

*Type of the Paper (Original Research)*

# Impact of Sugarcane Bagasse Ash Amendment on Soil Attenuation and Leachate Dynamics: Insights from Multivariate Analysis

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Key Words	Landfill leachate, Sugarcane bagasse ash (SCBA), Soil-leachate interaction, Lysimeter experiment, Contaminant attenuation, Pearson correlation analysis Multivariate statistical analysis
DOI	<a href="https://doi.org/10.46488/NEPT.2026.v25i04.B4446">https://doi.org/10.46488/NEPT.2026.v25i04.B4446</a> (DOI will be active only after the final publication of the paper)
Citation for the Paper	Krutika M.I., Lokeshappa B., Rashma Shetty and Srinivasa P. C., 2026 Impact of sugarcane bagasse ash amendment on soil attenuation and leachate dynamics: insights from multivariate analysis, 25(4), B4446. <a href="https://doi.org/10.46488/NEPT.2026.v25i04.B4446">https://doi.org/10.46488/NEPT.2026.v25i04.B4446</a>

**Abstract:** Landfill leachate composition is strongly governed by soil–leachate interactions that control contaminant mobility, attenuation, and long-term environmental impact. The study demonstrates the influence of Sugarcane Bagasse Ash (SCBA) amended soil on leachate quality through controlled lysimeter experiments and comparative validation with field leachate characteristics from a municipal solid waste (MSW) landfill site. Two cover soil configurations were examined: (i) loam soil and (ii) clay loam amended with SCBA. Simulated rainfall was applied by adding 4.62 L of water weekly over a 17-week monitoring period and collected leachate was analysed for physicochemical parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), hardness, chloride, biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Results indicate that the SCBA-amended clay loam significantly improved contaminant attenuation compared to un-amended loam soil, producing lower EC, TDS, hardness, chloride, BOD, and COD values. The observed reduction is attributed to enhanced adsorption, cation exchange capacity, filtration effects, secondary mineral formation, and accelerated organic degradation mechanisms induced by SCBA incorporation. Experimental findings were further validated against the actual physicochemical characteristics of leachate collected from an operational MSW landfill site under similar ground conditions. A Multivariate statistical analysis was employed to interpret the governing processes. Pearson correlation analysis revealed strong relationships among key parameters, notably EC, Total Hardness–Mg, and COD–BOD at  $p < 0.01$ , highlighting coupled mineralisation and organic degradation pathways. A constitutive model developed in the laboratory to simulate soil–leachate interaction behaviour showed good agreement with both experimental and field observations, confirming the reliability of the proposed attenuation mechanism.

## 1. Introduction

Landfill leachate composition is largely controlled by interactions between percolating leachate and the surrounding soil matrix, which influence contaminant mobility, transformation, and retention. These soil–leachate interactions determine the extent to which pollutants migrate through the subsurface environment or are attenuated within the soil system. Factors such as soil texture, mineral composition, permeability, and adsorption capacity play a critical role in regulating the transport of dissolved and suspended contaminants. Landfilling, although considered the least preferred option in the municipal solid waste management hierarchy, remains widely practiced due to its operational simplicity and relatively low cost (Ergene et al., 2022). However, landfill operations inevitably generate leachate formed through the percolation of precipitation and inherent waste moisture, producing a complex effluent rich in dissolved organic matter, inorganic salts, nutrients, heavy metals, and other pollutants (Christensen et al., 2001). The composition and strength of leachate depend on several factors including waste composition, landfill age, climatic conditions, and the degree of biochemical degradation occurring within the waste mass (Kjeldsen et al., 2002). Seasonal variations further influence leachate characteristics, as increased rainfall generally dilutes leachate concentration while dry periods tend to increase pollutant strength (Yaqout et al., 2003).

Soil layers in landfill systems act as natural attenuation barriers by reducing contaminant migration through mechanisms such as adsorption, biodegradation, ion exchange, precipitation, and filtration (Aish et al., 2014). However, the attenuation capacity of natural soils is limited, and certain contaminants may eventually migrate once adsorption sites become saturated (Tuffaha, 2006). To improve contaminant retention, agricultural by-products have recently been explored as sustainable and low-cost adsorbent materials (Mor et al., 2019). Among these, Sugarcane Bagasse Ash (SCBA) has gained attention due to its porous structure and high silica and alumina content, which enhance adsorption and ion exchange processes (Lang et al., 2024).

Previous studies on Sugarcane Bagasse Ash (SCBA) have predominantly focused on short-term adsorption experiments or synthetic wastewater treatment under simplified laboratory conditions, with limited emphasis on realistic landfill environments and long-term contaminant attenuation behaviour. In contrast, the present study introduces a comprehensive lysimeter-scale landfill simulation framework integrating SCBA-amended clay loam soil with geotechnical characterization, long-term leachate monitoring, and multivariate statistical analysis.

A major novelty of this work is the transformation of SCBA from a conventional agricultural waste residue into a functional landfill liner amendment material capable of simultaneously enhancing soil engineering properties and leachate attenuation performance. The incorporation of SCBA significantly improved clay fraction, plasticity, adsorption capacity, and contaminant retention behaviour, resulting in superior reduction of COD, BOD, EC, TDS, chloride, and suspended solids compared to natural loam soil.

Unlike previous investigations limited to pollutant removal assessment, this study establishes a direct linkage between soil modification, contaminant migration, and landfill stabilisation processes under controlled long-term

conditions. The comparative dual-lysimeter system further provides realistic insight into soil–leachate interactions and contaminant transport mechanisms within landfill environments. In addition, the integration of Pearson’s correlation analysis, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA) provides a robust mechanistic interpretation of leachate evolution by identifying the dominant processes governing mineralisation, ionic enrichment, and organic degradation. The strong agreement between PCA and HCA validates the reliability of the proposed analytical framework. Overall, this study presents a novel waste-to-resource approach by demonstrating the potential application of SCBA-amended clay loam soil as a sustainable and cost-effective landfill liner material for enhanced leachate attenuation and environmental protection.

## 2.1 Study Area and Municipal Solid Waste Collection

The present study was carried out using municipal solid waste (MSW) collected from Davangere city, Karnataka, India, which is one of the rapidly developing urban centers in the central part of the Karnataka state. According to recent municipal statistics, the city has an estimated population of approximately 552,000 as of 2024, with an average per capita solid waste generation rate of about 0.35 kg per person per day. Geographically, Davangere is situated at 14.28° N latitude and 75.59° E longitude, with an average elevation of approximately 602.7 m above mean sea level. The municipal solid waste generated within the city is transported and disposed of at the designated landfill site located at Avaragolla village, which lies nearly 12 km away from the main urban area as shown in the figure-1(a) and figure-1(b). The climatic conditions of the region are characterised by a semi-arid tropical climate, with an average annual rainfall of around 644 mm, most of which occurs during the southwest monsoon season. The surrounding soil strata in the region predominantly consist of black cotton soil and red loamy soils, which provide a suitable natural environment for studying soil–leachate interaction processes.



Figure-1(a): Municipal Landfill site, Avaragolla, Davangere



Figure-1(b): A view of Solid waste dumped at MSW site

For the purpose of this experimental investigation, municipal solid waste was collected and characterized to represent the typical waste composition generated within the city as represented in figure-2. The composition data used in this study were obtained from the Karnataka State Pollution Control Board (KSPCB), Davangere, in order to ensure that the experimental conditions realistically replicate the actual waste characteristics of the landfill site.

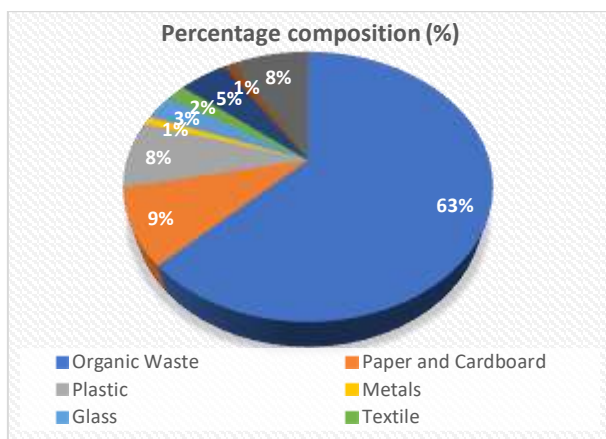


Figure-2: Graphical representation of composition of Solid waste



Figure-3: Sample of organic waste collected from municipal transfer stations

The waste collected from the municipal transfer stations was manually segregated to isolate the organic fraction, which forms the dominant biodegradable component of MSW and is primarily responsible for leachate generation during decomposition. The segregated waste was then mechanically chopped to a particle size less than 200 mm, which facilitates better packing of the waste within the lysimeter and improves the percolation of water through the waste matrix. Based on laboratory measurements, the average bulk density of the municipal waste was determined to be 275 kg/m<sup>3</sup>. The quantity of waste required for filling each lysimeter column was estimated using the relationship:

$$Q=A \times H \times \rho$$

Where, Q represents the quantity of waste (kg), A denotes the cross-sectional area of the lysimeter (m<sup>2</sup>), H represents the height of the waste layer (1 m), and  $\rho$  is the bulk density of the waste (kg/m<sup>3</sup>). This calculation ensured uniform waste loading across all lysimeter units and enabled accurate comparison of leachate generation under different soil configurations.

## 2.2 Preparation of Soil and Adsorbent Material

Soil samples used in the experimental study were collected from various locations surrounding the landfill site to represent the natural soil conditions prevailing in the study region. Sampling was performed using core cutters, which allowed the extraction of relatively undisturbed soil samples for the determination of physical and geotechnical properties. The collected soil samples were subjected to a series of laboratory tests in accordance with the Indian Standard (IS) code procedures, including determination of grain size distribution, moisture content, bulk density, and plasticity characteristics. Soil classification was carried out using the USDA soil textural classification system, which categorizes soils based on the relative proportions of sand, silt, and clay fractions.

Two types of soil configurations were prepared for the lysimeter experiments. In the first configuration, black cotton soil and lateritic soil were mixed in equal proportions (1:1) to obtain a composite soil mixture designated

as Soil-1. Hydrometer analysis and particle size distribution results indicated that this mixture falls within the loam soil category, characterized by a balanced proportion of sand, silt, and clay particles. In the second configuration, Sugarcane Bagasse Ash (SCBA) was incorporated into Soil 1 to enhance its adsorption and contaminant retention capacity. SCBA is an agricultural by-product generated during the combustion of sugarcane bagasse in sugar industries for energy production. The SCBA used in this study was collected from a nearby local sugar mill, after which it was oven dried to remove moisture and subsequently sieved through a 300  $\mu\text{m}$  sieve to obtain a uniform particle size suitable for mixing with soil.

The dried and sieved SCBA was then mixed with Soil 1 in a 3:1 ratio (soil:SCBA) to obtain Soil 2, which served as the modified soil medium for evaluating the effect of SCBA on leachate attenuation. The soil to SCBA ratio of 3:1 (75% soil and 25% SCBA by weight) was selected based on previous studies demonstrating that agricultural ash additions in the range of 10–30% improve adsorption capacity, specific surface area, and contaminant retention while maintaining acceptable geotechnical properties and hydraulic performance [Mangi et al., (2017)]. The presence of SCBA in the soil mixture increases the surface area, porosity, and silica content, thereby improving its capacity to adsorb both organic and inorganic contaminants present in landfill leachate. Hydrometer analysis indicated that the addition of SCBA altered the soil texture, resulting in a clay loam classification for Soil 2 according to the USDA textural triangle. This modified soil was therefore expected to exhibit enhanced contaminant retention through mechanisms such as adsorption, ion exchange, and filtration.

### 2.3 Collection of Rainfall Data for experimentation

Rainfall data were collected from the Meteorological Department, Davanagere, to simulate realistic climatic conditions for the lysimeter experiment. Historical precipitation and evaporation data for the monsoon period (June–October) for the years 2021, 2022, and 2023 were analyzed to determine the average rainfall pattern in the study area. The compiled rainfall and evaporation data are presented in Table-1. The results indicate that July recorded the highest average precipitation (279.70 mm), followed by October (136.87 mm) and August (123.41 mm), while September showed comparatively lower rainfall (64.64 mm). The total average precipitation during the monsoon season was calculated as 706.43 mm, whereas the corresponding total evaporation was approximately 470.93 mm. Based on these climatic conditions, the quantity of water required to simulate rainfall within the lysimeter column was estimated. Considering the dimensions of the lysimeter and the average precipitation values, the calculated equivalent rainfall volume was approximately 4.62 L. Therefore, to replicate natural rainfall conditions under controlled laboratory settings, approximately 4.62 L of water was added weekly to both Lysimeter 1 and Lysimeter 2 throughout the experimental monitoring period. This approach ensured that the leachate generation process in the lysimeter system closely resembled the rainfall-driven percolation conditions occurring in actual landfill environments. The detailed rainfall and evaporation data used for the calculation are summarized in Table-1.

**Table-1: Rainfall data (Rainfall and Precipitation, Meteorological department Davangere)**

Month	Precipitation, mm				Evaporation, mm			
	2021	2022	2023	Average	2021	2022	2023	Average
June	171.09	72.73	61.52	101.78	95.4	105.2	116.2	105.6
July	334.09	351.97	153.05	279.70	83.2	74.9	45.1	67.73

August	66.70	290.65	12.89	123.41	85.2	65.3	129	93.16
September	36.55	133.46	23.92	64.64	98	90.9	92.2	93.7
October	213.337	194.85	2.42	136.87	111.3	99.4	121.5	110.73
Total Precipitation				706.43				470.93

## 2.4 Lysimeter Design and Experimental Setup

A laboratory-scale lysimeter system was constructed to simulate landfill conditions and to evaluate the generation and migration of leachate through different soil configurations under controlled environmental conditions. The lysimeter columns were fabricated using polyvinyl chloride (PVC) material due to its durability, chemical resistance, and ease of fabrication. Each lysimeter had a total height of 1.8 m and an internal diameter of 0.25 m, which allowed sufficient space to replicate waste layering, soil cover placement, and rainfall infiltration processes similar to those occurring in actual landfill systems.

The internal structure of the lysimeter consisted of multiple layers designed to simulate landfill conditions. At the base of each lysimeter, a 20 cm thick layer of coarse gravel was placed to serve as a drainage layer, ensuring that leachate generated within the waste column could freely flow towards the outlet without obstruction. Above the gravel layer, a hexagonal mesh (hex netting) was installed to prevent fine soil particles from migrating downward and clogging the drainage layer. Figures 4 and 5 illustrate the typical lysimeter configuration and the fabricated laboratory-scale lysimeter used in this study. Sample 1 represents the simulated landfill leachate conditions within the lysimeter system; Sample 2 corresponds to Lysimeter 1 containing Soil 1 (loam soil), and Sample 3 corresponds to Lysimeter 2 containing Soil 2 (SCBA-amended clay loam soil). The organic fraction of municipal solid waste was then placed above this mesh and compacted manually using a hammer until a uniform waste height of approximately 1 m was achieved. Compaction was carried out carefully to achieve a consistent density and to mimic the compaction conditions typically encountered in landfill operations.

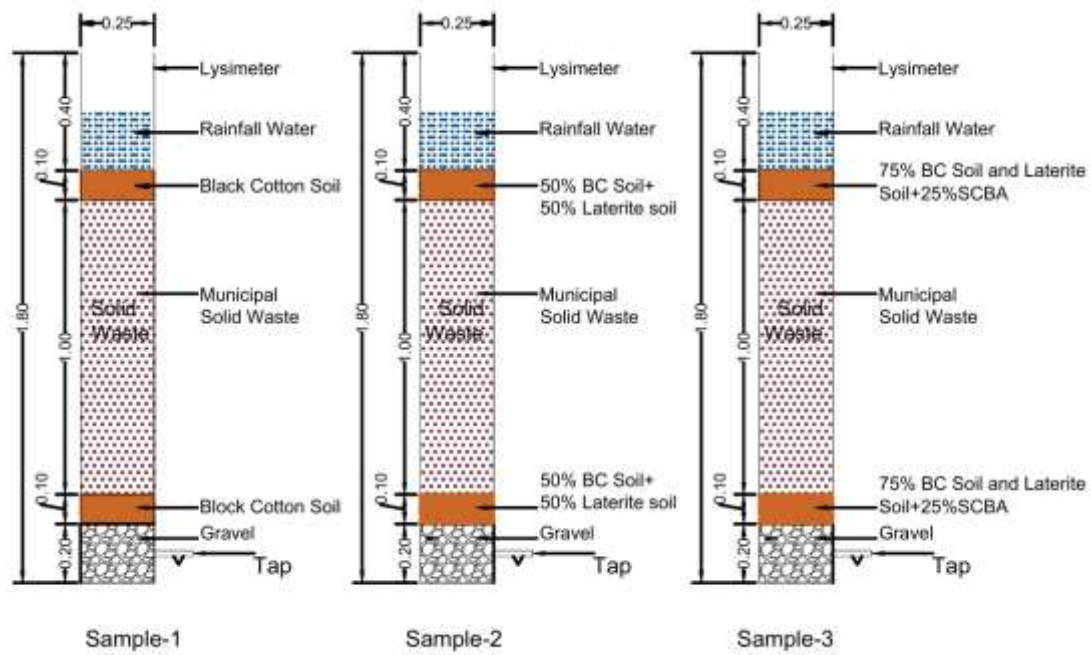


Figure-4: Typical representation of Lysimeter setup for soil sample 1, 2 and 3.

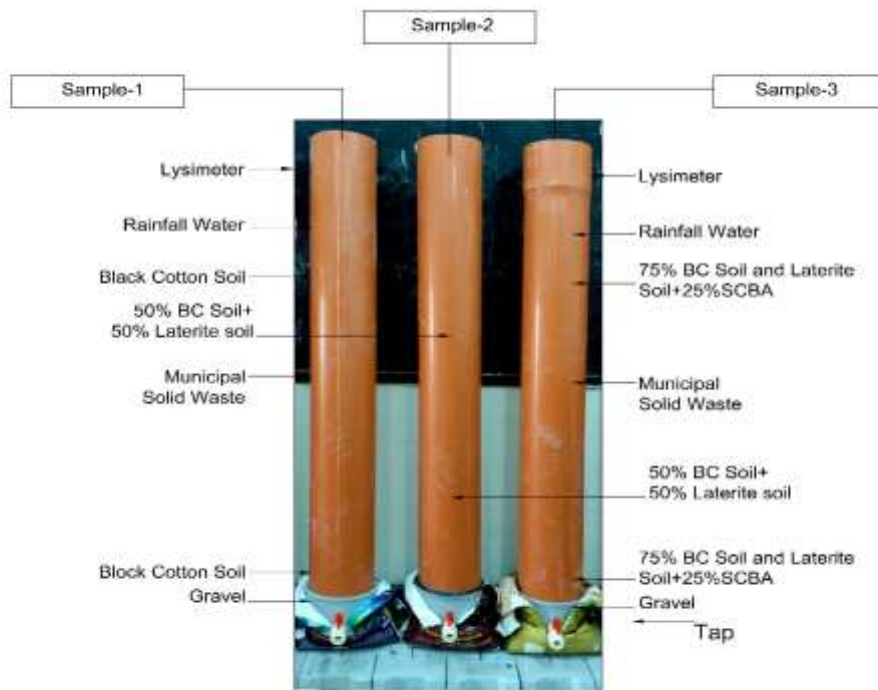


Figure-5: The lysimeter columns fabricated using polyvinyl chloride (PVC) pipe at Environmental Engineering laboratory

Two lysimeters were prepared using different soil configurations. In Lysimeter 1, (Soil 1) was used as the cover layer and was placed both above and below the waste layer to a thickness of approximately 10 cm. In Lysimeter 2, the SCBA-modified soil (Soil 2) was used in a similar configuration. These soil layers were designed to simulate landfill cover and liner materials that influence leachate movement and contaminant attenuation. A freeboard of 40 cm was maintained above the waste layer to allow space for rainfall simulation and water infiltration. Additionally, a tap outlet was installed near the base of the lysimeter column to facilitate periodic collection of the generated leachate samples for laboratory analysis.

## 2.5 Rainfall Simulation and Leachate Generation

To simulate natural rainfall infiltration within the landfill environment, controlled quantities of water were added to the top surface of the lysimeter at regular intervals. A total volume of 4.62 liters of water was applied once every seven days for a period of 17 weeks, thereby reproducing periodic rainfall conditions that promote leachate formation. The quantity of water applied during each cycle was calculated based on regional climatic data using the equation proposed by Aish (2014):

$$L = P(1 - C) - E \quad \text{—————} \quad 1$$

$$L = 706.43(1 - 0.2) - 470.93$$

$$L = 94.214 \text{ mm}$$

Where as  $W = L * A$

$$W = 94.214 * 0.04908$$

$$W = 4.62 \text{ l}$$

Where, L represents the depth of leachate water (mm), P denotes precipitation (mm), C represents the runoff coefficient (C=0.2) [Paris 1996], and E indicates evaporation losses (mm). Climatic data related to rainfall and evaporation used in the calculations were obtained from the local irrigation department records.

The periodic addition of water allowed moisture to infiltrate through the waste mass and interact with the soil layers and adsorbent materials present in the lysimeter. As the water percolated through the decomposing waste, it dissolved organic and inorganic constituents, resulting in the formation of landfill leachate. The generated leachate subsequently migrated downward through the soil layers and accumulated at the base of the lysimeter, from where it was collected for analysis.

## 2.6 Leachate Collection and Physicochemical Analysis

Leachate samples produced during the experiment were collected at seven-day intervals by opening the outlet valve located at the base of each lysimeter column. The collected samples were stored in clean polyethylene bottles and transported to the laboratory for further analysis. Prior to analysis, the samples were preserved and handled according to standard laboratory procedures to prevent contamination and chemical alteration.

The leachate samples were analysed for several important physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, chloride concentration, colour, suspended solids, biochemical oxygen demand (BOD), and chemical oxygen demand (COD). These parameters were selected because they provide a comprehensive indication of the organic and inorganic pollutant load present in landfill leachate. All analytical procedures were carried out in accordance with the Standard Methods for the Examination of Water and Wastewater published by the American Public Health Association (APHA, 2017). These standardized analytical techniques ensure reliability, accuracy, and comparability of the obtained experimental data.

## **2.7 Statistical Data Analysis**

To interpret the experimental results and identify relationships among the measured leachate parameters, statistical analyses were conducted using IBM SPSS Statistics software (Version 27.0.1). Initially, descriptive statistical methods were employed to summarize the dataset and to determine key statistical indicators such as the mean, standard deviation, and range for each physicochemical parameter measured in the leachate samples. This preliminary analysis helped in understanding the variability and distribution of the measured parameters.

Prior to conducting multivariate statistical analysis, the dataset was normalized in order to eliminate the influence of differences in measurement units and scale among the parameters. Normalization ensures that each variable contributes equally to the statistical analysis and improves the reliability of the resulting interpretations (Aruga et al., 1995). Pearson's correlation analysis was subsequently performed to determine the degree of association between different physicochemical parameters and to identify possible relationships among variables influencing leachate quality.

## **2.8 Principal Component Analysis and Factor Analysis (PCA/FA)**

Principal Component Analysis (PCA) was applied to the normalized dataset in order to reduce the dimensionality of the data while retaining the maximum possible variance. PCA transforms the original correlated variables into a smaller number of independent variables known as principal components (PCs) through linear combinations of the original dataset. These principal components represent the dominant factors controlling variations in leachate composition and help identify the most influential parameters affecting leachate quality.

Factor Analysis (FA) was subsequently performed to further simplify the structure of the dataset by rotating the principal component axes using the vari max rotation method. This rotation process generates varifactors (VFs)

that provide a clearer interpretation of the underlying relationships between variables. The FA model can be expressed mathematically as:

$$Z_{ji} = a_{f1}f_{1i} + a_{f2}f_{2i} + \dots + a_{fm}f_{mi} + \dots + a_{fm}f_{mi} + e_{fi} \quad \text{—————}$$

2

Where,  $Z$  represents the measured variable,  $a$  represents the factor loading,  $f$  represents the factor score,  $e$  denotes the residual error,  $i$  represents the sample number, and  $m$  represents the total number of factors. Factor loadings were categorized into strong ( $>0.75$ ), moderate ( $0.75-0.50$ ), and weak ( $0.50-0.30$ ) according to the classification criteria proposed by Liu et al. (2003).

## 2.9 Cluster Analysis (CA)

Cluster Analysis (CA) was employed to classify leachate samples into groups based on similarities in their physicochemical characteristics. In this study, Hierarchical Agglomerative Clustering (HCA) was applied using Ward's method as the linkage technique and squared Euclidean distance as the similarity measure. Ward's method operates by minimizing the total within-cluster variance at each stage of the clustering process, thereby producing compact and homogeneous clusters.

The results of the cluster analysis were presented in the form of a dendrogram, which graphically illustrates the degree of similarity between samples and the hierarchical relationships among clusters. This approach allows the identification of groups of samples with similar chemical characteristics and provides insights into the spatial and temporal variability of leachate quality within the experimental system.

## 3. Results and discussions

This section evaluates the influence of soil characteristics and Sugarcane Bagasse Ash (SCBA) incorporation on the attenuation of landfill leachate using controlled lysimeter experiments. Initial analysis focuses on the geotechnical properties of the soils, which determine permeability, adsorption capacity, and overall suitability for contaminant containment. This is followed by a physicochemical assessment of leachate quality to understand variations in parameters such as pH, EC, TDS, hardness, and organic load between the two lysimeter systems. To further interpret the relationships among these parameters, Pearson's correlation analysis is performed to identify significant interactions between inorganic ions and organic pollution indicators. Subsequently, Principal Component Analysis (PCA) is applied to determine the dominant processes controlling leachate evolution and to reduce dataset dimensionality. Finally, Hierarchical Cluster Analysis (HCA) is used to classify leachate samples based on similarity patterns, providing additional insight into the governing geochemical and biodegradation mechanisms. The detailed interpretations and quantitative results for each of these aspects are presented in the following subsections.

### 3.1 Soil Characterization for Lysimeter Study

Soil samples were collected from areas to ensure minimal prior contamination and to simulate natural soil–leachate interactions within the lysimeter system. The geotechnical properties of the collected soil were determined in accordance with relevant Indian Standard (IS) codes to evaluate its suitability for use in the experimental setup. To enhance the treatment efficiency and adsorption capacity of the soil in a cost-effective manner, Sugarcane Bagasse Ash (SCBA) was incorporated into the soil at a proportion of 1:3 (SCBA: Soil). Prior to testing, the samples were air-dried, pulverized, and passed through a 4.75 mm sieve to obtain a uniform material suitable for laboratory analysis. Based on the classification tests, the unclassified soil was identified as loam, while the soil blended with SCBA exhibited characteristics of clay loam. The change in soil texture indicates an increase in the finer fraction due to the addition of SCBA, which is expected to improve the soil’s adsorption capacity, reduce permeability, and enhance its effectiveness in attenuating contaminants during the lysimeter leachate treatment process.

### 3.2 Geotechnical Properties of Soil Samples

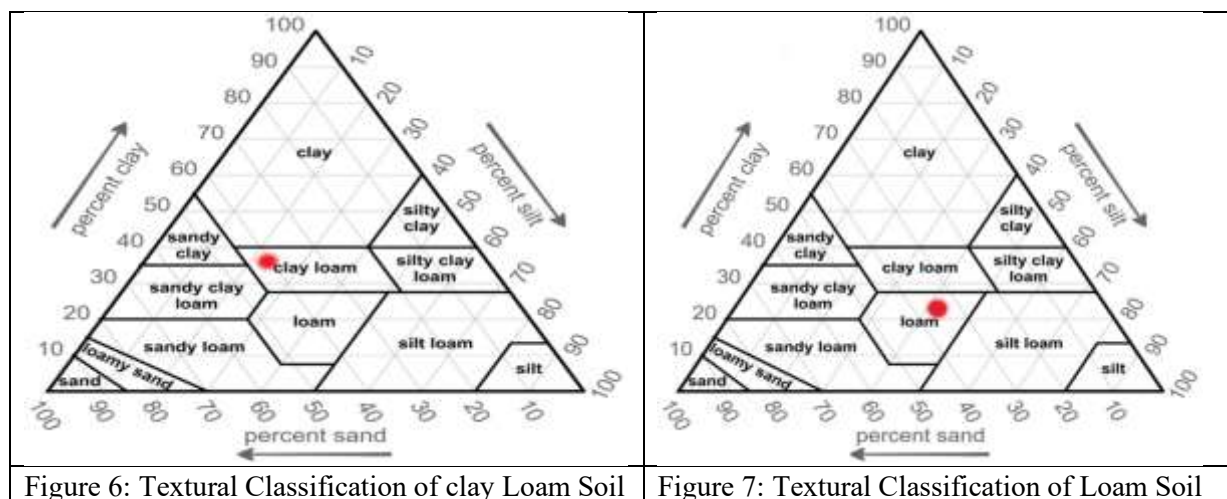
The geotechnical analysis indicates notable differences between Soil 1 and Soil 2 due to the incorporation of Sugarcane Bagasse Ash (SCBA). Soil 1 was classified as loam, whereas Soil 2 showed clay loam characteristics with a higher clay fraction. Table-2 shows the Geotechnical Characterization of Soil Samples Used in Lysimeter Study. The grain size distribution and Atterberg limits indicate that Soil 2 possesses improved cohesion, moderate plasticity, and lower permeability compared to Soil 1. Both soils exhibited low swelling potential and slightly alkaline pH, which are favourable for contaminant adsorption and stabilization (Das et.al (2020)). The increased clay content in Soil 2 enhances surface area and adsorption capacity, improving its ability to retain pollutants. Overall, Soil 2 demonstrates better suitability for leachate attenuation and environmental containment in the lysimeter study.

Table-2: Geotechnical Characterization of Soil Samples Used in Lysimeter Study

Parameter	Test Method	Soil 1 (Loam)	Soil 2 (Clay Loam – with SCBA)
Specific Gravity	Pycnometer Method	2.60	2.65
Gravel (%)	Sieve Analysis	25	33
Sand (%)	Sieve Analysis	12	6
Silt (%)	Hydrometer Analysis	40	24
Clay (%)	Hydrometer Analysis	23	37
Liquid Limit (%)	Casagrande Method	39	43
Plastic Limit (%)	IS Method	30	21
Plasticity Index (%)	LL – PL	9	22
Differential Free Swelling (%)	Free Swell Method	20	30
pH	pH Meter	7.6	7.7
Soil Type (Textural Classification)	USDA Textural Triangle	Loam	Clay Loam

The geotechnical characterization of the two soil samples indicates noticeable differences in their physical and engineering properties due to the incorporation of Sugarcane Bagasse Ash (SCBA). Soil 1 was classified as loam, while Soil 2 exhibited clay loam characteristics with a higher clay fraction, which contributes to improved cohesion and reduced permeability (Karnchanawang et.al (2009)). The specific gravity values remained within the typical

range for natural soils, indicating that the addition of SCBA did not significantly alter the mineral composition of the soil matrix. Grain size analysis showed that Soil 2 contains a higher clay content and lower silt fraction compared to Soil 1, which enhances adsorption capacity and contaminant retention potential. Figure 6 and figure 7 shows the textural classification of soil.



The Atterberg limit results further indicate that Soil 2 possesses slightly higher plasticity, suggesting improved structural stability and moisture retention. Differential free swell values for both soils fall within the low swelling range, confirming the absence of highly expansive clay minerals (Lambe et.al (1969)). Additionally, the slightly alkaline pH observed in both soils is favourable for adsorption and precipitation of contaminants present in landfill leachate. Overall, the results indicate that Soil 2, due to its higher clay content and moderate plasticity, offers better suitability for contaminant attenuation and environmental containment in lysimeter-based leachate studies.

### 3.3 Field and Lysimeter Leachate Characteristics

The physicochemical characteristics of municipal solid waste (MSW) landfill leachate collected from the Avaragolla landfill site, Davanagere which is represented in table-3, were compared with the leachate generated under controlled laboratory conditions using lysimeter prototype models filled with study area soils. The field leachate represents the actual conditions prevailing at the landfill site and reflects the complex interactions among waste composition, microbial decomposition, rainfall infiltration, and geochemical processes occurring within the landfill mass. Such field observations provide an important baseline for understanding the nature of contaminants released from municipal solid waste disposal systems which are depicted in the figure 4 and 5.

Table-3: Initial Physicochemical Characteristics of Landfill Leachate

Parameter	Initial Characteristics of Landfill Leachate
pH	5.6
TSS (mg/L)	1800
EC (mS/cm)	5.6
TDS (mg/L)	3072

Total Hardness (mg/L)	11650
Magnesium (mg/L)	1200
Calcium (mg/L)	5000
Chloride (mg/L)	4397
COD (mg/L)	13600
BOD (mg/L)	3428.57
Colour (Pt-Co)	9600

To simulate these landfill conditions under controlled experimental conditions, laboratory lysimeter experiments were conducted using the soils collected from the study area. The lysimeter system was designed to replicate the natural landfill environment by allowing rainfall infiltration through the lysimeter and facilitating the generation and collection of leachate over time. Periodic monitoring of physicochemical parameters shown in the table 4 enabled the evaluation, stabilization and attenuation of leachate characteristics during the experimental period.

Table-4: Lysimeter Readings (landfill simulation with study area soil)

WEEK	pH	TSS (mg/l)	EC (mS/cm)	TDS (mg/l)	Total Hardness (mg/l)	Mg (mg/l)	Ca (mg/l)	Chloride (mg/l)	COD (mg/l)	BOD (mg/l)	Colour (pt-co)
W1	6.2	400	4.5	2880	6850	924	1200	430	6000	3133	7050
W2	6.7	570	4.6	2944	7400	912	1440	450	6800	3605.91	7100
W3	7.5	790	5.2	4160	7800	960	1520	590	8000	4492.61	7294
W4	7.8	910	5.4	4320	8200	1008	1600	610	10000	5201.97	8488
W5	8.3	1290	5.9	4720	9000	1080	1800	720	11600	5733.99	9500
W6	8.2	1500	6.3	5040	9600	1152	1920	840	12000	6147.78	9600
W7	7.8	1800	5.6	4480	10200	1248	2000	960	10000	3960.59	8200
W8	7.9	1700	5.1	4080	6500	1792	2280	720	6000	2778.32	6900
W9	7.5	1500	4.5	2880	4900	1600	1960	520	4500	1241.37	5200
W10	7.4	1320	4	2560	4500	2576	1840	360	3800	1004.92	4146
W11	7.2	1200	3.0	1950	8400	2000	1650	1300	3300	931.62	1545
W12	6.8	910	2.3	1520	2400	1567	1460	1900	2990	890.36	1223
W13	6.2	790	14.4	9370	4000	1945	920	4100	2400	720.56	1230
W14	6.2	710	14.7	9570	3900	1928	840	3900	1900	635.63	1156
W15	6.1	490	15.1	9790	4700	920	720	700	1850	601.2	805
W16	6	500	1.7	1080	6400	925	720	500	1760	512.35	607
W17	6.1	540	12.4	8090	4800	944	680	200	1540	499.65	575

A comparative evaluation between the field leachate and lysimeter-generated leachate indicates that the laboratory prototype successfully reproduced the general physicochemical behaviour of landfill leachate observed at the site depicted in the table 5 and 6. Both systems exhibited characteristics typical of municipal solid waste leachate, including high organic load, elevated dissolved ions, and strong mineralization resulting from waste degradation and leaching processes (Dabrowska et al., 2021). The pH of the leachate in the lysimeter experiments generally remained within circumneutral to slightly alkaline conditions, which is commonly associated with anaerobic decomposition and carbonate buffering processes during landfill stabilization (Saghi et al., 2024). This behaviour is consistent with the progressive transition from the acidogenic phase to the methanogenic phase of landfill degradation.

Table-5: Leachate Characteristics of Lysimeter-1 for loam soil mixture

Peak TDS values in the loam soil lysimeter ranged from 650 mg/L to 9440 mg/L, which were higher than those

WEEK	pH	TSS (mg/l)	EC (mS/cm)	TDS (mg/l)	Total Hardness (mg/l)	Mg (mg/l)	Ca (mg/l)	Chloride (mg/l)	COD (mg/l)	BOD (mg/l)	Colour (pt-co)
W1	7.4	690	6	4800	3680	643	400	280	12800	3780	4010
W2	7.3	740	6.25	5000	3720	643	432	310	13600	3840	4120
W3	7.1	810	6.4	5120	3800	644	448	320	14400	3960	4250
W4	7.1	870	6.7	5360	3920	663	464	350	14800	4020	4360
W5	6.9	920	6.85	5480	4080	682	496	370	15600	4140	4490
W6	6.9	1000	7	5600	4200	701	512	400	16000	4320	4600
W7	7.2	1050	6.75	5400	4080	696	480	380	15200	4260	4490
W8	7.3	1100	6.69	5352	3960	672	464	350	14000	4200	4375
W9	7.4	1150	6.56	5248	3880	662	448	320	12800	4080	4250
W10	8	1068	4.43	2880	12300	2913	3280	800	11960	4932	2053
W11	7.6	987	1.66	1080	3500	832	680	2200	10569	3899	1648
W12	8	875	11.8	7680	3100	681	5280	2700	10247	3765	1238
W13	8.1	768	13.1	8520	2100	496	720	1700	9872	2876	1145
W14	7.9	678	14.5	9440	3500	833	600	400	8799	2700	1120
W15	7.9	623	13.8	9020	3100	731	1160	500	7698	2630	902
W16	7.4	580	1.09	706	1700	391	1440	100	7628	2498	875
W17	7.2	520	1.04	650	1452	280	1263	100	6859	2380	879

observed in the clay loam soil system. This indicates stronger mineralization and ionic enrichment in the loam soil leachate. In contrast, the clay loam soil generally exhibited lower EC and TDS values, suggesting partial attenuation of dissolved ions through mechanisms such as adsorption, precipitation, and dilution processes (Ezeonuegbu et al., 2021). Similarly, total hardness and major cations ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) were considerably higher in the loam soil leachate, indicating significant dissolution of carbonate and silicate minerals and stronger geochemical influence on leachate composition. The clay loam soil showed comparatively lower and more uniform hardness values, which may be attributed to the partial retention of divalent cations through cation exchange reactions and secondary mineral formation (Kengannavar et al., 2015). Chloride concentrations, commonly used as a conservative tracer, were also higher in the loam soil lysimeter, confirming greater leachate mobility and lower contaminant attenuation capacity relative to the clay loam soil. Organic pollution indicators such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), and colour were high in both soil systems, reflecting the presence of significant organic contamination typical of landfill leachate. However, the loam soil consistently produced higher COD and BOD values, indicating greater solubilization and transport of biodegradable and refractory organic matter (Naveen et al., 2017). These observations suggest that the clay loam soil system demonstrates improved contaminant retention and attenuation compared to the loam soil lysimeter.

**Table-6: Leachate Characteristics of Lysimeter 2 for SCBA soil mixture**

WEEK	pH	TSS (mg/l)	EC (mS/cm)	TDS (mg/l)	Total Hardness (mg/l)	Mg (mg/l)	Ca (mg/l)	Chloride (mg/l)	COD (mg/l)	BOD (mg/l)	Colour (pt-co)
W1	7.14	580	3.7	2368	3360	585	368	230	8800	2640	7486
W2	7	600	3.9	2496	3440	595	400	250	9600	2820	7600
W3	6.9	700	4.1	2624	3600	605	432	270	10800	2940	7720
W4	6.82	760	4.4	2816	3800	644	448	290	11600	3000	7850
W5	6.71	810	4.5	2880	3920	653	480	320	12400	3180	7940
W6	6.65	860	4.8	3072	4120	691	496	340	12800	3300	8110
W7	6.8	900	4.6	2944	4000	682	464	310	12000	3240	7900
W8	6.92	940	4.48	2867	3920	670	448	290	11200	3180	7820
W9	7	1000	4.4	2816	3800	660	416	270	10000	3060	7800
W10	8	1100	4.43	2880	5900	1399	1600	1100	9872	3003	4663
W11	7.6	986	2.54	1650	3500	828	1000	3100	9250	2863	4265
W12	8.1	920	14.85	9650	3100	679	5480	2900	8730	2260	3275
W13	8	875	1.92	1250	2100	492	1080	2900	8250	2105	1085
W14	8.1	798	1.6	1080	3300	769	1920	900	7580	1840	1120
W15	7.9	753	1.57	1020	2800	663	800	500	7258	1530	1028
W16	6.3	684	1.57	1020	2300	544	800	800	6842	1300	1033
W17	6.2	578	1.4	1082	2150	520	780	350	5780	1258	1007

Clay loam soil exhibited a comparatively lower organic load, particularly during the later monitoring periods, indicating improved biodegradation and retention of organic compounds within the soil matrix. The colour values also decreased more rapidly in the clay loam system, suggesting progressive stabilization and transformation of humic and fulvic substances during the leachate evolution process. In contrast, total suspended solids (TSS) were generally higher in the loam soil lysimeter, reflecting greater mobilization of particulate matter and colloidal particles, which can enhance contaminant transport through the soil column. The lower TSS concentrations observed in the clay loam soil indicate more effective filtration and retention of suspended solids within the soil structure (Oyediran et al., 2020). Overall, the results suggest that loam soil facilitates higher contaminant mobility, stronger mineral dissolution, and increased organic pollution load, indicating comparatively lower attenuation capacity and greater environmental risk. Conversely, clay loam soil demonstrates improved buffering capacity, adsorption potential, and biodegradation efficiency, emphasizing the significant role of soil characteristics in controlling landfill leachate quality and its environmental impact.

After comparison between the two laboratory lysimeter systems, representing loam soil (Lysimeter 1) and clay loam soil (Lysimeter 2), revealed noticeable differences in leachate behaviour due to variations in soil properties and soil–leachate interactions. The loam soil lysimeter generally exhibited relatively stable pH values, suggesting stronger buffering behaviour and continuous mineral dissolution within the soil–waste matrix. In contrast, the clay loam soil system showed slightly greater variability in leachate chemistry, which may be attributed to enhanced adsorption, ion exchange, and filtration mechanisms associated with higher clay content.

Electrical conductivity and total dissolved solids tended to be more pronounced in the loam soil lysimeter, indicating higher mobility of dissolved salts and ions within the leachate. This suggests that loam soil possesses comparatively lower attenuation capacity, allowing greater transport of soluble constituents through the soil matrix. Conversely, the clay loam soil demonstrated improved contaminant attenuation due to the presence of finer particles and higher surface area, which facilitate adsorption and retention of dissolved ions. These observations highlight the significant role of soil type in controlling the physicochemical evolution of landfill leachate and its potential migration through subsurface environments (Aswad et al., 2024; Sarkar et al., 2024).

Overall, the combined analysis of field and laboratory data demonstrates that lysimeter-based experimental models can effectively replicate the general behaviour of landfill leachate while allowing controlled investigation of soil–leachate interactions. The results emphasize that soil characteristics strongly influence leachate quality, contaminant mobility, and natural attenuation processes within landfill systems. Such insights are essential for designing improved landfill liner materials and sustainable waste containment strategies aimed at minimizing environmental contamination.

### 3.4 Pearson’s Correlation Analysis of Leachate Parameters

Pearson’s correlation analysis was performed to examine the linear relationships among the major leachate quality parameters, including pH, TSS, EC, TDS, total hardness (TH), Mg, Ca, chloride (Cl), COD, BOD, and colour. The correlation matrix helps identify the degree of association between variables and provides insight into the governing geochemical and biochemical processes influencing leachate composition. Table 7 shows the Pearson’s Correlation Matrix of the Physicochemical Parameters for the Leachate. Strong positive correlations indicate that two parameters increase or decrease simultaneously due to common controlling mechanisms such as mineral dissolution, organic degradation, or ion mobility. The correlation structure obtained in this study revealed distinct clusters of interacting variables, highlighting the interdependence of physicochemical parameters within the leachate system. These relationships are consistent with patterns reported in previous investigations on landfill leachate chemistry and its evolution over time (Singh et al., 2005). The results of the correlation analysis therefore provide important evidence for understanding the processes controlling contaminant transport and transformation within the lysimeter system.

**Table-7: Pearson’s Correlation Matrix of the Physicochemical Parameters for the Leachate.**

	pH	TSS	EC	TDS	TH	Mg	Ca	Cl	COD	BOD	Color
pH	1										
TSS	.236	1									
EC	.407*	.099	1								
TDS	.367*	.152	.986**	1							
TH	.162	.513**	.024	.036	1						
Mg	.326	.438**	.021	.006	.955**	1					
Ca	.533**	.133	.369*	.307	.191	.320	1				
Cl	.553**	.283	.195	.138	-.083	.077	.598**	1			

COD	-.208	.547**	.201	.322	.383*	.142	-.257	-.255	1		
BOD	.042	.596**	.248	.342*	.583**	.407*	-.049	-.128	.876**	1	
Color	-.522**	.192	-.114	-.106	.184	-.057	-.371*	-.358*	.467**	.297	1

\*\*Correlation is significant at the 0.01 level, and \*is significant at the 0.05 level.

r = pearson's correlation coefficient , p = probability

Pearson's correlation analysis revealed several statistically significant relationships among the leachate parameters. EC and TDS exhibited a very strong positive correlation ( $r = 0.986$ ,  $p < 0.01$ ), confirming that electrical conductivity is primarily governed by dissolved ionic constituents in the leachate. Total hardness showed a very strong positive correlation with Mg ( $r = 0.955$ ,  $p < 0.01$ ), indicating that magnesium is a major contributor to hardness in the landfill leachate system. TSS exhibited significant positive correlations with TH ( $r = 0.513$ ,  $p < 0.01$ ), Mg ( $r = 0.438$ ,  $p < 0.01$ ), COD ( $r = 0.547$ ,  $p < 0.01$ ), and BOD ( $r = 0.596$ ,  $p < 0.01$ ), suggesting that suspended particulate matter is closely associated with both inorganic mineral content and organic pollutant load. Calcium showed significant positive correlations with pH ( $r = 0.533$ ,  $p < 0.01$ ) and EC ( $r = 0.369$ ,  $p < 0.05$ ), reflecting mineral dissolution and ionic enrichment processes within the landfill system. Similarly, chloride exhibited strong positive correlations with pH ( $r = 0.553$ ,  $p < 0.01$ ) and Ca ( $r = 0.598$ ,  $p < 0.01$ ), indicating co-mobilization of soluble inorganic ions during leachate migration. COD and BOD demonstrated a very strong positive correlation ( $r = 0.876$ ,  $p < 0.01$ ), confirming their close association with biodegradable organic matter and landfill stabilization processes. Colour also showed a significant positive correlation with COD ( $r = 0.467$ ,  $p < 0.01$ ), indicating that darker leachate is associated with elevated concentrations of dissolved organic compounds such as humic and fulvic substances. In contrast, colour exhibited significant negative correlations with pH ( $r = -0.522$ ,  $p < 0.01$ ), Ca ( $r = -0.371$ ,  $p < 0.05$ ), and Cl ( $r = -0.358$ ,  $p < 0.05$ ), suggesting that highly coloured leachate is generally associated with acidic and less mineralized conditions. Overall, the correlation analysis identified two major interacting groups within the leachate system in that inorganic mineralization indicators represented by EC, TDS, TH, Mg, Ca, and Cl, and organic pollution indicators represented by COD, BOD, colour, and TSS.

### 3.5 Factor Analysis of Leachate Quality Using PCA

Principal Component Analysis (PCA) was performed to identify the dominant factors governing the variability of landfill leachate characteristics and to reduce the dimensionality of the dataset. The first three principal components (PC1, PC2, and PC3) collectively explained approximately 76.73% of the total variance, indicating that these components adequately represent the major physicochemical processes influencing leachate evolution, as presented in Table 8. PC1 is mainly associated with organic stabilization and mineralization, showing strong influence from parameters such as pH, Ca, Cl, COD, BOD, and colour, reflecting the transition of leachate from organic-rich to more stabilized conditions. PC2 represents the hardness and particulate pollution factor, dominated by total hardness, magnesium, BOD, and TSS, indicating mineral dissolution and particulate transport within the leachate. PC3 corresponds to the salinity and ionic strength factor, primarily influenced by TDS and electrical conductivity, which reflect the presence of dissolved salts and ionic contaminants. The scree plot analysis further confirms that the first

three components possess eigenvalues greater than unity and capture the most significant variance in the dataset, while subsequent components contribute minimal additional information. These results demonstrate that PCA effectively identifies the key processes controlling leachate evolution, including organic degradation, mineral dissolution, and ionic enrichment within the landfill system.

Table-8: Rotated Component Matrix of PCA

Components	Eigenvalue	% of Variance	Cumulative %
pH	3.53	32.133	32.133
TSS	3.02	27.427	59.560
EC	1.89	17.169	76.729
TDS	0.96	8.700	85.428
TH	0.65	5.864	91.292
Mg	0.39	3.570	94.863
Ca	0.28	2.550	97.412
Cl	0.22	1.961	99.373
COD	0.07	.590	99.963
BOD	0.00	.027	99.990
COLOUR	0.00	.010	100.000

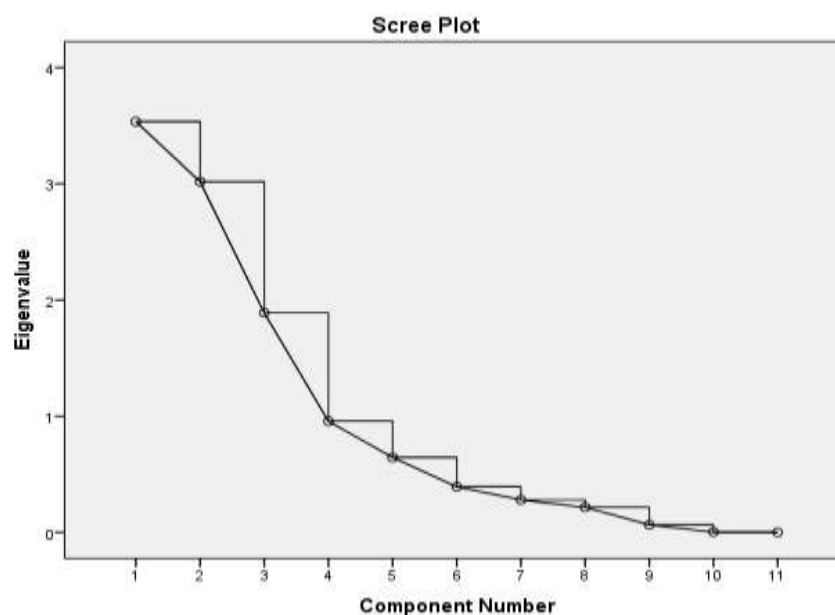


Figure-8: Scree plot for PCA results with 11 leachate parameters

### 3.6 Interpretation of Principal Components

The rotated loading matrix is now presented separately to facilitate identification of the variables contributing to each component represented in the table 9. PC1 accounted for 32.13% of the total variance and was strongly associated with total hardness (0.933), magnesium (0.854), TSS (0.748), and BOD (0.748), along with a moderate contribution from COD (0.569). This component primarily represents the mineralisation and particulate organic pollution factor, indicating the combined influence of dissolved mineral constituents, suspended solids, and biodegradable organic matter within the landfill leachate. The high loadings of hardness and magnesium suggest significant mineral dissolution processes, while the association with TSS, COD, and BOD reflects simultaneous transport of particulate and organic contaminants.

Table 9: Rotated Component Matrix of Physicochemical Parameters for Landfill Leachate

Components	PC1	PC2	PC3
pH	.191	.788	.260
TSS	.748	.022	.186
EC	.011	.261	.920
TDS	.052	.179	.956
TH	.933	.052	-.095
Mg	.854	.307	-.180
Ca	.172	.782	.181
Cl	.040	.737	.104
COD	.569	-.575	.469
BOD	.748	-.321	.430
COLOUR	.230	-.715	.025

PCA; Rotation Method: Varimax with Kaiser Normalization

PC2 explained 27.43% of the total variance and showed strong positive loadings for pH (0.788), calcium (0.782), and chloride (0.737), with a strong negative loading for colour (-0.715). This component represents the organic stabilization and ionic interaction factor, reflecting the transition of leachate from acidic, highly coloured organic-rich conditions toward more stabilized and mineralized phases. The positive association of pH, calcium, and chloride indicates enhanced ionic enrichment and buffering behaviour, whereas the negative loading of colour suggests progressive degradation of humic and fulvic organic compounds during landfill stabilization.

PC3 contributed 17.17% of the total variance and was dominated by electrical conductivity (0.920) and TDS (0.956), with moderate contributions from COD (0.469) and BOD (0.430). This component corresponds to the salinity and ionic strength factor, representing the accumulation and mobility of dissolved ionic species within the leachate system. The strong relationship between EC and TDS confirms that conductivity is primarily controlled by dissolved salts and mineral ions present in the landfill leachate. The scree plot (Fig. 8) further confirms that the first three principal components possess eigenvalues greater than unity and contribute the most significant variance within the dataset. A sharp decline in eigenvalues was observed after PC3, followed by gradual stabilization of the curve,

indicating that the remaining components contribute only minor additional information. Therefore, the first three components were considered sufficient to explain the dominant physicochemical and biodegradation processes controlling landfill leachate evolution.

Table 10 : KMO And Bartlett's Test

<b>KMO and Bartlett's Test</b>		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.456
	Approx. Chi-Square	473.640
Bartlett's Test of Sphericity	df	55
	Sig.	.000

Although the KMO value (0.456) in the table 10 indicates moderate sampling adequacy, the application of PCA in the present study remains statistically and environmentally justifiable. Environmental leachate datasets commonly exhibit high variability due to the complex interactions among geochemical, biological, and hydrological processes occurring within landfill systems. In addition, lysimeter-based studies generally involve small sample sizes due to the time-dependent nature of long-term experimental monitoring. Therefore, PCA in the present work was primarily applied as an exploratory multivariate tool to identify the dominant processes governing leachate evolution rather than for strict predictive modelling. The highly significant Bartlett's Test of Sphericity ( $p < 0.001$ ) confirmed sufficient intercorrelations among the variables, supporting the suitability of the dataset for component extraction. Furthermore, the rotated component matrix produced meaningful and environmentally interpretable factor loadings associated with mineralisation, organic degradation, and ionic enrichment processes, demonstrating the reliability and practical significance of the PCA results.

### 3.7 Scree Plot Interpretation of PCA

Principal Component Analysis (PCA) was performed to identify the dominant factors controlling the variability of leachate quality parameters and to reduce the dimensionality of the dataset. The scree plot (Fig. 8) illustrates the relationship between eigenvalues and the corresponding principal components and helps determine the number of significant components to retain. A sharp decline in eigenvalues is observed from the first to the third principal component, followed by a gradual leveling off. The eigenvalues for PC1, PC2, and PC3 were approximately 3.535, 3.017, and 1.889, respectively, all exceeding unity and satisfying the Kaiser criterion for significant component retention. Together, these three components explained approximately 76.73% of the total variance in the leachate dataset, indicating that they adequately represent the major physicochemical and environmental processes governing landfill leachate evolution. The dominance of PC1, characterized by the highest eigenvalue, suggests that a major factor strongly controls leachate composition, typically associated with overall pollution load and organic strength, represented by parameters such as COD, BOD, TDS, electrical conductivity, and major ions (Ahmed et al., 2021). PC2 represents secondary processes such as mineral dissolution, ion exchange, and buffering interactions, which influence leachate chemistry independently of the organic pollution load. PC3, although contributing a smaller proportion of variance, reflects site-specific or environmental factors such as microbial activity, redox conditions,

and rainfall infiltration (Li et al., 2021). Eigenvalues beyond the third component remain below unity, indicating minimal contribution to data interpretation. Therefore, retaining three principal components adequately explains the variability in leachate quality parameters and supports the effectiveness of PCA as a tool for leachate characterization and landfill management (Zhang et al., 2024).

### 3.8 Hierarchical Cluster Analysis (HCA)

Hierarchical Cluster Analysis (HCA) was carried out to examine similarity patterns among the leachate samples and to support the findings obtained from Principal Component Analysis. The analysis was performed using Ward's linkage method with squared Euclidean distance, which is widely used for environmental datasets because it minimises within-cluster variance (Nkansah et al., 2010). The resulting dendrogram (Fig. 9) indicates that the leachate samples can be broadly classified into three major clusters at a rescaled distance of approximately 15–18, reflecting considerable heterogeneity in leachate composition due to variations in geochemical interactions, organic degradation stages, and hydrological influences within the landfill system (Panda et al., 2021). Cluster I consists of samples grouped at lower rescaled distances, indicating high similarity among the leachate characteristics. This cluster represents highly mineralised leachate dominated by dissolved ions, hardness, and elevated electrical conductivity resulting from mineral dissolution and prolonged soil–waste interaction processes (Shrestha et al., 2007; Naveen et al., 2022). The close linkage among samples within this cluster suggests relatively stable inorganic chemical behaviour and strong ionic enrichment.

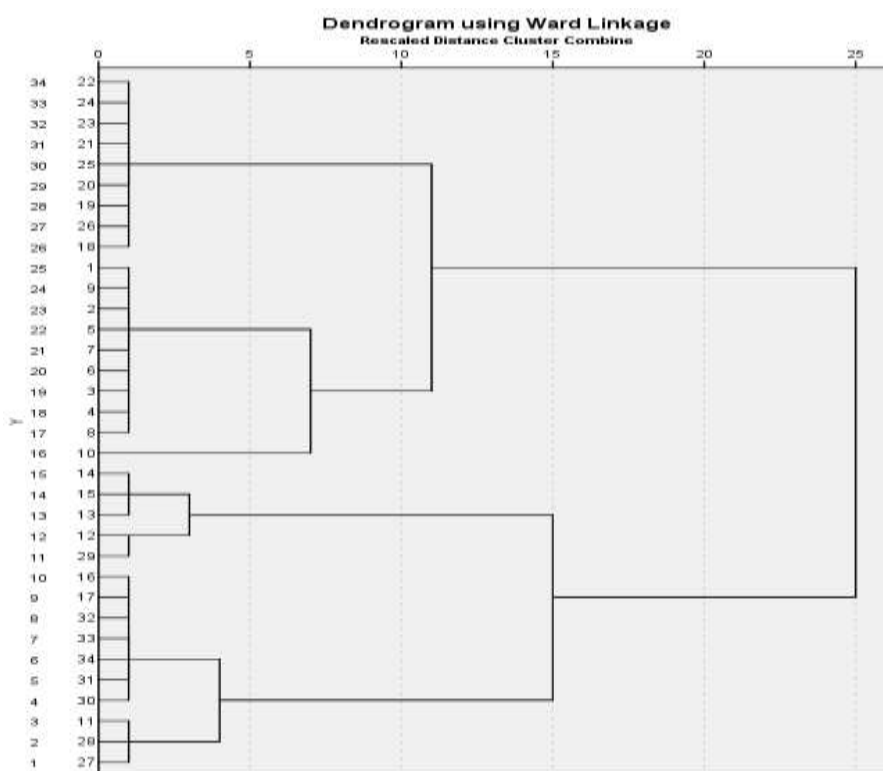


Figure-9: Dendrograms showing the clustering of standardized 11 leachate parameters

Cluster II forms a distinct subgroup separated from Cluster I at moderately rescaled distances. This cluster is primarily associated with organic-rich leachate influenced by biological degradation and landfill stabilisation processes. Samples within this group are characterised by stronger associations with COD, BOD, and colour, reflecting active decomposition of biodegradable organic matter and the presence of humic substances generated during anaerobic waste degradation (Singh et al., 2023; Zhang et al., 2024). The separation of this cluster from the mineralized group highlights the independent contribution of biodegradation processes in controlling leachate chemistry. Cluster III is distinctly separated from the other two clusters at higher rescaled distances, indicating substantial compositional variation. This cluster likely represents diluted or physically influenced leachate affected by rainfall infiltration, surface runoff interaction, or operational disturbances within the landfill system (Kenna et al., 2003). The larger linkage distance suggests comparatively lower dissolved concentrations and greater variability in suspended solids, indicating the influence of short-term hydrological and environmental conditions rather than long-term geochemical stabilisation processes. Similar clustering behaviour has been reported in previous landfill leachate studies conducted under variable climatic and operational conditions (Singh et al., 2023; Zhang et al., 2024).

### 3.9 Integrated HCA Interpretation with PCA Results

The clustering pattern observed in the Dendrogram is in strong agreement with the PCA results. Samples grouped under Cluster I correspond to the inorganic mineralisation and ionic strength factor (PC1), while Cluster II aligns with the organic pollution and biodegradation factor (PC2). Cluster III reflects the influence of suspended solids dynamics and phase interactions (PC3) (Jolliffe et.al (2002)). This consistency between HCA and PCA confirms the robustness of the multivariate analysis and strengthens the interpretation of the dominant processes governing leachate quality. Overall, the Dendrogram demonstrates that the composition of landfill leachate is controlled by a combination of geochemical mineralisation, biological degradation, and physical transport mechanisms. The application of HCA provides a clear classification of leachate samples and supports its usefulness as a diagnostic tool for understanding leachate evolution and guiding landfill monitoring and management strategies.

### 3.10 Quantitative Validation Metrics

The validation results in fig 10 indicate that both lysimeter systems successfully reproduced the general physicochemical characteristics of landfill leachate while demonstrating contaminant attenuation through soil–leachate interactions. The SCBA-amended clay loam system (Lysimeter 2) exhibited substantial reductions in several key contamination indicators compared with the loam soil system (Lysimeter 1). The highest attenuation improvements were observed for TDS (49.03%), EC (42.99%), BOD (30.12%), and COD (19.76%), indicating enhanced retention of dissolved salts and organic pollutants within the SCBA-amended soil matrix which was represented in the table 11. Moderate improvements were also observed for total hardness (10.54%), Mg (11.27%), and Ca (6.22%), suggesting improved ion retention and adsorption processes resulting from the increased surface area and reactive silica content provided by SCBA.

Table 11: Validation of Lysimeter Performance Against Field Leachate Characteristics and Improvement Achieved by SCBA-Amended Soil

Parameter	Field	Mean Lysimeter 1	Deviation (%)	Mean Lysimeter 2	Deviation (%)	Improvement of SCBA (%)
pH	5.6	7.45	33.09	7.18	28.3	3.6
TSS (mg/L)	1800	848.76	52.85	814.35	54.76	4.05
EC (mS/cm)	5.6	7.1	26.7	4.04	27.77	42.99
TDS (mg/L)	3072	5137.41	67.23	2618.53	14.76	49.03
Total Hardness (mg/L)	11650	3886.59	66.64	3477.06	70.15	10.54
Mg (mg/L)	1200	774.29	35.48	687	42.75	11.27
Ca (mg/L)	5000	1092.18	78.16	1024.24	79.52	6.22
Chloride (mg/L)	4397	681.18	84.51	889.41	79.77	-30.57
COD (mg/L)	13600	11931.29	12.27	9574.24	29.6	19.76
BOD (mg/L)	3428.57	3663.53	6.85	2559.94	25.34	30.12
Colour (Pt-Co)	9600	2870.88	70.09	5158.94	46.26	-79.70

In contrast, chloride did not exhibit significant attenuation and showed a higher mean concentration in Lysimeter 2 compared with Lysimeter 1. This observation is consistent with previous studies, which report that chloride behaves as a highly mobile conservative tracer in landfill leachate and is generally not retained effectively by adsorption or ion-exchange mechanisms within soil media (Christensen et al., 2001; Kjeldsen et al., 2002). Therefore, the higher chloride concentration observed in the SCBA-amended system should not be interpreted as a limitation of the amendment but rather as a reflection of the inherent mobility of chloride ions in porous media.

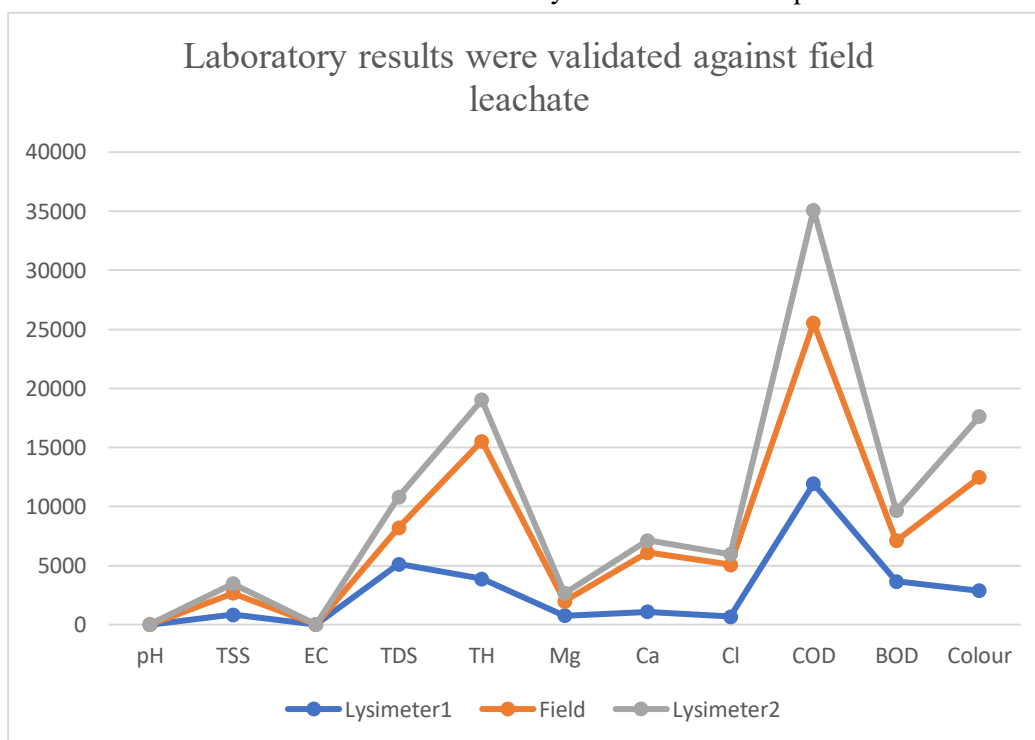


Fig 10: Comparison of mean physicochemical characteristics of field landfill leachate, Lysimeter 1 (loam soil), and Lysimeter 2 (SCBA-amended soil)

Similarly, the higher average colour values observed in Lysimeter 2 may be attributed to the release and transport of dissolved humic substances and coloured organic fractions during the early stages of leachate percolation. Previous investigations have reported that colour removal in natural adsorbent systems is often less predictable than COD and BOD removal because colour-causing compounds consist of complex high-molecular-weight organic molecules with

varying adsorption behaviour (Renou et al., 2008; Naveen et al., 2017). Despite the higher overall mean colour value, the later monitoring periods showed a progressive decline in colour concentration, indicating continued stabilization and transformation of dissolved organic matter within the SCBA-amended soil system.

Overall, the results demonstrate that SCBA amendment significantly enhanced the attenuation of dissolved solids and organic pollutants while having limited influence on chloride mobility, which is consistent with findings reported in previous landfill leachate treatment studies. These observations confirm that the primary benefit of SCBA lies in improving adsorption, filtration, and organic contaminant retention rather than the removal of conservative inorganic ions.

#### 4. Conclusion

The present study evaluated the influence of soil type and the incorporation of a low-cost adsorbent on landfill leachate behaviour using controlled lysimeter experiments conducted over a 17-week monitoring period. Geotechnical characterization confirmed that the addition of Sugarcane Bagasse Ash (SCBA) improved the soil properties by increasing the clay fraction from 23% to 37% and the plasticity index from 9% to 22%, while reducing the differential free swell from 30% to 20%. These changes enhanced the structural stability and adsorption potential of the clay loam soil system. Physicochemical analysis indicated that both lysimeters produced highly contaminated leachate typical of municipal solid waste landfills, with COD values reaching up to 16,000 mg/L and TDS up to 9,650 mg/L. However, the results showed progressive stabilization of leachate quality over time. A COD reduction of approximately 46% was observed in the loam soil lysimeter, whereas the clay loam–SCBA system achieved about 52% reduction in BOD, indicating improved biodegradation and adsorption processes. Lower values of EC, TDS, and TSS in the clay loam lysimeter further confirm its stronger filtration capacity and ion retention ability compared to the loam soil system. The pH in both lysimeters remained within near-neutral to slightly alkaline conditions, with loam soil showing relatively stable buffering and clay loam exhibiting slight acidification during later stages due to organic acid formation.

Correlation analysis revealed strong relationships among several parameters, particularly EC–TDS ( $r = 0.986$ ), TH–Mg ( $r = 0.955$ ), and COD–BOD ( $r = 0.876$ ), indicating coupled mineralization and biodegradation mechanisms in the leachate. PCA identified three significant components explaining the majority of dataset variance, representing mineralization processes, organic degradation, and suspended solid dynamics. HCA further classified the leachate samples into three groups corresponding to mineralized, organic-rich, and diluted phases, which supports the interpretation obtained from PCA.

Overall, the comparative evaluation demonstrates that clay loam soil amended with SCBA exhibits superior contaminant attenuation capacity due to increased clay content, enhanced adsorption surface area, and improved cation exchange behaviour. The results indicate that SCBA-amended clay loam soil exhibits promising contaminant attenuation characteristics and may have potential as a sustainable landfill barrier material. However, comprehensive evaluation of hydraulic conductivity, mechanical stability, long-term durability, and field-scale performance is required before its suitability as a landfill liner or cover material can be conclusively established. Although the clay loam–SCBA system exhibited lower contaminant concentrations and improved attenuation trends compared with the loam soil system, these observations are based on single-lysimeter comparisons and should be interpreted as

indicative trends. Future studies incorporating replicated lysimeter experiments are recommended to statistically validate the observed behaviour. In addition, heavy metal characterization of both the landfill leachate and SCBA was beyond the scope of the present investigation; therefore, conclusions regarding contaminant attenuation are limited to the measured physicochemical indicators. The integration of lysimeter experimentation and multivariate statistical analysis provides a reliable framework for understanding landfill leachate evolution and for designing sustainable waste containment systems. Future research should focus on long-term field validation and the evaluation of heavy metal removal efficiency to further optimize the application of SCBA based adsorbent materials in landfill engineering.

**Author Contributions:** The student was responsible for conceptualization, methodology, field and laboratory investigations, data curation, formal analysis, and preparation of the original draft. The supervisor contributed to conceptualization, methodological refinement, interpretation of results, critical review and editing of the manuscript, and overall supervision

**Funding:** “This research received no external funding”

**Conflicts of Interest:** “The authors declare no conflicts of interest.”

#### **Acknowledgements**

The authors express their sincere gratitude to the **Department of Environmental Engineering, University of BDT college**, for providing laboratory facilities and technical support throughout the study. The authors also thank the **Davanagere City Corporation** and the **Karnataka State Pollution Control Board (KSPCB), Davanagere**, for supplying waste composition data and relevant field information used in this research.

The authors extend their appreciation to **Dr. Rashma Shetty** for her continuous guidance, supervision, and constructive suggestions that greatly improved the quality of this work.

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