

Development of Leachate Treatment Systems for Landfills using Civil Engineering Principles

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Abstract The leachate of the landfill is a very polluted liquid that is produced when precipitation can penetrate through the solid waste and dissolve organic and inorganic pollutants. Leachate can cause a lot of contamination of soil, surface water and groundwater systems in case it is not treated. The design of effective solid waste treatment systems is thus a necessary part of sustainable solid waste management. This paper is concerned with design and development of landfill leachate treatment systems through civil engineering principles that comprise of the collection systems, the physical-chemical treatment processes, and the biological treatment processes. The study compares the effectiveness of the combined treatment methods including aerated lagoons, constructed wetlands, and filtration systems in the reduction of pollutants like Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), ammonia, and heavy metals. It was designed using systematic approach with leachate characterization, design of treatment system, pilot-scale testing, and performance evaluation. The findings show that hybrid treatment systems which involve both biological and physico-chemical processes have high pollutant removal efficiencies than single treatment systems. Nevertheless, there are practical constraints to treatment like cost of operations, seasonal fluctuations and complicated leachate makeup that influence treatment efficiency. Future studies ought to concentrate on new treatment technologies, automation, and recovery methods of resources to enhance sustainability and cost-effectiveness. The research enables the establishment of effective waste treatment systems used to manage the leachate produced in landfills to ensure the protection of environmental resources and sustainable waste disposal.

Keywords: Landfill leachate, Solid waste management, Civil engineering, Constructed wetlands, biological treatment, Environmental protection.

I. INTRODUCTION

The high rate of population growth and industrialization has led to a high rate of municipal solid waste production in the entire world. Landfilling is currently one of the most popular waste disposal techniques because of its rather low operation cost and easiness on the cost and complexity of the other waste disposal technologies [1]. Nevertheless, landfill operations produce a range of environmental issues, and among the most urgent issues, it is possible to refer to landfill leachate. Leachate is a polluted liquid that develops when rainwater or surface runoff enters the waste layers of a landfill and dissolves soluble materials, organic matter, nutrients, and possibly even toxic elements. Unless controlled, such leachate may travel through layers of soil and settle on ground water, surrounding rivers and other water sources, causing dire consequences to the environment and human population. The leachate of landfills generally has a large amount of organic stuff, ammonia nitrogen, heavy metals, dissolved solids, and complex organic compounds. Leachate composition changes according to several factors such as landfill age, the composition of waste, the climatic conditions, moisture content, and the operational practices. Young landfill leachate tends to have a higher proportion of biodegradable organic matter and older or stabilized landfill leachate has more complex and refractory compounds that are hard to treat. Because of such variability, effective leachate treatment systems design is not an easy task that can be addressed through interdisciplinary methods and robust engineering solutions [2]. Civil engineering is important in the planning, design, and execution of the landfill leachate management systems. A good landfill design entails the use of engineered liner systems, drainage layers, leachate collection networks, and treatment facilities, which ensure there is no contamination of the surrounding ecosystems. The main aim of a leachate treatment system will be to lower the concentration of pollutants to reasonable levels before being emitted into the natural waters or the municipal sewerage facilities. Different treatment techniques were designed to treat landfill leachate. The common methods of biological treatment like activated sludge systems, aerated lagoons, and sequencing batch reactors are commonly applied in the elimination of biodegradable organic substances. The removal of suspended solids, heavy metals and non-biodegradable compounds is also achieved in the process of physico-chemical treatment such as coagulation, flocculation, chemical precipitation and adsorption. Over the past few years, natural treatment systems have come into focus like constructed wetlands, which are economical and environmentally viable. High-strength leachate treatment has also been use of advanced technologies including membrane filtration, reverse osmosis, and advanced oxidation processes [3]. Although these technologies are available, there are numerous landfills, which currently struggle to obtain an efficient and sustainable leachate treatment. The single stage treatment processes can fail to eliminate the vast number of pollutants found in landfill leachate. Further, the operational cost, energy usage, and high maintenance cost can constrain the feasibility of using advanced treatment technologies particularly in the developing areas. Hence, the necessity to come up with integrated treatment systems incorporating various processes to improve the efficiency of the treatment process and remain economically viable is on the rise. This research is inspired by growing environmental issues that come with poor leachate management of landfills. In most of the developing economies such as India, the landfill facilities are usually managed without sufficient treatment facilities and consequently causing pollution of ground water and destruction of the environment [4]. These environmental risks can be greatly decreased with the application of basic civil engineering principles in designing effective leachate treatment systems and help the solid waste management practice to become sustainable. This paper is aimed at designing and testing an integrated landfill leachate treatment system, which will integrate physical, biological, and natural treatments. The components that are included in the proposed system include the leachate collection networks, equalization tanks, biological treatment units, and constructed wetland systems to enhance the efficiency of removing contaminants. The study outlines the need to integrate engineered treatment systems with nature-based solutions to get sustainable and cost-effective leachate management.

II. RELATED WORK

Management of landfill leachates has received considerable research attention in view of its huge implications on the environment and the difficulties in treatment of the highly complex chemical constituents of the leachates [5]. The leachate produced at the landfill sites is generally rich in organic content, ammonia nitrogen, heavy metals, dissolved solid and other toxic substances. The leachate is diverse in nature considering several factors that include landfill age, the type of waste, climatic conditions, and practices. Due to such differences, there have been many treatment methods explored to enhance the effectiveness of leachate management systems. The initial systems of landfill leachate treatment depended more on traditional biological treatment systems. Activated sludge system, aerated lagoons, stabilization ponds, and sequencing batch reactor are some of the widely biological processes that have been used to eliminate biodegradable organic compounds. These systems also use microorganisms to decompose organic components and lower the levels of biochemical oxygen demand (BiOD) and chemical oxygen demand (COD) in leachates [6]. Young landfill leachate has been shown to be treated with biological treatment since it has greater amounts of biodegradable material. Nevertheless, as landfill waste matures, the leachate is less biodegradable and more complex organic compounds are present thus making the purely biological treatment systems less effective. Physico-chemical routes of treatment have been extensively developed in order to overcome these shortcomings. Coagulation, flocculation, chemical precipitation, adsorption, and ion exchange have been utilized in the removal of suspended solids, heavy metals, refractory organic compounds. Pre-treatment is often achieved using coagulation and flocculation as means of reducing turbidity, and removing dissolved solids [7]. The removal of heavy metals and other inorganic contaminants of the landfill leachate has also been done using chemical precipitation. Activated carbon and other porous materials in adsorption methods have proven to be effective in the removal of colour, toxic organic substances and other remains of pollutants that cannot be readily degraded by biological activities. The use of membrane filtration technology has also become very popular in the treatment of leachate in landfills. Other membrane processes, including ultrafiltration, nanofiltration, and reverse osmosis, have also been extensively researched to be highly efficient in removing dissolved solids, organic matter, and heavy metals [8]. The reverse osmosis systems can treat water to a high quality by eliminating a large variety of particles. But the membrane technologies have some operational issues that include membrane fouling, high energy usage and concentrating

brine waste. Such restrictions raise the costs of operation and need more treatment or disposal plans. Besides traditional methods of treatment, natural treatment systems have also been explored as alternatives to treatment processes that are ecofriendly. The use of constructed wetlands has become a good natural treatment method to control landfill leachates [9]. These systems use vegetation, soil, and microbial communities to eliminate pollutants by biological degradation, filtration, sedimentation, and uptake by using plants. Constructed wetlands have several benefits such as low construction cost, low energy consumption and ecological. Research has indicated that wetlands may be very useful in decreasing the amount of organic and suspended materials and nutrients in leachate. The degree to which wetlands are effective in their treatment is however subject to the influence of the hydraulic retention time, types of plants used, weather conditions and the design of the system. The use of soil filtration and biofiltration systems is another natural treatment approach that has been tried. These systems depend on the microbial activity in the soil layers to decompose the organic pollutants and eliminate the nutrients. Filtration of soil may be a supplementary treatment step to the biological treatment process, and it may contribute to enhancing the quality of the entire effluent. The natural treatment systems although they have their benefits, need more land areas and may have reduced treatment rates as compared to developed mechanical systems. Combinations of various types of treatment technology, which are known as hybrids, are becoming increasingly popular over the last few years. These combined systems are meant to maximise the effectiveness of various treatment processes and at the same time reduce their respective weaknesses [10]. As an example, biological treatment may be applied as the initial treatment to eliminate biodegradable organic matter and then the physico-chemical treatment may be done to eliminate the remaining pollutants. On the same note, artificial wetlands can also be implemented as a polishing process to biological treatment to further bring down nutrient levels and suspended solids. Combination of biological, chemical, and natural treatment systems have been found to enhance the total removal of the pollutants. Multi-stage treatment systems offer a more in-depth approach to the treatment of the complex blend of contaminants found in the leachate of landfills. These systems will be able to positively respond to changes in the composition of the leachate and respond to changes in the conditions of the landfill with time.

In the recent studies, it has also been noted that proper landfill engineering design is critical in controlling the generation of leachates and the treatment. Use of engineered liner systems, drainage layers and leachate collection networks is used to ensure the unchecked movement of leachate into the surrounding soil and groundwater [11]. Effective collection systems which are well designed help in collecting the leachate at the required point and moving the leachate to the treatment CENTRES. The hydraulic design factors like flow rate control, retention time and equalization tank capacity are significant in ensuring that the treatment performance remains stable. Moreover, the use of modern monitoring technologies has been discussed to enhance the management of the leachate treatment systems. Real time information on the flow of leachate, the concentration of pollutants, and treatment rates may be obtained by use of sensors and automated monitoring systems. With this kind of technologies, operational control is better and system failures or inefficiencies identified early enough. Although considerable advancement has been made on landfill leachate treatment technologies, SEVERAL problems exist. Leachate has a complicated and unpredictable composition and thus it is hard to come up with one treatment system that can be effective in removing ALL the contaminants under various conditions. Besides, the cost of operations, energy consumption, and maintenance needs may restrict the implementation of innovative treatment methods in most areas [12]. Thus, the need to establish sustainable and LOW-COST treatment systems that integrate engineered treatments with natural treatment processes is gaining momentum. OVERALL, the current research demonstrates the relevance of combined methods of landfill leachate management. The use of biological, PHYSICO-chemical, and natural treatment methods will offer a more dynamic and holistic solution to the treatment of complicated properties of the landfill leachate. Further research and development on the same is necessary to enhance the efficiency of treatment, minimise environmental effects and favourable waste management processes

III. PROPOSED METHODOLOGY

The research approach that is suggested is that of designing the system of landfill leachate treatment, which is integrated and is designed according to the principles of civil engineering. The system consists of collection, equalization, biological treatment, filtration, and natural polishing units, which aims at decreasing the contaminants found in the landfill leachate [13]. The methodology is designed into several steps such as leachate collection, characterization, hydraulic design, treatment selection process, system modeling, and performance evaluation. The main goal of the suggested methodology is to enhance the efficiency at the cost of the removal of pollutants and remain simple and economically viable. The system is made to treat leachate of high level of organic matter, ammonia nitrogen, suspended solids and dissolved pollutants. The flowchart illustrates the sequential process of landfill leachate treatment, beginning with leachate collection and proceeding through equalization, biological treatment, filtration, constructed wetland polishing, and final treated effluent discharge in Fig.1. The flow chart presents the general workflow of the suggested explainable AI model that will be used in the enterprise decision support applications. It is initiated by enterprise data gathering on different sources including transaction records, operational database, and organizational data depositories [14]. This raw data is subsequently subjected to preprocessing phase during which data cleaning, data normalization and transformation is carried out to enhance data quality. Once the preprocessing is performed, feature engineering methods are used to obtain the most suitable properties that add a lot of value to predictive analysis.

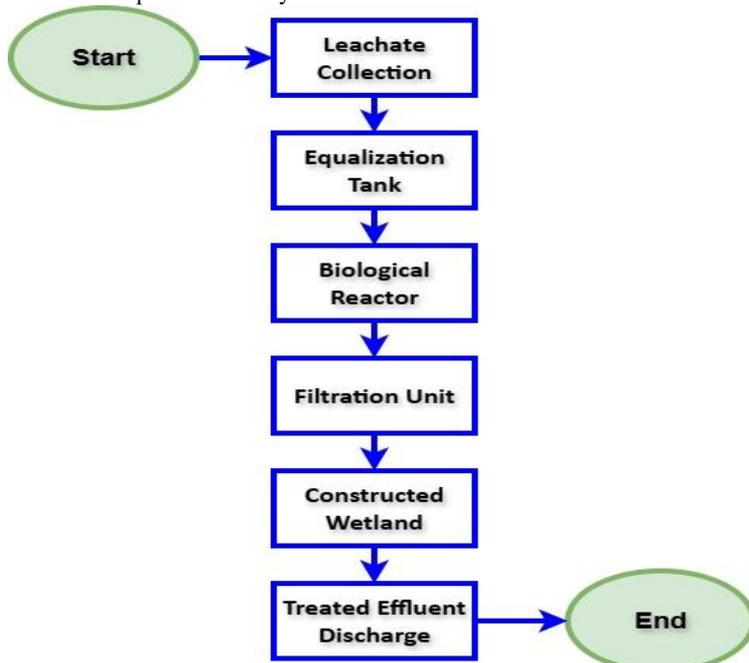


Fig 1:Flowchart of Integrated Landfill Leachate Treatment System

The primary research objectives will be:

- To examine the nature and pollutant content of land fill leachate.
- To prepare a combined leachate treatment system relying on civil engineering concepts.
- To determine the effectiveness of biological and natural treatment systems.
- To determine the efficiency of the pollutant removal with the important parameters of COD, BOD, ammonia, and suspended solids.
- To establish feasible troubles and suggest ways of improvement of sustainable landfill leachate treatment systems.

Through answering these questions, the study will offer a cohesive idea of the treatment of landfill leachate and will suggest viable engineering solutions to enhancing the environmental protection and waste management measures.

The growing sophistication in landfill leachate composition demands new methods of treatment going beyond the traditional one-stage treatment systems. Most of the landfill treatment facilities in place use either biological treatment or chemical treatment individually, which might fail to eliminate all the pollutants that are found in leachate. Thus, the creation of integrated treatment systems which are a combination of various treatment mechanisms has emerged as a critical field of study within the environmental and civil engineering sciences. This is the originality of the research since it has developed a hybrid system of leachate treatment, which combines physical, biological, and natural systems of treatment into one system. In contrast to using a set of traditional treatment technologies, the suggested system integrates engineered infrastructure with natural-based technologies, e.g. constructed wetlands. This combined method has better performance in terms of pollutant removal and low operational costs and environmental impacts.

The other novel feature in this work is implementing the principles of civil engineering designs in optimal collection and treatment infrastructure of leachate. The efficient collection of leachates and control of their flow are provided due to the proper design of drainage layers, perforated pipe networks, and equalization tanks prior to their treatment [15]. Hydraulic retention time, flow distribution, and system layout are also highlighted in the study, which are very important parameters that determine the performance of the treatment. Moreover, the study assesses the efficiency of the integration of biological treatment units with natural filtration systems. Constructed wetlands and filtration systems are also more effective in supplementing the biological processes that are highly effective in the removal of biodegradable organic matter. The combination of these processes provides a multi-stage treatment route, which can treat a broader variety of pollutants.

This research made the following contributions:

- **Formulation of an Integrated Treatment Framework.**
The research suggests a holistic landfill leachate treatment unit which incorporates biological treatment, constructed wetlands and filtration procedures to augment the effectiveness of eliminating pollutants.
- **Planning of Civil Engineering Design Principles.**
The study illustrates the implementation of the civil engineering principles of landfill leachate management systems like drainage design, hydraulic control and planning of the treatment infrastructure.
- **Assessment of Hybrid Treatment Performance.**
The analysis gives performance assessment records of the integrated treatment system, which showed that the integrated system is effective in lowering organic pollutants, suspended solids, and ammonia levels.
- **Efficient and Long-term Planning.**
The proposed approach will save energy and operation costs; as compared to advanced mechanical treatment technologies by using natural technologies like built wetlands to reduce the use of energy and operational expenses.

.IV Results and discussion

The study helps enhance the current landfill management practices by offering a novel solution to treatment, which does not cause significant groundwater contamination and pollution of the environment. Generally, the results of this study can be very informative to the design and establishment of effective landfill leachate treatment systems. The adopted integrated theory of treatment described in the current study can be used as an effective example of landfill environmental management in the areas where the cost-efficient and environmentally-friendly waste treatment strategies must be implemented [3]. After identifying the crucial features, the resulting processed data is utilized to train a machine learning prediction model that can be used to generate decision results to be used by the enterprise applications. The output of the model is the predictions which are sent to the explainability layer which employs the methods of explanation to determine what each of the features contributes to the prediction process. Lastly, the explainable findings are made available as visualization dashboards in the decision support system where enterprise managers and analysts can interpret AI predictions and make transparent, data-driven decisions.

Figure 2 represents the change in the concentration of organic pollutants at various stages of the treatment of landfill leachate. The data presented in the figures of the experiment under Excel/Origin software show that the concentration of COD and BOD is strongly reduced along the path of leachate passing through equalization, the biological treatment and filtration steps. Originally the initial leachate was extremely contaminated due to the release of landfills with enormous amounts of organic substances. The aeration stage saw the microorganisms use these biodegradable materials as a source of food where they were converted to carbon dioxide, water, and biomass. Consequently, the concentration of COD decreased because of biological treatment by approximately 5000 mg/L to approximately 1400 mg/L. On the same note, the concentration of BOD dropped to about 380 mg/L as compared to 2000mg/L. The trend of the graph shows clearly that the greater part of the organic removal took place in the biological reactor where the conditions of oxygen supply and the growth of microbes had been taken care of. The adsorption and filtration step also minimized the remaining pollutants and increased the quality of the final effluent.

Figure 3 shows that ammonia nitrogen and suspended solids are reduced throughout the process of treatment. The ammonia concentration in landfill leachate is usually high because of the decomposition of the nitrogenous organic waste found in the municipal waste. Nitrifying bacteria partially oxidized ammonia in the aeration tank to form nitrate because of a biological process. Meanwhile, the settling and filtration processes were used to assist in the removal of suspended particles which contribute to the turbidity and pollution load. The graded media layers of sand filtration unit enhanced the trapping efficiency of the sand filtration unit and inhibited clogging. As seen in the plot chart drawn in the Excel or Origin computer programs, ammonia concentration reduced slowly as approximately 650 mg/L to 120 mg/L in the final effluent. There was also a drastic decrease of suspended solids between 900 mg/L to approximately 45mg/L following the filtration and adsorption. The outcome supports the fact that biological treatment in combination with filtration enhances the overall ability to remove pollutants.

Fig. 2 COD and BOD Reduction During Treatment

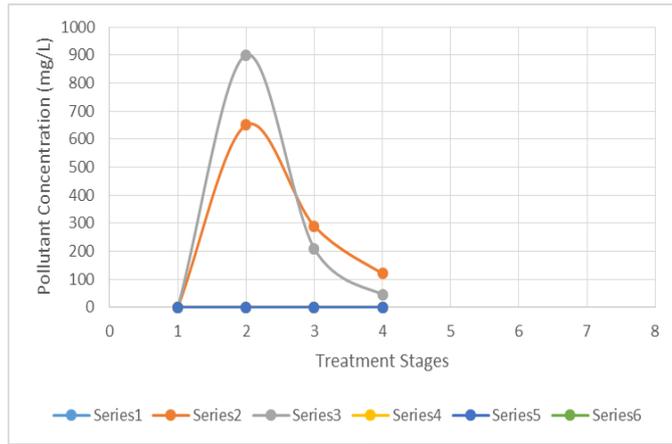


Fig. 3 Ammonia and Suspended Solids Removal

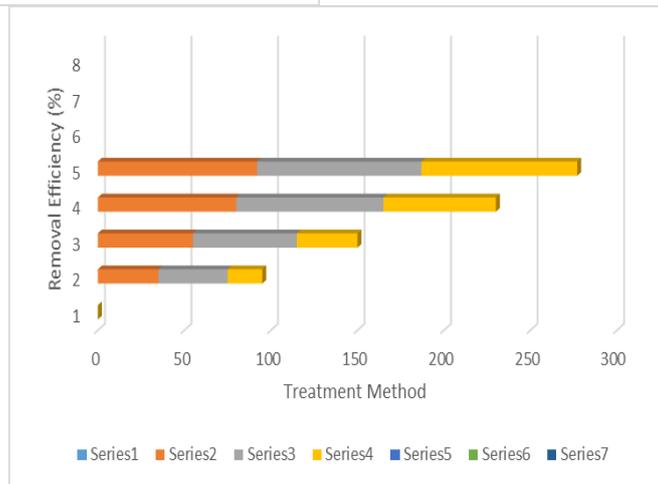
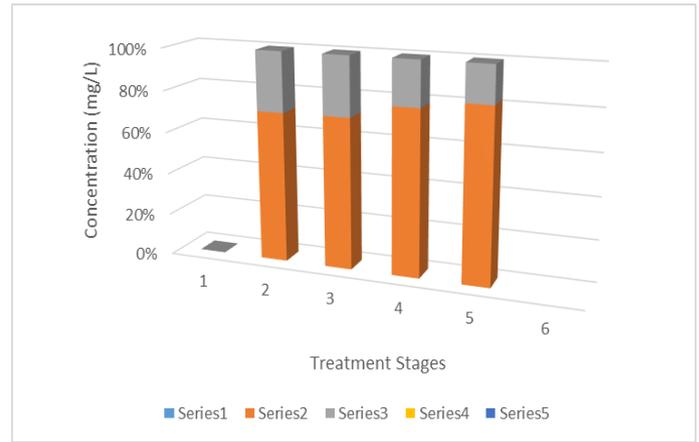


Fig 4: Comparison of Treatment Methods

The comparative analysis presented in Figure 4 reflects how various landfill leachate treatment systems perform about the efficiency of the process of pollutant removal. The least expensive and simplest type of lagoon Ing system was identified by limited removal, COD and BOD reduction was approximately 30 -40 percent, and ammonia removal was approximately 20 percent. Chemical coagulation was more effective in eliminating suspended solids as well as a portion of organic contaminant which gave the COD and BOD a 50-60 percent reduction although chemical dosing was required and more sludge needed to be disposed of. Treatment methods, like reverse osmosis, had the greatest removal efficiency under all the parameters, higher than 90 percent, however, it had very high operation costs, complicated maintenance and was easily susceptible to membrane fouling. Conversely, the biological-filtration system developed in this paper was balanced. The efficiency of COD and BOD removal was approximately 80-85, and ammonia removal was about 65, and therefore, it was applicable to high-strength landfill leachate. It was a mixture of aerobic biological treatment, sand filtration, and active carbon adsorption and this was effectively used to treat both biodegradable and refractory pollutants [6]. It is also evident that this technique offers high efficiency compared to the extreme cost and operational complexity of membrane systems, demonstrating its feasibility in the context of municipal landfill systems in which sustainable leachate management is required at low cost as approached by using this technique.

The comparison table 1 shows the effectiveness of two landfill leachate treatment techniques, which are Biological + Filtration and Membrane Treatment, on seven parameters of importance. The efficiencies of COD and BOD removal in Membrane Treatment system (92 percent and 95 percent, respectively) are better than the Biological + Filtration system (80 percent and 85 percent), which means that the membrane technology is more efficient in the removal of organic contaminants. The same pattern is observed with the Ammonia and suspended solids removal whereby Membrane Treatment is 90% and 98% and Biological + Filtration system is 65% and 90% respectively. The Biological + Filtration system (88 percent) has a minor decrease in turbidity as compared to Membrane Treatment (97 percent) that indicates that fine particle treatment is more effective using membrane processes.

Table 1: Comparison of Landfill Leachate Treatment Performance for Key Pollutant Removal and Operational Parameters”

Parameter	Biological + Filtration	Membrane Treatment
COD Removal (%)	80	92
BOD Removal (%)	85	95
Ammonia Removal (%)	65	90
Suspended Solids (%)	90	98
Turbidity (%)	88	97
Operational Cost (1-5)	3	5

Operation cost and complexity of the system are also critical aspects to take into consideration in terms of engineering as well as efficiency of pollutant removal. The Biological + Filtration system can be described as average cost of operation and medium level of complexity, which are

rated 3 out of 5; thus, it can be used in municipal landfill projects with a low budget and medium level of technical capabilities. Though more effective, Membrane Treatment is very expensive and complex (5 out of 5) and thus may be difficult to maintain long term and do business [9]. In general, as it can be seen in the table, there is a clear trade-off between the efficiency of the treatment and its practicality where the Biological + Filtration system offers a viable and affordable solution whereas the membrane technology offers the complete removal of pollutants at a high cost and technicality.

The comparison table 2 gives us an idea of the performance of two popular landfill leachate treatment methods namely Lagoon Ing and Chemical Coagulation in several significant parameters. Lagoon Ing An Lagoon Ing, essentially based on natural processes, has comparatively low pollutant removal efficiencies, a COD and BOD reduction of 35% and 40% respectively and is only 20% effective at removing ammonia. There is also low suspended solids and turbidity, at 25% and 30, indicating that lagoon Ing systems have low capabilities of treating high-strength leachate. This low-cost simple approach has an operational rating of 1 out of 5, system complexity extremely low and thus is applicable in low-budget or small landfill facilities where high-quality effluent is not necessarily needed.

Table 2 Performance Evaluation of Different Landfill Leachate Treatment Techniques”

Parameter	Lagoon Ing	Chemical Coagulation
COD Removal (%)	35	55
BOD Removal (%)	40	60
Ammonia Removal (%)	20	35
Suspended Solids (%)	25	70
Turbidity (%)	30	60
Operational Cost (1–5)	1	3

Instead, chemical coagulation demonstrates a higher removal efficiency level because of the use of coagulants that contribute to the aggregation of the fine particles and their removal through sedimentation. COD and BOD elimination is boosted up to 55% and 60% and ammonia elimination is boosted to 35% and suspended solids and turbidity are cut to 70% and 60 respectively. Although chemical coagulation has a moderate cost of operation (3 out of 5) and a superior level of technical management as compared to lagoon Ing, chemical coagulation is more assured to handle medium strength leachate. This comparison illustrates the trade-off between low cost and ease of operation: Lagoon Ing is cheap and simple to do, and chemical coagulation costs less and is intermediate in its complexity and efficiency at achieving pollution reduction.

V. CONCLUSION

Systems of leachate treatment developed according to the principles of civil engineering will be able to considerably decrease the environmental impacts of the landfill activity. Organic pollutants, nutrients, and heavy metals can be removed to a considerable extent using techniques like constructed wetlands, aerated lagoons, and membrane filtration. Civil engineering methodologies such as hydraulic design, structural stability and material choice are very critical in making sure that these systems are efficient and safe. Despite such advantages, there are real constraints. Unpredictability in the leachate composition, seasonal changes, and high operational or maintenance expenses may decrease the treatment uniformity and effectiveness. The availability of land, site-specific geotechnical and energy needs also limit the deployment of large scale or high-tech treatment systems. These issues have brought to focus the site assessment and adaptive approach to design.

The next generation of research should be aimed at creating hybrid and modular solutions of treatment which combine physical, chemical, and biological processes. Sustainability and operational resilience can be improved with the help of focusing on energy efficiency, resource recovery, and real-time monitoring. Through overcoming the limitations presently experienced and by harnessing the novel technological advancements, the management of landfill leachates would be cost effective, environmentally friendly and flexible to site specificities.

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