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Chetan G. More and Pralhad P. Walvekar

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An Evidence-Based Experimental Methodology for Directional Hydraulic Conductivity Measurement of Aged Municipal Solid Waste

Chetan G. More[1] and Pralhad P. Walvekar[2]

[1]Research Scholar, Department of Civil Engineering, Anantrao Pawar College of Engineering and Research, Parvati, Pune, Savitribai Phule Pune University, Maharashtra, India

[1]chetan.more145@gmail.com

[2]Associate Professor, Zeal College of Engineering and Research, Pune, Maharashtra, India;

[2]pralhad.walvekar@zealeducation.com

Corresponding author: Chetan G. More; chetan.more145@gmail.com

ORCID IDs: [1]0009-0003-0248-6024 and [2]0009-0002-4539-5555

Abstract

Understanding hydraulic conductivity (K) in municipal solid waste (MSW) is critical for landfill bioreactors and waste-to-energy systems that employ leachate recirculation, as it influences leachate transport, moisture distribution, and biodegradation. This study presents one of the few investigations of directional K in aged Indian MSW using a purpose-designed dual-direction testing system. Surpassing conventional permeameters, which measure directional flow using separate specimens or require sample transfer that alters the internal waste fabric, the proposed apparatus enables sequential measurement of vertical hydraulic conductivity (Kv) and horizontal hydraulic conductivity (Kh) on the same large-scale specimen without rehandling or fabric disturbance, thereby eliminating inter-specimen variability. Twelve MSW samples representing aged waste (2–6 years), collected from depths of 6–9 meters at Phursungi landfill (Pune, India), were combined to prepare a single large-scale composite specimen reflecting average bulk field composition for apparatus evaluation. The specimen was tested in a dual-direction apparatus without rehandling or transferring it during sequential Kv and Kh measurements. A dual-direction laboratory setup was used to measure Kv and Kh under saturated conditions for 1.5 months. For low-density MSW (<900 kg/m³), characterized by predominance of flat, two-dimensional particles, the constant-head method provided stable and reliable measurements under medium-flow conditions. The Kh reached 1.779×10^{-7} m/s, whereas Kv remained consistently lower, yielding an average anisotropy ratio (Kh/Kv) of 1.78. These findings improve the understanding of anisotropic flow behavior in aged MSW and support the hydraulic design and optimization of leachate recirculation systems for sustainable waste-to-energy applications.

Keywords

Municipal Solid Waste, Hydraulic Conductivity, Anisotropy, Constant Head Method, Waste Characterization.

1. INTRODUCTION

India, holding the title of the world's most populous country, at 17.5% of the global population (Chand Malav et al. 2020), generates a staggering 160,038.9 tonnes of solid waste daily (Mondal and Mandal 2024). Continued urbanization is expected to increase global MSW generation to nearly 3.40 billion tonnes annually by 2050, intensifying the need for scientifically designed landfill management, biomining, and waste-to-energy systems (Dutta and Jinsart 2020).

Reliable prediction of leachate migration is fundamental to the performance of these systems, making K one of the key engineering parameters governing moisture redistribution, biodegradation, gas generation, and overall landfill stability (Singh and Sharma 2016). Laboratory determination of K is commonly performed using either constant-head or falling-head permeameter methods; however, the suitability of each method depends strongly on the physical characteristics, density, degradation state, and composition of MSW (Patil 2022; Meena et al. 2023).

Although considerable research has been devoted to the hydraulic behaviour of MSW, methodological gaps remain unaddressed. Existing studies primarily focus on K measurements without establishing a systematic relationship between representative landfill sampling, waste characterization, laboratory method selection, and directional K assessment (Zhang et al. 2018; Cheela et al. 2021; Karimi et al. 2024). In addition, Kv and Kh are measured using separate setups, either as distinct specimens or by transferring the specimen (Ke et al. 2022a). This will introduce uncertainty due to specimen heterogeneity and limit reliable evaluation of anisotropic flow behaviour in aged landfill waste. Consequently, an evidence-based methodology that integrates representative sampling, physical characterization, laboratory method selection, and directional K measurement within a single experimental investigation remains unavailable.

Accordingly, this study develops an evidence-based experimental methodology to evaluate the directional K of aged MSW collected from Phursungi dumping yard, Pune, India. The specific objectives of the study are to:

(i) Establish a representative sampling and specimen preparation procedure for landfill MSW;

(ii) Establish characterization-based criteria for selecting an appropriate laboratory K measurement method for aged municipal solid waste;

(iii) Develop and validate a purpose-designed dual-direction laboratory apparatus capable of measuring both Kv and Kh on the same composite specimen without specimen transfer; and

(iv) Investigate the temporal evolution of directional K and flow anisotropy in aged MSW during progressive saturation under laboratory conditions.

The study is organized to progressively establish the experimental methodology before evaluating directional K. Section 2 describes the representative sampling procedure, physical characterization, laboratory setup, and hydraulic testing methodology. Section 3 presents the experimental observations, followed by an interpretation of directional K and anisotropic flow behaviour. Finally, the principal findings and study limitations are summarized.

2. BACKGROUND RESEARCH

2.1 MSW Sampling and Subsampling

Accurate laboratory determination of K begins with the retrieval of representative waste specimens, because the measured hydraulic response depends on the physical characteristics of the sampled material. The heterogeneous composition of MSW introduces substantial spatial and temporal variability, making representative sampling the first prerequisite for obtaining reliable physical and hydraulic properties. The sample collection approach can be broadly classified into primary (source-level) and secondary (composite) approaches. Three primary sampling approaches have been documented in the literature based on the source point. Household, commercial, and industrial sampling collections are shown in Fig. 1. Although primary sampling accurately characterizes waste generation at the source, it predominantly represents fresh waste. This approach is suitable for analyzing waste generation by source and its variation with respect to regional, economic, or socioeconomic factors in composition. It therefore cannot reproduce the degradation state, compaction history, and particle interactions characteristic of aged landfill waste required for K investigations (Rana et al. 2018; Zhang et al. 2018; Cheela et al. 2021)

In addition to the primary sample collection approach, the literature identifies three distinct secondary sampling approaches, as illustrated in Fig. 1. Vehicle-based sampling involves composite grab collection from waste loads at the discharge point. While specific protocols vary, a common standard involves retrieving 5–10% of the volume from randomly selected vehicles over seven consecutive days to account for daily fluctuations (Sarnobat et al. 2019; Singhal et al. 2022). This methodology is widely implemented across Indian urban centers for baseline characterization, aligning with the MSW Management Manual (2016) and IS 18231 guidelines. However, several researchers have argued that a more robust longitudinal assessment requires extending the collection period beyond a single week to capture broader operational trends (Haile et al. 2020). Although vehicle-based composite sampling is widely adopted for municipal waste characterization, its primary objective is estimation of incoming waste composition rather than reproducing the hydraulic characteristics of landfill deposits.

A parallel secondary approach involves sampling at transfer stations, where refuse from residential, commercial, and agricultural streams is aggregated. Here, thorough mixing yields a more homogenized distribution of the grab sample (Verma and Tripathi 2016). Pivotal studies by Zoroufchi Benis et al. 2019) indicate that physicochemical properties and composition can shift from minimal to substantial, depending on the climatic cycle. For instance, (Denafas et al. 2014) documented up to an 8% variance in composition between winter and summer across various economic strata. Both vehicle and transfer station methodologies primarily capture the "incoming" waste stream rather than the stabilized waste within a landfill environment.

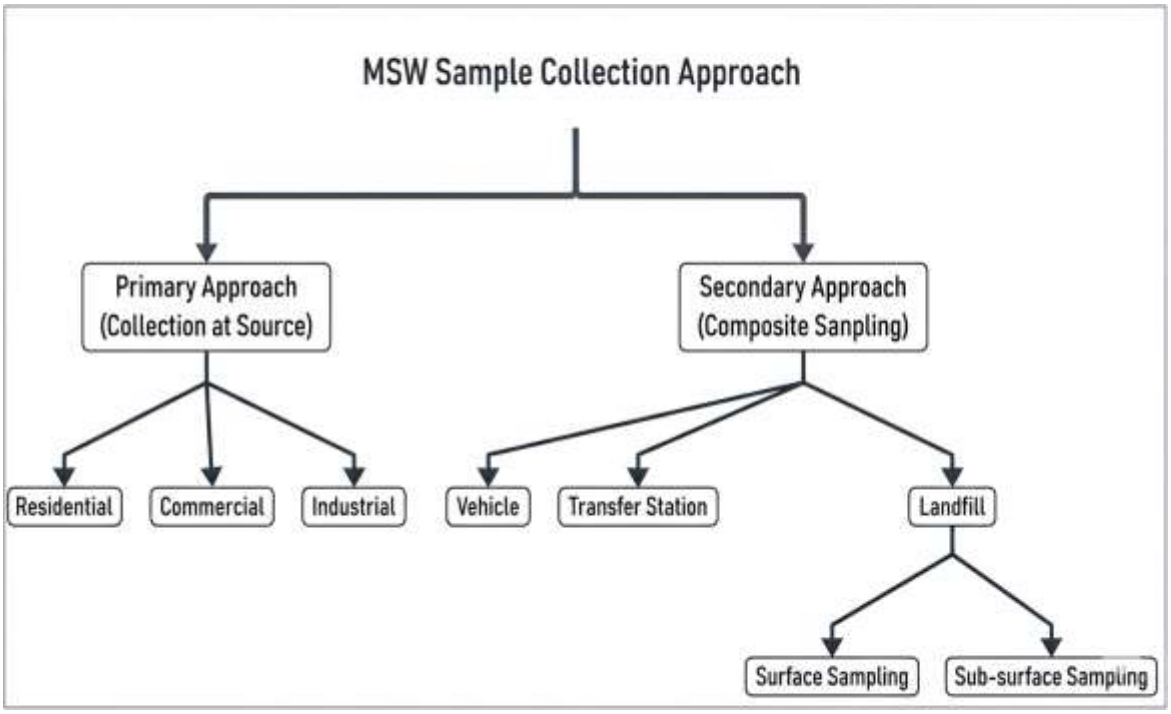


Fig. 1: Methodological workflow for field data collection and sample acquisition of MSW.

Direct sampling from dumping yards or sanitary landfills remains the most practical method for retrieving in-situ waste samples. This approach allows for stratified collection at both the surface and subsurface (Aguilar-Virgen et al. 2013; Abylkhani et al. 2019; Ibikunle et al. 2020), providing access to materials with different degradation ages and overburden pressure histories. Instead of repeated weekly collections, characterization at such depths is generally based on one-time, depth-specific excavation or boring to examine older waste strata (Kumar et al. 2016)**.** Consequently, landfill sampling provides the most representative material for K investigations because it preserves the degradation state, overburden history, and structural characteristics governing fluid flow through MSW.

After acquiring bulk specimens, a sub-sampling approach is essential to translate large-scale waste volumes into manageable laboratory samples without compromising representativeness. The literature identifies the Coning and Quartering technique as the primary method for this reduction (Zoroufchi Benis et al. 2019). This process involves systematically homogenizing the bulk material, often starting with approximately 100 kg and reducing it to a 50 kg subset to enable more detailed physical characterization (Jani et al. 2016). Variations of this technique have been documented across different research contexts. For instance, some protocols employ a simplified "quartile method," which parallels the quartering technique but omits the initial coning step (Azam et al. 2020). Other experimental approaches involve more intensive mechanical preparation, such as shredding waste into a "cake" structure to assess its composition.

Table 1: Literature-derived K ranges for MSW under constant-head and falling-head test configurations.

Reference	Waste state	Particle size (mm)	Dry density (kg/m3)	Moisture content (%)	Reported K (m/s)	Preferred laboratory method
(Azam et al. 2020)	Fresh shredded sample	Shredded to < 1/8 of the permeability cylinder size	~300	132.2	4.7 x 10-6 to 1.2 x 10-4	Constant head
(Patil et al. 2022)	Fresh shredded sample	16	Not reported	Not reported	9.85 x 10-5 to 1.1 x 10-4	Constant head
(Gyabaah et al. 2023)	Fresh shredded sample	91–96% particles < 4.80	1035–1051	45	2.55×10-5 to 0.96×10-4	Falling head
(Tanaji Mali et al. 2011)	Fresh shredded sample	100 mm: 53%; 50 mm: 16%; 20 mm: 11%	420	70	10-8 to 10-4	Constant head
(Tanaji Mali et al. 2011)	Fresh and aged sample	Not reported	Not reported	22–81	1.45 x 10-5 to 9.7 x 10-4	Constant head
(Hussain et al. 2021)	Fresh and degraded shredded sample	Maximum size = 25	Not reported	40–55	10-1	Constant head
(Al-Isawi et al. 2021)	Shredded sample	<20	244–601	20.4–79.1	4.9 x 10-5 to 1.6 x 10-3	Constant head

However, this remains less common due to potential alterations in the material's original physical fabric (Owusu-Nimo et al. 2019). The process is typically designed to ensure that the final 12.5 - 50 kg specimen accurately reflects the divisional and temporal variations in the waste stream (Sarnobat et al. 2019). Accordingly, representative sub-sampling not only preserves the physical integrity of the recovered landfill material but also establishes the foundation for selecting an appropriate laboratory methodology for K determination.

2.2 Laboratory Method Selection

A review of published laboratory investigations indicates that the selection of K testing methods is governed by five commonly recurring characteristics of MSW, namely dry density, expected hydraulic conductivity, waste degradation state, moisture content, and particle size. These parameters collectively control pore connectivity, flow regime, and specimen permeability, thereby influencing the suitability of constant-head or falling-head testing (More and Gawande 2015; Patil 2022; Meena et al. 2023; Alshawaf et al. 2025). Although additional factors such as waste fabric, fibrous inclusions, and testing boundary conditions may influence hydraulic behaviour, these five governing characteristics consistently emerge as the primary variables governing laboratory method selection across the reviewed studies. The methodological pattern is consistent across the reviewed studies, as summarized in Table 1, indicating that the falling-head method is better suited to aged, degraded, or relatively fine-graded waste, where flow is slower and the conductivity is lower.

Conversely, the constant-head method is more appropriate for coarse and structurally open waste, where measurable discharge can be maintained more easily. Constant-head is the more practical choice when waste retains large interconnected voids, fibrous inclusions, and sufficient hydraulic openness. Furthermore, the reviewed studies predominantly report K measurements in a single direction or on separate specimens, making direct evaluation of flow anisotropy difficult because of the inherent heterogeneity of MSW. This limitation highlights the need for laboratory methodology capable of measuring both Kv and Kh on the same representative specimen. While lower hydraulic conductivity values (< 10^{-5} m/s) generally suggest falling-head testing in standard small permeameters, constant-head testing remains practical in large-scale testing setups where greater cross-sectional areas provide stable, measurable discharge while maintaining constant hydraulic gradient conditions.

2.3 Hierarchical Priority in Method Selection

Although the five recurring characteristics provide a rational basis for laboratory method selection, they frequently occur in conflicting combinations within heterogeneous MSW, making engineering judgment necessary during test selection. For example, a sample may be aged and degraded, with a high dry density (> 900 kg/m³), favouring the falling-head method, which also contains large particles (> 50 mm), such as plastics, suggesting a porous, constant-head approach. To resolve such conflicting conditions, among the five governing parameters identified from the literature, expected K and dry density consistently exert the strongest influence on laboratory method selection because they directly determine the measurable flow regime. Consequently, when conflicting waste characteristics are present, these parameters should receive greater consideration during method selection (More and Gawande 2015; Alshawaf et al. 2025). While large particles create macro-pores, in aged and highly compacted waste, these pores are typically "clogged" or filled by the degraded organic medium and compressed fines. Accordingly, the overall hydraulic behaviour is governed by the matrix density rather than the individual coarse inclusions. Therefore, priority should be given to the falling-head method in high-density, aged scenarios to ensure that the sensitivity required for low-flow regimes is maintained without the risk of internal erosion (piping), which can occur under constant hydraulic gradients.

The literature review demonstrates that no single waste characteristic is sufficient for selecting an appropriate laboratory K test. Instead, published studies consistently indicate that dry density, expected hydraulic conductivity, waste degradation state, moisture content, and particle size collectively govern the hydraulic response of MSW. These observations provide the scientific basis for the laboratory method selection criteria summarized in Table 2. The literature-derived criteria, therefore, provide the scientific rationale for the experimental methodology presented in the subsequent section, where representative aged landfill waste is characterized before laboratory determination of directional K.

Table 2: Evidence-based criteria for selecting laboratory K test methods for MSW derived from published literature.

Parameter	Falling-Head (Priority)	Constant-Head (Priority)
Dry Density (Kg/m^3)	>900	< 900
Permeameter Scale / Flow Regime	Small cell (A < 0.05 m^2); Low flow rate	Large cell (A ≥ 0.15 m^2); Stable measurable discharge
Expected K (m/s)	In small cell (< 10^{-7}) In large cell (< 10^{-9} to 10^{-5})	In small cell (> 10^{-5}) In large cell (< 10^{-8} to 10^{-4})
Waste State	Aged / Degraded	Fresh / Unshredded
Moisture Content (%)	Preferably ≤ 50	Preferably ≥ 50
Particle Size	Fine graded / Highly Decomposed	Coarse, bulky

3. MATERIALS AND METHODS

3.1. Representative Field Sampling and Specimen Preparation

Representative field sampling forms the basis for reliable laboratory determination of K because the measured response directly reflects the physical condition and degradation state of the recovered MSW specimen. A comparative review of the available sampling options, as shown in Table 3, revealed that each method offers a trade-off between field representativeness, accessibility, safety, and resource demand. This study adopted a landfill-based sampling approach. Extracting samples from the sub-surface of a landfill provides the most accurate reflection of in-situ conditions and accounts for depth-wise stratified variation, despite the "Very High" resource and safety requirements involved.

Table 3: Comparative Evaluation of Sampling Approaches for K Measurement.

Criteria	Collection at Source	Vehicle	Transfer Station	Landfill (at Surface)	Landfill (at Subsurface)
Reflects in-situ conditions	✗	✗	✗	Partially	✓
Resource Requirements	Low	Low	Moderate	Moderate	Very High
Stratified Sampling	✗	✗	✓	✗	✓
Accessibility	Low	Moderate	Moderate	Moderate	Very High
Adequate Sample Volume	✓	✓	✓	✓	✓
Safety	Low	Moderate	Moderate	Moderate	Very High

The comparative assessment indicates that although landfill sub-surface sampling requires substantially greater resources and operational safety measures, it provides the highest degree of representativeness for K investigations because it preserves the degradation state, stress history, and in-situ waste structure.

For laboratory characterization, the collected waste requires controlled reduction to obtain representative test portions without disturbing the original heterogeneity. Several subsampling approaches have been reported in the literature. Among these, coning and quartering remain the most widely accepted approaches because they are simple, low-cost, and can proportionally reduce a mixed waste sample while maintaining representativeness across size fractions. The selected sub-sampling technique should therefore reduce specimen size while preserving both compositional diversity and the original structural characteristics governing hydraulic behaviour. In line with the Central Public Health and Environmental Engineering Organisation (CPHEEO, 2016) manual, coning and quartering were adopted in this study as they offer the most balanced combination of practicality, standardization, and reliability for MSW characterization in Indian field conditions.

Although no universally accepted criterion exists for determining the number of landfill samples, previous MSW characterization studies generally recommend 10–12 bulk samples for representative field investigations involving specimens of approximately 100 kg (Singhal et al. 2022). Based on these recommendations, twelve sampling locations were selected to capture spatial variability across the target landfill zone. Rather than testing each excavation point independently, the recovered materials were combined into a single large-scale composite specimen to represent the overall bulk composition of the 6–9 m depth stratum. While compositing provides a unified baseline rather than independent spatial replicates, it mitigates extreme localized compositional bias, providing a homogenized composite matrix suitable for evaluating the dual-direction apparatus and directional flow behavior.

Fig. 2: Field-scale loading of the MSW sample into the designed permeameter.

To interpret these field samples as laboratory-scale specimens, a systematic preparation protocol was executed to maintain their structural and compositional integrity. Upon collection, bulk waste was extracted using an excavator (Hyundai Robex 210) from each designated sampling point and transported to a single location. The excavator model was capable of measuring the weight of the material in the bucket, which ranged from 71 to 106 kg across the 12 discrete sample points. The sample was thoroughly homogenized, and the process was repeated until the target volume required for the characteristics and K testing was reached. The samples were collected in a transport bag for characterization, and the specimens were loaded directly into the designed apparatus for laboratory K measurement, as shown in Fig. 2. An immediate manual inspection was performed to identify and remove hazardous or anomalous objects that could compromise testing safety or apparatus performance. The samples collected from the composite specimen were subsequently subjected to systematic physical characterization to establish the engineering parameters governing laboratory K testing.

3.2. Physical Characterization for Laboratory Method Selection

The assessment methods were selected to align with the widely used Indian and ASTM standards, as shown in Table 4.

Table 4: Laboratory Assessment Methodologies for MSW Parameters.

Parameter	Method / Standard Reference
Bulk Density	Core-Cutter Method as per IS 2720 29-1975 (reaffirmed 2020)
Waste Composition	Manual sorting as per ASTM D5231-92(2024)

Particle Size	Sieve analysis as per IS 2720 Part 4 -1985 (Reaffirmed in 2020)
Moisture Content	IS 9235: 1979 (reaffirmed in 2009)

3.2.1 Bulk Density

Bulk density was determined in the case study field using the core-cutter method, as per IS 2720 Part 29-1975 (reaffirmed 2020). While originally developed for soils, this method is appropriate for aged landfill strata having a substantial soil-like fine matrix, providing a reproducible field baseline for sample density. At each location, a standard steel core cutter with an internal diameter of 100 mm and a height of 130 mm was driven into the surface with the help of a suitable rammer; the enclosed waste mass was extracted and weighed, and the bulk density was calculated as the ratio of the wet mass to the cutter volume, as shown in Fig. 3.

The bulk density across the 12 specimens ranged from a minimum of 562.12 kg/m³ to a maximum of 970.47 kg/m³, with a mean of 798.37 kg/m³. The upper end of this range reflects zones of greater self-compaction at depth and probable accumulation of denser inert fractions, such as soil, construction debris, and stone, consistent with the high soil/inert material fraction (39.93%) observed in the composition analysis.

The lower values, particularly 562.12 kg/m³, are indicative of zones with elevated void ratios and lower inert content, where the waste matrix underwent less consolidation. The mean bulk density of 798.37 kg/m³ exceeds the typical range of 300–700 kg/m³ reported for freshly deposited Indian open dump waste by the Central Pollution Control Board (CPCB) 2022 report. It approaches values more commonly associated with partially consolidated dump material, as samples are excavated at an intermediate depth. Bulk density alone cannot fully describe the hydraulic behaviour of MSW because flow is also influenced by waste composition and particle arrangement. Therefore, compositional characterization was subsequently performed.

Fig. 3: Arranging the multi-step field process from left to right (a to d) a) Surface area cleaned and levelled, b) Core cutter driven into the soil using a dolly and rammer, c) Core cutter excavated and removed with surrounding soil, d) Core cutter with soil sample weighed.

3.2.2 Waste Composition

Physical composition of each sub-sample was determined by manual sorting in accordance with ASTM D5231-92 (2024). Following coning and quartering to a manageable volume of approximately 50-55 kg, the material was spread on a clean, flat tarpaulin and segregated into 14 visible fractions. Each fraction was weighed separately on a field balance. The composition is reported as the average percentage of the total dry mass across all 12 samples, as shown in Fig. 4.

The composition profile varies from that of the high-organic, food-dominated stream, as mentioned in the CPCB 2022 report. Soil and inert material constituted the single largest fraction at 39.93%, and plastic sheets and rigid plastics together accounted for 14.43%, making them the second largest fraction. The organic fraction, which would have been considerably higher at the time of disposal, diminished to 9.48%, confirming that the sampled material was in an intermediate to late stage of active decomposition.

The composition profile has direct consequences for setup design. The high proportion of flat 2D particles, such as plastic film, synthetic/textile, and paper/cardboard, accounts for approximately 22% of the dry mass, creating a preferential horizontal layering structure within the waste body. Such layering is the primary physical mechanism responsible for anisotropy in MSW K; the Kh systematically exceeds Kv. This compositional evidence provides a direct justification for designing a dual-direction setup capable of measuring both Kv and Kh on the same specimen. While composition defines the constituent materials, particle size distribution governs pore connectivity and therefore provides additional information relevant to K testing.

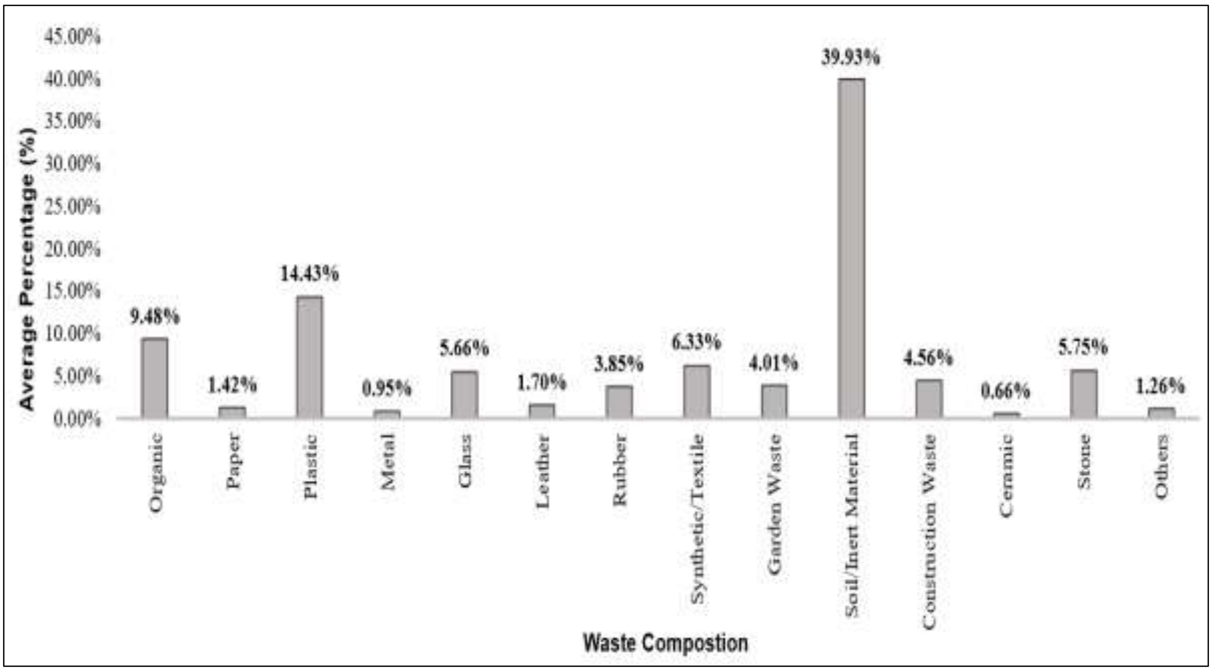


Fig. 4: Average Percentage Composition of MSW Material Categories.

3.2.3 Particle Size Distribution

The particle size distribution (PSD) was determined by sieve analysis in accordance with IS 2720 Part 4 -1985 (Reaffirmed in 2020). A representative test portion of 2 kg was oven-dried and passed through a mechanized sieve stack arranged from coarsest to finest. The percentage retained on each sieve was calculated gravimetrically. The PSD indicates predominantly coarse-grained material: 35.44% of the total waste mass was retained on the 4.75 mm sieve. The gradation is dominated by the coarser fractions, a cumulative 60.28% retained by 2.36 mm, indicating a gravelly, open-structured waste skeleton with substantial interparticle voids. Finer fractions decreased steeply beyond 1.18 mm, with only 6.93% retained at 925 µm, falling to 1.88% at the 90 µm boundary. The total material passing the 90 µm sieve, representing the true fines fraction, was estimated at less than 2% of the total dry mass, indicating that the site MSW at the sampled depth was decidedly not fine-grained in the geotechnical sense.

Two design decisions followed directly from the PSD results. First, the maximum particle size was 70 mm, which served as the primary constraint for the laboratory setup design, to avoid wall effects. In addition, the dominance of coarser fractions (> 4.75 mm) rather than ultrafine degradation products confirms that the pore structure remains relatively open, providing measurable and stable permeability. Because K is influenced not only by pore geometry but also by the initial degree of saturation, moisture content was evaluated as the final parameter governing laboratory testing conditions.

3.2.4 Moisture Content

Moisture content was determined using the oven-dry method in accordance with IS 9235:1979 (reaffirmed, 2009). A sub-portion from each coned and quartered working sample was transported and stored in zip-locked plastic bags and placed in an oven at 70 ± 2 °C for a minimum of 24 hours until a constant weight was achieved. The adopted drying temperature of 70°C, rather than the conventional geotechnical standard of 105°C, was specifically retained to prevent the thermal decomposition of volatile organic compounds (Sarnobat et al. 2019).

Moisture content exhibited considerable variability across the twelve specimens, ranging from 9.27% to 24.88%, with a computed mean of 18.52%. The anomalously low value recorded at 9.27% likely reflects a localized dry zone, as a pocket dominated by construction debris or stones, rather than a systematic trend. The relatively wide spread of values (standard deviation ≈ 4.3%) underscores the inherent spatial heterogeneity of waste at the case study site.

The mean moisture content of 18.52% is substantially lower than the 50% threshold above which the constant head method is explicitly preferred for MSW K testing. This finding has important implications. Specimens with moisture content below 40% required a controlled pre-saturation protocol before setup testing. This moisture condition also supports the characterization-based selection of the constant-head method, as the specimen is saturated in a controlled manner before hydraulic testing while maintaining stable flow conditions. To establish reproducible hydraulic testing conditions, specimens were subjected to a standardized two-stage saturation protocol. In Stage 1 (Imbibition Phase), the specimen was inundated from bottom to top for a minimum of 48 hours under a low hydraulic head ($\Delta h < 0.05$ m) to promote matrix wetting and passive displacement of entrapped pore air. In Stage 2 (Flow Equilibration Phase), water was continuously circulated through the permeameter for a minimum of 2 hours before data logging until objective hydraulic steady-state criteria were satisfied.

3.2.5 Integrated Interpretation: Physical Characterisation as a basis for Laboratory Design

Taken together, the characterization parameters point to a coherent and internally consistent portrait of MSW. The waste is moderately dense (mean 798 kg/m³), with a drier mean moisture content of 18.52%, dominated by inert and plastic fractions (54% combined), and coarse-grained with minimal fines (< 2% passing 90 µm). Each of these characteristics directly influences a specific element of laboratory testing.

Although the measured hydraulic conductivity ($K \approx 10^{-7}$ m/s) lies near the lower range traditionally associated with falling-head soil testing, the large cross-sectional area of the permeameter ($A_v = 0.27$ m^2, $A_h = 0.9$ m^2) enabled stable and easily measurable discharge under constant head. Maintaining a constant head prevented pressure-decay fluctuations that can trigger internal particle rearrangement or localized clogging in heterogeneous waste. Furthermore, comparative validation runs performed using the falling-head method on the same specimen yielded Kh = 1.67 x 10^{-7} m/s, demonstrating close agreement (6.2% relative variance) with constant-head measurements (1.78 x 10^{-7} m/s) and confirming the validity of constant-head testing for this system.

The coarse gradation and low fines content (< 2%), mean density less than 900 kg/m³, and high proportion of flat 2D particles justified the primary use of the constant head permeameter method. The mean moisture content of 18.52% established the 48-hour pre-saturation requirement. In this way, the physical characterisation programme served not merely as a descriptive exercise but as the quantitative foundation for design decisions in the laboratory setup. Collectively, these observations confirmed that the recovered landfill waste satisfied the literature-derived criteria for constant-head K testing summarized in Table 2, thereby providing the basis for the subsequent experimental investigation. The laboratory apparatus was therefore designed as a direct consequence of the physical characteristics identified during field characterization rather than as a predefined testing system, thereby ensuring consistency between waste properties and experimental methodology.

3.3. Development of the Dual-Direction K Apparatus

Based on the outcomes of the physical characterization, a purpose-designed dual-direction permeameter was developed to satisfy the specimen dimensions, particle-size constraints, and directional flow requirements identified in the preceding section. A custom-engineered, dual-direction setup was developed, as shown in Fig. 5. Unlike standard geotechnical apparatuses, this setup was specifically designed to accommodate heterogeneity and maximum particle size, adhering to the requirement that the permeameter be 600 mm (length) × 450 mm (width) × 600 mm (height) to eliminate preferential edge flow (wall effects). A 30 mm mild steel plate was used as the base structural component, with 15 mm diameter holes provided at 30 mm spacing to ensure uniform water distribution throughout the specimen. On the lateral side, a 450 mm high acrylic sheet was installed to provide clear visibility of the flow zone and specimen condition during testing. This acrylic panel was externally supported by 10 mm square bars to maintain rigidity and structural stability under saturation.

The total height of the setup was divided into two functional zones. The lower 300 mm portion (horizontal plate) was kept fully closed during Kv testing to prevent undesired side leakage and short-circuit flow, and kept open while calculating Kh. The developed permeameter was designed to overcome several limitations associated with conventional laboratory systems used for K testing of heterogeneous MSW. The principal advantage of the developed permeameter is its ability to determine both Kv and Kh within the same representative specimen while preserving the original waste fabric and particle orientation throughout testing. Compared with conventional cylindrical rigid-wall permeameters and other predominantly vertical-flow build-up permeameter arrangements, the present setup was designed to address five limitations that are particularly important for heterogeneous MSW. First, the permeameter dimensions were scaled up to test large, unshredded waste macro-components and ensure an appropriate specimen-to-particle size ratio. To maintain a conservative specimen-to-particle diameter ratio of 8 (Reddy et al. 2009; Miguel et al. 2018). For a maximum particle size of 70 mm, a minimum internal width of 560 mm was required to prevent boundary-induced artificial porosity and localized pressure drops. Consequently, the permeameter width was finalized at 600 mm to safely accommodate these large, in-situ waste materials. Second, the larger cross-section and controlled chamber geometry helped minimize wall-boundary effects, which are more pronounced in small cylindrical cells when coarse particles, flexible plastics, and elongated inclusions bridge against the wall and create artificial preferential flow paths (Miguel et al. 2018; Azam et al. 2020; Hussain et al. 2021).

Third, the setup was intended to preserve disturbance control by testing the waste in a minimally altered state rather than after shredding or extensive recompacting, which can destroy the in-situ arrangement of fibrous and planar particles. Fourth, unlike conventional systems that generally measure only vertical K, the developed permeameter is capable of measuring both Kh and Kv on the same specimen, thereby reducing inter-sample variability and improving confidence in the anisotropy ratio. Finally, the transparent side panel and directional flow-control arrangement allowed direct observation of saturation behaviour, bubble release, and possible short-circuit flow without changing the specimen fabric between test stages. In this sense, the setup is not merely a modified permeameter, but a purpose-built platform for preserving waste texture and capturing directional hydraulic behaviour under controlled laboratory conditions.

Before testing, the assembled permeameter underwent a rigorous validation protocol to ensure structural integrity and eliminate boundary leakage. To prevent preferential sidewall flow along rigid vertical boundaries, a common artifact in coarse waste testing, a 10 mm thick circumferential low-permeability bentonite-grease seal was applied to all internal acrylic-wall perimeter interfaces before specimen placement. Boundary seal integrity was verified during fluid tracer trials using a food-grade dye solution; visual observation through the transparent acrylic window confirmed uniform advancing flow fronts without perimeter short-circuiting or sidewall bypass flow.

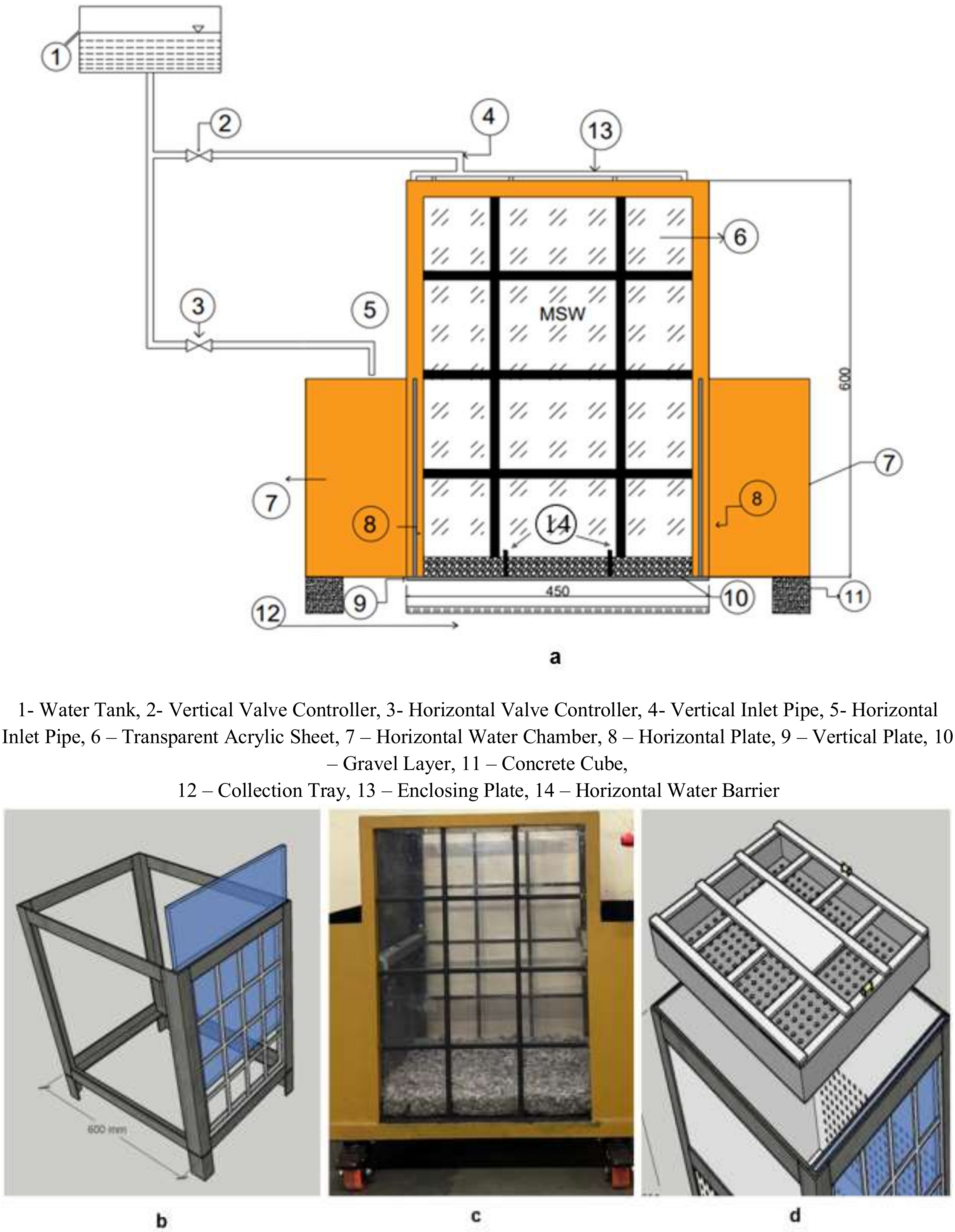
3.4 Testing Procedure

Following specimen preparation, the representative composite MSW sample was placed uniformly within the permeameter, achieving an initial dry density of 798.37 kg/m^3 and a target void ratio (e) of 1.40 (Supplementary A). To ensure reproducible testing conditions, specimens were subjected to a standardized two-stage saturation protocol. In Stage 1 (Imbibition Phase), the specimen was inundated from bottom to top for 48 hours under a low hydraulic head ($\Delta h < 0.05$ m) to hydrate the matrix and passively displace entrapped pore air. In Stage 2 (Flow Equilibration Phase), water was continuously circulated through the permeameter about 2 hours before logging. Full saturation and steady Darcian flow were objectively confirmed when three consecutive criteria were satisfied: (i) the ratio of volumetric outflow to inflow rate (Q_{out}/Q_{in}) reached 1.00 ± 0.02 across three 15-minute intervals, (ii) the Δh stabilized within ±1 mm, and (iii) discharge volume per unit time (Q/t) demonstrated strict linearity.

Testing was conducted under constant-head conditions for both flow directions under an identical hydraulic gradient of i = 0.40. For Kv, water was introduced through the top manifold, flowing across a path length Lv = 0.60 m through a cross-sectional area Av = 0.27 m^2 (0.60 m length x 0.45 m width) under an applied head difference Δh_v= 0.240 m. For Kh, flow was directed laterally along Lh = 0.60 m through an effective flow cross-sectional area Ah = 0.09 m^2 (0.60 m length x 0.15 m effective flow height) under an applied head difference Δh_h= 0.240 m. For each testing run, a standard target discharge volume of V = 400 mL was collected in the discharge vessel, and the elapsed flow time (t, in seconds) and fluid temperature (T = 24 ±1 ºC) were recorded. To evaluate hydraulic measurement repeatability, triplicate discharge readings were recorded for each flow direction under steady-state conditions; these triplicate values represent measurement repeatability on the single composite specimen rather than independent specimen-level replication.

3.5. Calculation of Hydraulic Conductivity

Hydraulic testing adapted the constant-head principles of ASTM D5084 to a large-scale rectangular testing chamber, ensuring that Kh and Kv could be determined under valid Darcian flow conditions while accommodating coarse particles up to 70 mm. Separate K values were calculated for vertical and horizontal flow directions using the corresponding flow path lengths and cross-sectional areas. The governing equations and parameter values are provided in Supplementary B.



1- Water Tank, 2- Vertical Valve Controller, 3- Horizontal Valve Controller, 4- Vertical Inlet Pipe, 5- Horizontal Inlet Pipe, 6 – Transparent Acrylic Sheet, 7 – Horizontal Water Chamber, 8 – Horizontal Plate, 9 – Vertical Plate, 10 – Gravel Layer, 11 – Concrete Cube,
12 – Collection Tray, 13 – Enclosing Plate, 14 – Horizontal Water Barrier

Fig. 5: Structural layout and components of the experimental permeameter: (a) schematic diagram of the complete assembly, (b) engineering design of the acrylic partition sheet, (c) photographic view of the fabricated acrylic sheet, and (d) details of the top enclosing steel plate.

4. RESULTS AND DISCUSSION

4.1 Characterization-based decision-support outline for laboratory K testing

The proposed decision-support outline was developed by integrating the findings of the present investigation with the evidence synthesized from the literature review. Rather than functioning as a simple flowchart for selecting constant-head or falling-head permeability tests, the outline establishes a structured methodology that links representative sampling, specimen preparation, physical characterization, and expected hydraulic behaviour to laboratory method selection. This integrated approach recognizes that K testing of MSW should be guided by the collective influence of waste characteristics rather than by any single parameter. Consequently, the decision-based outline provides a reproducible basis for selecting appropriate laboratory testing methods for heterogeneous landfill waste and may contribute towards greater methodological consistency in future investigations. Unlike conventional approaches in which laboratory test selection is often based primarily on anticipated K or try-and-test testing, the proposed outline incorporates representative sampling, physical characterization, and waste state as sequential decision criteria, thereby reducing uncertainty with method selection for heterogeneous landfill waste.

4.2 Interrelation of physical characteristics

The physical characterization results should be interpreted as an interconnected system rather than as independent material properties because the hydraulic behavior of MSW emerges from the combined influence of density, composition, degradation state, moisture condition, and particle arrangement. Accordingly, the measured physical characteristics are discussed collectively to explain the observed directional hydraulic response. The sampled MSW exhibits the characteristics of a partially degraded, moderately compacted in situ waste mass that has undergone self-weight consolidation, biodegradation, and progressive internal rearrangement over time. In such materials, density is a primary control on hydraulic response because increasing compaction typically reduces void ratio and disrupts the continuity of preferential flow paths, thereby lowering permeability (Dixon and Langer 2006; Karimi et al. 2024). Moisture content is equally important, but it should not be treated as the sole variable; in aged MSW, it is closely linked to waste composition, organic content, and the extent of decomposition, all of which influence the capacity to retain water and the structural evolution during degradation. Therefore, the physical characteristics observed in the case study samples should not be treated independently; rather, they should be interpreted as an interdependent system that governs the hydraulic behavior of the waste.

The present waste stream also contains a substantial fraction of flat, flexible, and sheet-like particles, which tend to reorient under self-weight and localized compression into sub-horizontal arrangements. This textural tendency is hydraulically important because it promotes lateral continuity of voids while simultaneously restricting through-thickness flow across layered interfaces. This behaviour provides a mechanistic explanation for the consistently higher Kh observed during the experimental programme. As a result, the physical characteristics are not only descriptive indices; together they define the internal fabric that governs anisotropic flow behaviour.

(Ahmad et al. 2023) have shown that compression can increase anisotropy by flattening pore geometry and aligning preferential flow paths, whereas degradation may reduce anisotropy by fragmenting large particles and modifying void connectivity. The present material appears to lie between these two end-member responses. Its aged and partially degraded condition suggests that some of the original large-particle structure has already been transformed; the retained plastic-rich and coarse-grained fabric still preserves sufficient directional organization to maintain a difference between horizontal and vertical flow. Therefore, the case-study waste should be understood as a hydro-bio-mechanical material system in which density, composition, degradation state, and particle arrangement act together to control hydraulic response (Sarnobat et al. 2019).

4.3 Evolution of Directional K and Flow Anisotropy

The directional hydraulic behaviour of MSW was evaluated using the custom-built dual-direction permeameter developed in this study, supporting the determination of both Kv and Kh with the same representative specimen. This experimental configuration minimizes variability arising from specimen heterogeneity and provides a more reliable basis for evaluating flow anisotropy than conventional approaches employing separate specimens for each flow direction. MSW samples from the landfill were collected and directly loaded into the designed setup using an excavator, as shown in Fig. 2**,** followed by appropriate compression to simulate field bulk density.

From an interpretative standpoint, the principal value of the setup lies in its ability to assess directional conductivity within the same continuous waste matrix. This is important because MSW is intrinsically heterogeneous, and separate specimens prepared for independent Kh and Kv measurements may differ in composition, orientation of planar particles, void distribution, and local degradation state. By reducing this inter-sample variability, the present configuration makes the observed anisotropy ratio more representative as a material response rather than an artefact of specimen preparation. Because both flow directions were evaluated on the same minimally disturbed specimen, the observed differences between Kh and Kv can be interpreted primarily as intrinsic material behaviour rather than experimental variability. Consequently, the temporal evolution of directional K provides insight into how degradation, settlement, and internal fabric collectively influence hydraulic response in aged landfill waste. This approach also reduces uncertainty associated with specimen-to-specimen variability, which is particularly important for highly heterogeneous geomaterials such as MSW (Rana et al. 2018; Ke et al. 2022a).

4.3.1 Horizontal and Vertical Hydraulic Conductivity

Both Kh and Kv increased progressively throughout the 1.5-month saturation period, indicating continuous evolution of the internal pore network during specimen stabilization. Although both flow directions exhibited increasing K, the magnitude and rate of increase differed, with Kh consistently exceeding Kv throughout the monitoring period. Both Kh and Kv were measured over eight readings spanning April to May 2026, as shown in Fig. 6. Kh followed an exponential growth model y = 7E-08e0.1081x; $R^2 = 0.685$, peaking at 1.779×10^{-7} m/s. In contrast, the Kv adhered to a linear progression y = 9E-09x + 3E-08; R2 = 0.691, reaching a maximum of 1.142×10^{-7} m/s. The moderate coefficients of determination reflect the inherent heterogeneity of MSW and the progressive nature of biological and structural changes that occur during saturation rather than purely deterministic hydraulic behaviour.

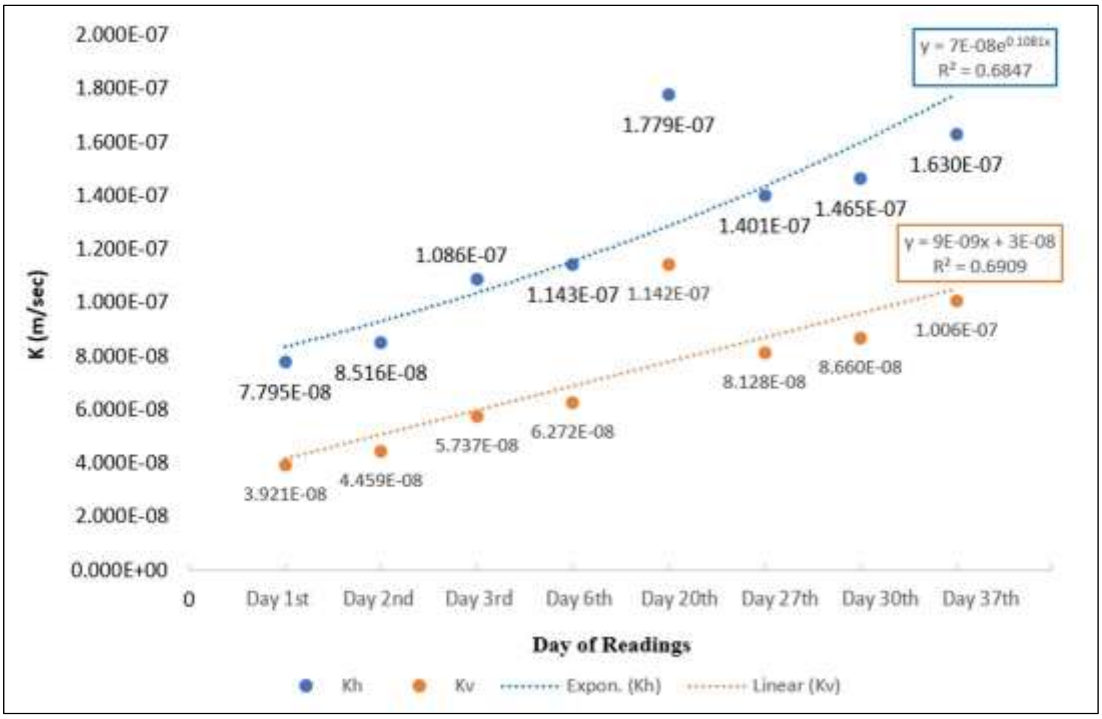


Fig. 6. Directional hydraulic conductivity profiles (Kh and Kv) measured over the monitoring timeframe.

This divergence in regression models suggests that the horizontal flow pathways are reinforced by a positive feedback mechanism: each newly formed lateral macropore is likely to have been generated by decomposition of the organic fraction, which opens additional preferential channels that accelerate further lateral pore connectivity for Kh. Vertical flow development, by contrast, is continuously restrained by the progressive horizontal reorientation of flat 2D particles (plastic film, textile, paper, which accounts for approximately 22%) under self-weight, which imposes an insistent geometric barrier to vertical throughflow and constrains Kv to a rate-limited linear progression, which is in line with the existing finding (Breitmeyer et al. 2019). Rather than attributing these temporal shifts solely to unmeasured biological decay, several plausible physical mechanisms may have operated simultaneously under saturated laboratory conditions. First, progressive dissolution and flushing of entrapped micro-air bubbles during sustained saturation can open previously occluded pore channels. Second, internal migration and localized washout of loose fine particles under continuous hydraulic flow may enlarge interstitial pore throats. Third, localized matrix settlement and structural reorientation under saturated fluid drag can alter internal pore connectivity. While organic degradation may contribute over extended timescales, the short-term increases observed here are best interpreted as a combination of progressive hydraulic saturation, fine-particle migration, and matrix restructuring.

The inclination is broadly consistent with prior MSW studies (Dixon and Jones 2005; Dixon and Langer 2006) showing that compression enhances directional contrast by flattening pore geometry and improving lateral connectivity; the degradation can progressively weaken that contrast by breaking down larger structural elements and reconfiguring the void network. In the present study, both Kh and Kv increased over time. However, the horizontal response remained stronger, indicating that degradation did not erase the inherited directional fabric of the waste. Instead, the results suggest a transitional condition in which biodegradation increased K overall, while the aged, minimally disturbed specimen still retained enough depositional structure and planar particle alignment to preserve preferential horizontal flow. The reduced rate of increase during the later stages of saturation suggests that the internal pore structure approached a relatively stable hydraulic configuration after the initial period of structural adjustment. Relative to studies on fresh or heavily reconstituted MSW, these observations indicate that directional K in aged MSW should be considered a time-dependent property rather than a constant design parameter. Incorporating this behaviour into landfill hydrological models may improve predictions of leachate recirculation efficiency, moisture redistribution, and long-term waste stabilization.

4.3.2. Temporal Evolution of Directional Flow Anisotropy

The Kh/Kv in this study remains consistently greater than 1, ranging from 1.56 to 1.99, confirming a persistent directional dependence of flow within the MSW matrix and indicating that sideways permeability exceeds vertical permeability throughout the monitoring period, which is in line with the existing study (Ke et al. 2022b). The observed decline in the anisotropy ratio, as shown in Fig. 7, suggests that the specimen gradually became less directionally contrasted as internal restructuring and settlement enhanced vertical connectivity relative to the early-stage condition. This behaviour supports the interpretation that degradation and internal settlement gradually reduced the contrast between directional flow paths, although not to the extent of reversing the dominant horizontal preference established by the original waste fabric.

Accordingly, anisotropy ratios provide a more informative descriptor of landfill hydraulic behaviour than individual conductivity values because they capture the combined influence of waste composition, degradation, settlement, and internal fabric evolution. This parameter, therefore, has considerable potential for improving the representation of preferential flow in landfill hydraulic models. Consequently, consideration of flow anisotropy alongside directional K may improve both laboratory characterization and field-scale prediction of leachate migration in aged landfill systems.

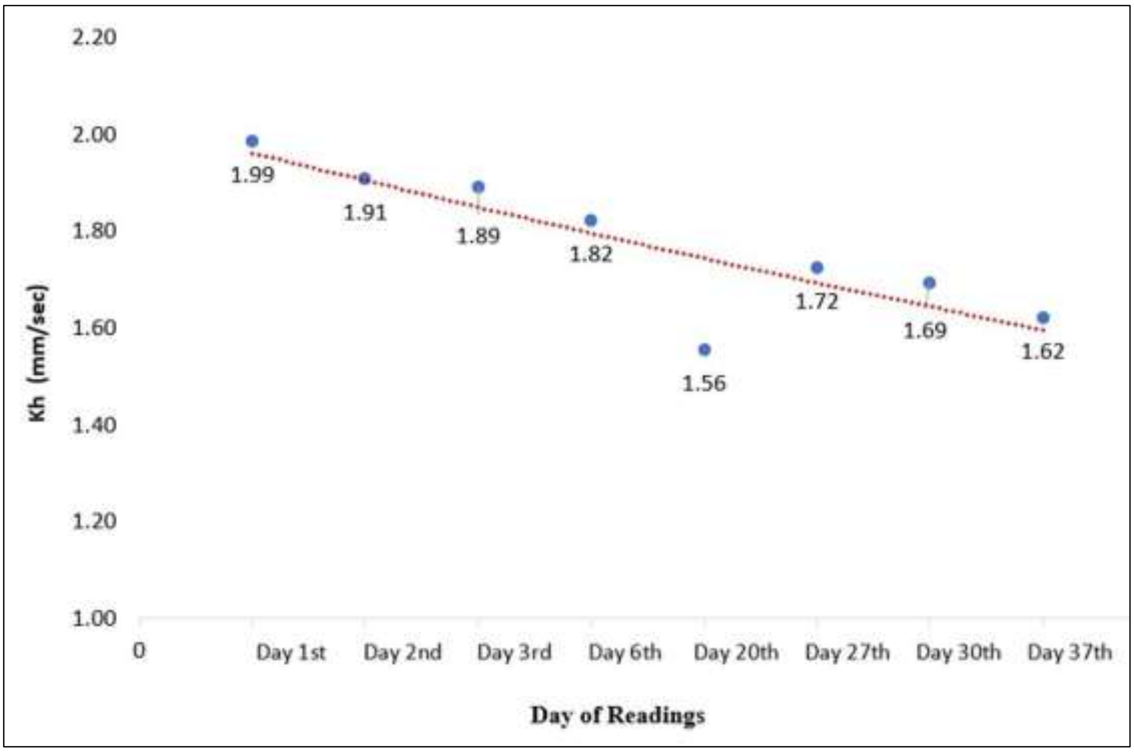


Fig. 7: Temporal evolution of Kh/Kv in MSW over Time.

The present findings should be interpreted within the scope of the experimental programme. The hydraulic behaviour was evaluated under controlled laboratory saturation without externally applied overburden stress or continuous biodegradation representative of long-term landfill conditions. Although the representative composite specimen reproduced the physical characteristics of the investigated landfill, future studies incorporating stress-controlled testing and multiple landfill sites would further strengthen the general applicability of the proposed methodology.

5. CONCLUSION AND LIMITATIONS

5.1. Conclusion

This study developed and experimentally validated an evidence-based methodology for determining the directional K of aged MSW by integrating representative landfill sampling, physical characterization, laboratory method selection, and dual-direction K measurement within a unified experimental workflow. Beyond reporting K values, the study establishes a characterization-driven approach for selecting laboratory testing methods and interpreting anisotropic flow behaviour in heterogeneous landfill waste. The following conclusions are derived from the experimental and characterization study:

1. The study establishes that bulk density, permeameter cross-sectional scale, and flow regime stability are the primary parameters governing laboratory K method selection. While high dry density (> 900 kg/m^3) or small-scale testing cells ($A < 0.05$ m^2) favour the falling-head method to measure low flow rates, large-scale testing cells ($A \geq 0.15$ m^2) with lower bulk densities (< 900 kg/m^3) favour the constant-head method. In large-scale permeameters, constant-head testing provides stable and easily measurable discharge even at conductivities near 10^{-7} m/s, maintaining a steady hydraulic gradient that avoids head-decay pressure fluctuations and reduces the potential for internal fines migration.

2. The progressive increase in both Kh and Kv, captured by linear and exponential fits, indicates that MSW K changes with structural evolution rather than remaining constant. The consistently higher Kh than Kv confirms the anisotropic evolution of preferential flow pathways, with horizontal paths forming more readily than vertical ones.

3. The developed dual-direction permeameter enabled the determination of both Kh and Kv within the same representative specimen while minimizing uncertainty associated with specimen heterogeneity. The maximum measured values of Kh (1.779×10^{-7} m/s) and Kv (1.142×10^{-7} m/s) characterize the investigated aged landfill waste under laboratory saturation conditions and provide reference data for future studies on Indian MSW.

4. The principal methodological contribution of the study lies in reducing uncertainty in directional hydraulic assessment by measuring Kh and Kv on the same minimally disturbed specimen. This feature improves interpretive reliability by limiting inter-sample variability and provides a more defensible basis for evaluating anisotropic flow in aged landfill waste than conventional single-direction testing alone.

5. The Kh/Kv remained persistently greater than unity, ranging between 1.56 and 1.99. This stability indicates that while absolute permeability fluctuates with saturation and internal particle migration, the directional flow preference is fundamentally established by the initial depositional fabric and remains maintained in the face of temporal changes.

Although the K values reported in this study are specific to the investigated landfill, the proposed characterization-based workflow is transferable to other landfill environments where waste heterogeneity and anisotropic flow influence laboratory testing. By enabling more reliable determination of directional K, the methodology provides a stronger basis for landfill hydrological modelling, optimization of leachate recirculation strategies, moisture redistribution analysis, and evaluation of waste-to-energy systems. The proposed workflow may also contribute towards greater methodological consistency in future investigations of landfill hydraulic behaviour. Overall, the proposed methodology reduces uncertainty in laboratory determination of directional K by integrating representative sampling, characterization-based method selection, and dual-direction testing within a single experimental workflow.

5.2. Limitations of the Study

The findings of this study should be interpreted within the scope of the adopted experimental programme. While the composite specimen captured the bulk physical composition of the sampled depth, a key limitation of this investigation is the reliance on a single composite specimen. The results demonstrate apparatus functionality and single-specimen hydraulic performance rather than statistically replicated specimen-level behavior. Furthermore, the measured K values represent laboratory-controlled saturation conditions without externally applied overburden stress. Consequently, the reported absolute conductivity values and anisotropy ratios should be interpreted as site-specific baseline trends and moderated when generalizing to broader, stress-dependent field conditions across different landfill sites. In addition, the 1.5-month monitoring period captures the short-term evolution of hydraulic behaviour during progressive saturation but does not account for long-term biological degradation, mineral precipitation, clogging, or seasonal environmental variations that may further modify K. Future research should therefore investigate the coupled effects of mechanical loading, long-term biodegradation, and multiple landfill sites to evaluate the broader applicability of the proposed methodology.

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SUPPLEMENTAL MATERIAL

Supplementary A: Step-by-step calculation of e.

Supplementary B: Values of K measurements

REFERENCES

1. Chand Malav L, Yadav KK, Gupta N, Kumar S, Sharma GK, Krishnan S, et al. A review on municipal solid waste as a renewable source for waste-to-energy project in India: Current practices, challenges, and future opportunities. J Clean Prod 2020;277:123227. https://doi.org/10.1016/j.jclepro.2020.123227.
2. Mondal S, Mandal B. Assessment of urban solid waste management in a Class II Indian city using geospatial and statistical approaches: A case study of Rampurhat municipality. Waste Management Bulletin 2024;1:74–92. https://doi.org/10.1016/j.wmb.2023.09.003.
3. Dutta A, Jinsart W. Waste generation and management status in the fast-expanding Indian cities: A review. J Air Waste Manage Assoc 2020;70:491–503. https://doi.org/10.1080/10962247.2020.1738285.
4. Singh P, Sharma VP. Integrated Plastic Waste Management: Environmental and Improved Health Approaches. Procedia Environ Sci 2016;35:692–700. https://doi.org/10.1016/j.proenv.2016.07.068.
5. Meena MD, Dotaniya ML, Meena BL, Rai PK, Antil RS, Meena HS, et al. Municipal solid waste: Opportunities, challenges and management policies in India: A review. Waste Management Bulletin 2023;1:4–18. https://doi.org/10.1016/j.wmb.2023.04.001.
6. Patil SA. Laboratory Investigation of Hydraulic Conductivity of Fresh and Degraded Municipal Solid Waste. 2022.
7. Karimi S, Bareither CA, Scalia J. A critical review of municipal solid waste hydraulic conductivity: A mini review. Waste Management and Research 2024;42:997–1007. https://doi.org/10.1177/0734242X231204814.
8. Zhang Z, Wang Y, Xu H, Fang Y, Wu D. Influence of effective stress and dry density on the permeability of municipal solid waste. Waste Management and Research 2018;36:471–80. https://doi.org/10.1177/0734242X18763520.
9. Cheela VRS, Goel S, John M, Dubey B. Characterization of municipal solid waste based on seasonal variations, source and socio-economic aspects. Waste Dispos Sustain Energy 2021;3:275–88. https://doi.org/10.1007/s42768-021-00084-x.
10. Ke H, Liu Y, Hu J, Qin R, Xu XB, Chen YM. Experimental study on anisotropy of hydraulic conductivity for municipal solid waste. Waste Management 2022;137:39–49. https://doi.org/10.1016/j.wasman.2021.10.030.
11. Rana R, Ganguly R, Gupta AK. Physico-chemical characterization of municipal solid waste from Tricity region of Northern India: a case study. J Mater Cycles Waste Manag 2018;20:678–89. https://doi.org/10.1007/s10163-017-0615-3.
12. Sarnobat M, Kulkarni G, Mali S. Characterization of Market Solid Waste at Source in Kolhapur City, Maharashtra, India. Advances in Waste Management, Springer Singapore; 2019, p. 467–78. https://doi.org/10.1007/978-981-13-0215-2_33.
13. Singhal A, Gupta AK, Dubey B, Ghangrekar MM. Seasonal characterization of municipal solid waste for selecting feasible waste treatment technology for Guwahati city, India. J Air Waste Manage Assoc 2022;72:147–60. https://doi.org/10.1080/10962247.2021.1980450.
14. Haile MZ, Mohammed ET, Gebretsadik FD. Physicochemical characterization of municipal solid waste in Sawla town, Gofa Zone, Ethiopia. Journal of Applied Sciences and Environmental Management 2020;23:2023. https://doi.org/10.4314/jasem.v23i11.19.
15. Verma N, Tripathi AK. Municipal Solid Waste (MSW) Composition, Quantification and Characterization at the three MSW Dumping Sites of Himachal Pradesh: A Case Study. Indian Journal of Forestry 2016;39:31–6. https://doi.org/10.54207/bsmps1000-2016-hx5y94.
16. Zoroufchi Benis K, Safaiyan A, Farajzadeh D, Khalili Nadji F, Shakerkhatibi M, Harati H, et al. Municipal solid waste characterization and household waste behaviors in a megacity in the northwest of Iran. International Journal of Environmental Science and Technology 2019;16:4863–72. https://doi.org/10.1007/s13762-018-1902-9.
17. Denafas G, Ruzgas T, Martuzevičius D, Shmarin S, Hoffmann M, Mykhaylenko V, et al. Seasonal variation of municipal solid waste generation and composition in four East European cities. Resour Conserv Recycl 2014;89:22–30. https://doi.org/10.1016/j.resconrec.2014.06.001.
18. Abylkhani B, Aiymbetov B, Yagofarova A, Tokmurzin D, Venetis C, Poulopoulos S, et al. Seasonal characterisation of municipal solid waste from Astana city, Kazakhstan: Composition and thermal properties of combustible fraction. Waste Management & Research: The Journal for a Sustainable Circular Economy 2019;37:1271–81. https://doi.org/10.1177/0734242X19875503.
19. Ibikunle RA, Titiladunayo IF, Lukman AF, Dahunsi SO, Akeju EA. Municipal solid waste sampling, quantification and seasonal characterization for power evaluation: Energy potential and statistical modelling. Fuel 2020;277:118122. https://doi.org/10.1016/j.fuel.2020.118122.

20. Aguilar-Virgen Q, Taboada-González P, Ojeda-Benítez S. Seasonal analysis of the generation and composition of solid waste: potential use—a case study. Environ Monit Assess 2013;185:4633–45. https://doi.org/10.1007/s10661-012-2893-5.
21. Kumar S, Dhar H, Nair V V., Bhattacharyya JK, Vaidya AN, Akolkar AB. Characterization of municipal solid waste in high-altitude sub-tropical regions. Environmental Technology (United Kingdom) 2016;37:2627–37. https://doi.org/10.1080/09593330.2016.1158322.
22. Jani Y, Kaczala F, Marchand C, Hogland M, Kriipsalu M, Hogland W, et al. Characterisation of excavated fine fraction and waste composition from a Swedish landfill. Waste Management and Research 2016;34:1292–9. https://doi.org/10.1177/0734242X16670000.
23. Azam M, Jahromy SS, Raza W, Raza N, Lee SS, Kim KH, et al. Status, characterization, and potential utilization of municipal solid waste as renewable energy source: Lahore case study in Pakistan. Environ Int 2020;134. https://doi.org/10.1016/j.envint.2019.105291.
24. Owusu-Nimo F, Oduro-Kwarteng S, Essandoh H, Wayo F, Shamudeen M. Characteristics and management of landfill solid waste in Kumasi, Ghana 2019. https://doi.org/10.1016/j.sciaf.2019.e0.
25. More CG, Gawande SM. Pre Monsoon Analysis of Solid Waste Characteristics as Per Depth at Phursungi Dumping Yard in Pune Region 2015;5.
26. Alshawaf M, Alwaeli M, Pikon K, Alolayan M. The characterization of municipal solid waste in Kuwait: a pathway to reform the waste management sector. Discover Sustainability 2025;6. https://doi.org/10.1007/s43621-025-01041-y.
27. Patil SA, Patil P, Wakchaure B-A. Hydraulic Conductivity of Fresh Municipal Solid Waste at Various Compositions and Compactive Efforts. 2022.
28. Gyabaah D, Awuah E, Antwi-Agyei P, Kuffour RA. Characterization of dumpsite waste of different ages in Ghana. Heliyon 2023;9. https://doi.org/10.1016/j.heliyon.2023.e15827.
29. Tanaji Mali S, Khare KC, Biradar AH. Characterisation of municipal solid waste at landfill, India. Proceedings of Institution of Civil Engineers: Waste and Resource Management 2011;164:247–55. https://doi.org/10.1680/warm.2011.164.4.247.
30. Hussain J, Chatterjee S, Haque E. Characterization of Waste Fractions Found in Landfills. Waste Management, Processing and Valorisation, Springer Nature; 2021, p. 43–59. https://doi.org/10.1007/978-981-16-7653-6_3.
31. Al-Isawi R, Idan IJ, Hassan AA, Alzubaidi HAM, Al-Kulabi N. Evaluation of the hydraulic conductivity for MSW using pilot plant test- A case study of Baghdad city/Iraq. IOP Conf. Ser. Earth Environ. Sci., vol. 779, IOP Publishing Ltd; 2021. https://doi.org/10.1088/1755-1315/779/1/012081.
32. Reddy KR, Hettiarachchi H, Parakalla NS, Gangathulasi J, Bogner JE. Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill, USA. Waste Management 2009;29:952–9. https://doi.org/10.1016/j.wasman.2008.05.011.
33. Miguel MG, Mortatti BC, da Paixão Filho JL, Pereira SY. Saturated Hydraulic Conductivity of Municipal Solid Waste Considering the Influence of Biodegradation. Journal of Environmental Engineering 2018;144. https://doi.org/10.1061/(asce)ee.1943-7870.0001432.
34. Dixon N, Langer U. Development of a MSW classification system for the evaluation of mechanical properties. Waste Management 2006;26:220–32. https://doi.org/10.1016/j.wasman.2005.02.018.
35. Ahmad S, Kashif MS, Alam J, Ghani A, Irfan M. Characterizing / Segregating Municipal Solid Waste and Finding its Recycling Potential in Bannu District. Sir Syed University Research Journal of Engineering & Technology 2023;13:53–60. https://doi.org/10.33317/ssurj.426.
36. Breitmeyer RJ, Benson CH, Edil TB. Effects of Compression and Decomposition on Saturated Hydraulic Conductivity of Municipal Solid Waste in Bioreactor Landfills. Journal of Geotechnical and Geoenvironmental Engineering 2019;145. https://doi.org/10.1061/(asce)gt.1943-5606.0002026.
37. Dixon N, Jones DR V. Engineering properties of municipal solid waste. Geotextiles and Geomembranes 2005;23:205–33. https://doi.org/10.1016/j.geotexmem.2004.11.002.