum of pollutants in landfill leachates.

CONCLUSIONS

The use of the aerated lagoon method for both young and old leachates does not allow for achieving final purification indicators; therefore, this method cannot be recommended as the sole solution in the leachate treatment system. However, this method can be effective as a pre-treatment in a multi-stage leachate treatment system. The advantages of such an approach include accessibility and low implementation costs, as well as a sufficient level of contaminant removal (a reduction in ammonium nitrogen concentration by 70% for old leachates and by 99% for young leachates; a reduction in COD by 31% for old leachates and by 26% for young leachates; a reduction in phosphates concentration by 93% for old leachates and by 81% for young leachates). After preliminary treatment using the aerated lagoon method, the load on the final purification stage is significantly reduced, which may involve reverse osmosis systems, municipal wastewater treatment plants, or constructed wetlands. The aerated lagoon method has a number of advantages, such as its cost-effectiveness and operational simplicity, which make it suitable for diverse settings, including low-resource contexts. While the current study was limited to lab-scale results, a framework for future research aimed at pilot and full-scale testing was provided, including considerations for environmental impacts, regulatory compliance, and integration with other treatment stages.

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