

Article

A Novel Technosol Formulation for Sustainable Landfill Top Covers Using Non-Hazardous Wastes

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Abstract: This study explores the potential of non-hazardous wastes for crafting an engineered soil-like material (Technosol) suitable for landfill capping applications. Three distinct materials—waste foundry sand (WFS), washing aggregate sludge (WAS), and composted biosolids (CBS)—were strategically combined to develop this innovative Technosol. The formulation process involved a comprehensive analysis of their physical–chemical properties, mineral composition, leachate quality, and a series of geotechnical assessments to ensure compliance with landfill top cover construction standards. The blend 90WFS/10WAS showed optimal geotechnical properties for constructing a protective layer, including maximum dry density (1.77 g cm^{-3}), void ratio (0.4), CBR index (23.2), cohesive strength (40 kPa), internal friction ($\phi = 30^\circ$), and permeability coefficient ($k = 1.48 \times 10^{-6} \text{ cm s}^{-1}$). Further enhancement was achieved by adding 10% CBS, resulting in the development of a functional organo-mineral topsoil horizon (81WFS/9WAS/10CBS). Importantly, leachate analysis confirmed the negligible environmental footprint of this Technosol. Moreover, a pot-based experiment with *Brassica juncea* planting validated its capacity to support plant growth and establish a vegetative cover on the landfill surface.

Keywords: landfill closure; soil top cover; Technosol; waste management; circular economy; geotechnical testing



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1. Introduction

Modern landfills require effective closure and long-term management to minimize environmental impacts on nearby ecosystems and ensure public safety. Upon reaching capacity, a final cover system becomes essential to protect the surrounding environment from potential landfill hazards. Although design practices vary depending on site-specific factors and regulatory requirements, this cover system typically comprises multiple, engineered layers designed to be stable, impermeable, and durable [1,2]. These layers act as a protective barrier, minimizing leachate generation and landfill gas leakage, while also offering opportunities for ecological restoration and post-closure land use planning.

In the European Union (EU), the Landfill Directive 1999/31/EC provides the main focus for design requirements. It mandates the implementation of a capping system with minimal shrinkage, high evapotranspiration rate, and low infiltration into the underlying waste body. An essential aspect of landfill closure is the construction of a topsoil cover (at least 1 m in thickness according to the EU Landfill Directive) comprised of a low-permeability layer overlain by a nutrient-rich vegetative horizon (Figure 1). The topsoil cover plays a critical role in preventing rainwater infiltration, erosion, and landslides, ensuring overall landfill stability. The vegetative cap layer further contributes to the sustainable and aesthetically pleasing reuse of landfill sites [3]. To ensure the effectiveness of landfill top covers, engineering best practices must be followed [4], including selecting appropriate materials, implementing proper thickness, and ensuring adequate compaction.

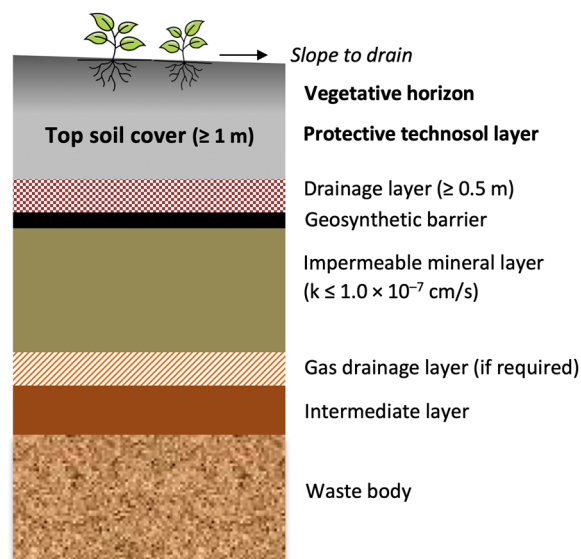


Figure 1. Simplified cross-section of a typical waste landfill (not to scale). This paper focuses on developing a waste-derived Technosol for the vegetative and the protective layers of the topsoil cover.

Conventional landfill covering materials often rely on limited natural resources (soil, clay, sand, gravel), raising concerns about resource depletion and environmental degradation. Transportation and processing of these materials can also contribute to carbon emissions. As a result, there is growing interest in exploring alternative covering materials [5–10], such as recycled products, industrial by-products, or technogenic soils (Technosols) that meet the required engineering and environmental standards [11–13].

In this context, the study explores the suitability of a waste-derived Technosol designed specifically for use as the final top cover material in landfills. Utilizing non-hazardous waste materials minimizes landfill disposal and offers a more sustainable and cost-effective alternative to traditional cover layer materials [14]. This innovative approach can potentially reduce resource and energy consumption, greenhouse gas emissions, and waste generation, aligning with the principles of a circular economy and sustainable waste management practices. However, reliable knowledge of the geotechnical and geo-environmental properties of wastes is crucial for their acceptance in the top cover layer at landfills [15].

The key objectives of this study were as follows: (1) to design a protective layer specifically tailored for landfill top covers by incorporating a balanced mix of non-hazardous waste materials to ensure sufficient permeability, erosion resistance, and stability; and (2) develop a nutrient-rich vegetative horizon to sustain healthy plant growth on the landfill surface, enhancing the aesthetic appearance of the final top cover. The findings will provide valuable insights into the technical feasibility and environmental benefits of utilizing non-hazardous wastes in Technosol design and construction, ultimately advancing the field of landfill engineering and supporting the transition towards a more resource-efficient and circular economy.

2. Materials and Methods

2.1. Selection and Characterization of Waste Materials

Three distinct non-hazardous wastes were selected as input materials for designing a Technosol for landfill top covers: (a) waste foundry sand (WFS); (b) washing aggregate sludge (WAS); and (c) composted biosolids (CBS). These waste materials, recognized by the European Waste Catalogue under the codes 100906, 010408, and 190503, respectively, are abundantly generated and readily available worldwide [16–18]. WFS, a by-product of the metal casting industry, is widely used for creating sand molds and cores. Over time, the sand degrades and becomes unsuitable for further casting operations, leading to its disposal in landfills. WAS is a silty-clay waste generated during the washing and screening

of aggregates for quality control in construction applications. This process produces a waste stream that requires proper management and disposal solutions. CBS originates from wastewater treatment processes. Composting stabilizes the organic components of the sewage sludge, transforming it into a nutrient-rich product that improves soil quality, improves water retention, and fosters plant growth.

Prior to constructing the Technosol, a comprehensive characterization of the selected waste materials was performed to assess their compatibility and ensure compliance with regulatory requirements. This involved a detailed evaluation of their physical–chemical properties, mineralogical and chemical composition, and leachate quality. Potentiometric measurements of pH, Eh, and electrical conductivity were conducted on representative samples, by stirring 10 g of solid waste in 25 mL of deionized water for 5 min, followed by a standing period of 30 min. pH measurements were performed using a CRISON BASIC 20 pH meter with a glass electrode calibrated with pH 4 and 7 buffer solutions at 25 °C. Electrical conductivity measurements were made using a CRISON GLP 31 conductivity meter equipped with a glass electrode calibrated with two standard KCl solutions. Each procedure was repeated three times, and the average values were recorded.

Mineralogical analysis was carried out by X-ray powder diffraction (XRD) to determine the bulk mineralogical composition and identify clay minerals in the fine fraction. The XRD patterns were obtained on a BRUKER D8-Advance diffractometer, using monochromatic Cu-K α radiation operated at 40 kV and 30 mA, with a step size of 0.015° and a scan speed of 0.1 s per step. Two types of samples were prepared: (a) randomly oriented powder samples to determine the bulk mineralogical composition; and (b) oriented aggregate samples to identify clay minerals in the fine fraction (<2 μ m). The oriented aggregates were air-dried and solvated with ethylene glycol to accurately identify smectite. Semi-quantitative mineral abundances were determined using intensity factors derived from integrated peak area values of diagnostic reflections [19].

Quantitative analysis of essential macronutrients and potentially toxic trace elements was achieved through inductively coupled plasma optical emission spectroscopy (ICP-OES) following a four-acid (HClO₄-HNO₃-HCl-HF) digestion process. For accuracy and precision, rigorous quality control procedures were implemented, including reagent blanks, duplicate analysis, and certified reference materials (OREAS series). The analysis of reference materials exhibited deviations from certified concentrations of less than 10% (relative standard deviation, RSD), achieving remarkable precision better than 2% RSD for most elements.

2.2. Technosol Formulation

A two-tiered, waste-derived Technosol system is proposed as a sustainable approach for developing landfill topsoil covers. This Technosol consists of an 80 cm thick protective layer overlaid by a 20 cm horizon designed to facilitate plant growth (Figure 1).

To construct the protective layer, the inorganic wastes (WFS and WAS) were thoroughly blended in controlled ratios to achieve a composite material with optimal geotechnical properties, capable of forming a reinforced barrier against infiltration and erosion. Three formulation ratios were evaluated for the protective layer: (a) 90WFS/10WAS, meaning 90% waste foundry sand and 10% waste aggregate sludge on a dry weight basis; (b) 80WFS/20WAS; and (c) 70WFS/30WAS. Given the finer grain size and more plastic nature of WAS, there was a concern about its potential impact on the long-term stability of the engineered material. Therefore, the proportion of fine-grained particles (less than 0.080 mm) in the mixture was limited to a maximum of 30% by dry weight, thus ensuring long-term performance and compliance with established civil engineering requirements for embankment fillings.

Among the tested formulations, the blend that exhibited the most optimal geotechnical properties, including high compaction, adequate bearing capacity, and appropriate hydraulic conductivity, was selected for further enhancement. To foster plant establishment and growth within the uppermost 20 cm layer of the landfill top cover, CBS was incorporated into the chosen formulation.

The amended topsoil cover was thoroughly homogenized by hand and then moistened with distilled water. It was then placed in polypropylene containers at room temperature for 14 days for equilibration before being transferred to pots (15 cm depth and diameter) and planted with *Brassica juncea* (brown mustard). This species was selected for its rapid growth rate and adaptability to diverse climatic conditions and soil types [20]. The pots were placed in a glasshouse environment and received regular irrigation with tap water to maintain optimal moisture levels for plant growth.

Following the pot experiment, a leaching test was conducted in accordance with European Standard EN-12457-4 [21] to measure the concentrations of potentially toxic trace elements leached from the Technosol. The leach solutions were analyzed for pH, Eh, and electrical conductivity, and their trace element contents were determined by inductively coupled plasma mass spectrometry (ICP-MS) with an Agilent 7700 instrument. Prior to analysis, the solutions were filtered through a 0.45 µm membrane filter and acidified with dilute nitric acid. For quality control, replicates, blank analysis, and standard reference material (SRM 1640a) were used. The analytical data exhibited an accuracy and reproducibility better than 8% RSD for most elements reported.

2.3. Geotechnical Testing Methods

Similar to road construction, landfill covers rely on compacted soil layers as a foundation. However, landfill final cover systems are complex engineering structures that demand a more comprehensive testing approach and adherence to specific safety and stability standards. Geotechnical properties required in landfill construction quality plans [22] were determined using standardized laboratory testing methods outlined in American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) protocols to ensure reliable and consistent results [23].

Grain-size distribution analysis for the coarse-grained material ($\phi > 0.075$ mm) was conducted using the sieving method outlined in the ASTM D6913 standard [24]. Additionally, the particle size distribution of the fine fraction was determined using the Mastersizer 3000 laser diffraction particle size analyzer. Liquid and plastic limits were measured on the particle fraction smaller than 0.4 mm, following the ASTM D4318 standard [25], providing representative results of the soil's plasticity behavior. The samples were classified according to the Unified Soil Classification System [26], based on grain size analysis and Atterberg limits.

Compaction properties were assessed using the standard Proctor test, a widely recognized and standardized procedure for determining the maximum dry unit weight (γ_{dmax}) and optimum moisture content of soils. Compaction curves were determined in accordance with the ASTM D698 standard [27]. Relative density of particles was determined for the particle fraction smaller than 4.75 mm, following the guidelines outlined by the ASTM D854 standard [28]. Void ratio (e) was subsequently derived from the relative density of the particles (G) and the maximum dry unit weight (γ_{dmax}), as follows:

$$e = G/\gamma_{dmax} - 1$$

Swelling potential, a critical factor for long-term stability, was evaluated using oedometer tests in accordance with the specifications of the ASTM D4546 standard [29]. This evaluation included both a free swelling test and a swelling pressure test, performed on carefully molded specimens compacted using the standard Proctor method. The California bearing ratio (CBR) test, based on the ASTM D1883 standard [30], assessed the strength and load-bearing capacity of the compacted soil. This test directly measures a strength index for samples compacted at the optimal moisture content identified through the standard Proctor test.

To determine the hydraulic conductivity of the sample, a permeability test was conducted in accordance with the ISO 17892-11 standard [31], using a triaxial cell with back-pressure saturation. The test involved a laterally confined cylindrical sample subjected to

controlled variations in hydraulic load, with water flow measured under both constant and variable loading conditions.

Finally, the chosen blend, exhibiting the most favorable combination of strength and permeability properties was subjected to a consolidated drained direct shear test following the ASTM D3080 standard [32], at a strain rate of 0.048 to 0.092 mm/min.

3. Results and Discussion

3.1. Physico-Chemical Properties and Mineral Constituents of Waste Materials

WFS showed an alkaline reaction (pH = 10.31) and low electrical conductivity (0.77 mS cm⁻¹). It primarily consisted of quartz and clay minerals, with minor feldspars and calcite (Table 1). The clay separate (<2 µm) was dominated by smectite with a well-ordered structure (Biscaye index = 0.79) with some mica, quartz, feldspars, and calcite. Smectite exhibited a basal spacing (001) of around 12.8 Å in the air-dried state, indicating the presence of a single layer of water molecules in the interlayer space [33], and exchangeable monovalent cations. Upon ethylene glycol solvation, the basal spacing increased to 17 Å (Figure 2a).

Table 1. Physical–chemical parameters and composition of the waste materials used as ingredients in Technosol formulation.

Material Properties and Constituents	Waste Material		
	Waste Foundry Sand (WFS)	Washing Aggregate Sludge (WAS)	Composted Biosolids (CBS)
Physico-chemical parameters			
pH (in water)	10.31 ± 0.04	6.24 ± 0.26	7.5 ± 0.16
Electrical cond. (mS cm ⁻¹)	0.77 ± 0.01	0.24 ± 0.02	3.2 ± 0.3
Mineral composition and organic matter content (wt %)			
Bulk sample	Quartz (65–70)	Clay minerals (7–80)	Organic matter (54)
	Clay minerals (20–25)	Quartz (15–20)	
	Feldspars (<5)	Feldspars (<5)	
	Calcite (<5)	Goethite (<5)	
Clay fraction	Smectite (75–80)	Kaolinite (70–75)	
	Mica (5–10)	Mica (20–25)	
	Quartz (<5)	Smectite (<5)	
	Feldspars (<5)	Quartz (<5)	
	Calcite (<5)		
Chemical composition			
Plant macronutrients (wt %)			
N	-	-	2.6
P	0.008	0.037	4.2
K	0.23	1.23	1.21
Ca	0.35	0.07	6.7
Mg	0.33	0.23	1.30
S	0.04	0.04	-
Potentially toxic trace elements (mg kg ⁻¹)			
As	3	36	-
Cd	<0.3	<0.3	<0.6
Co	<1	9	<10
Cr	13	58	33
Cu	10	19	161
Mn	138	82	642
Ni	5	33	<20
Pb	10	33	46
Zn	30	42	458

Given that WFS is composed of relatively pure silica sand, chemical analyses showed negligible concentrations of Ca, Mg, and K, all consistently below 1.0 wt %. Moreover, total concentrations of potentially toxic elements remained consistently low (Table 1), and fell well below the regional screening levels established for industrial land use. A significant concern regarding the utilization of WFS is the potential leaching of elevated trace metal levels [34]. However, elemental analysis of leachate generated from this waste revealed minimal metal release, with measured concentrations (in mg L^{-1}) remaining below 0.01 (Hg), 0.02 (Se), 0.05 (Cd and Sb), 0.1 (As, Cu, and Pb), 0.2 (Mo, Mn, and Zn), and 0.5 (Cr and Ni). Therefore, WFS exhibited a low leaching potential consistent with previous WFS applications [35]. Importantly, none of the measured trace elements exceeded toxicity thresholds for plant establishment [36]. In addition, the low sulphate (30 mg L^{-1}) and chloride ($<50 \text{ mg L}^{-1}$) concentrations suggest the minimal presence of soluble salts, which can also be detrimental to plant establishment.

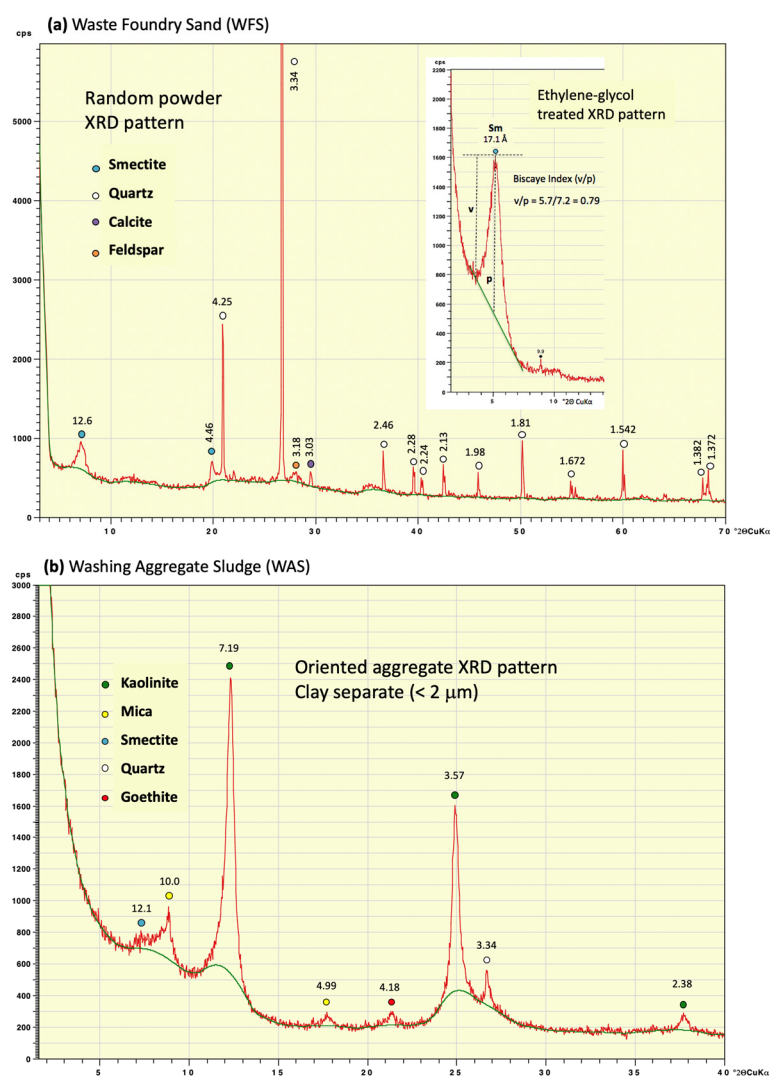


Figure 2. Mineral composition of the waste materials determined from the X-ray powder diffraction patterns.

WAS is made up of reddish yellow clays with a slightly acidic pH (6.24) and remarkably low electrical conductivity (0.24 mS cm^{-1}). Clay minerals comprised between 75 and 80% of the bulk sample, while quartz, and, to a lesser extent, feldspars and goethite were present as accessory minerals (Figure 2b). The clay fraction was dominated by kaolinite, with minor amounts of mica and quartz. Additionally, XRD analysis of the clay separate revealed the presence of smectite with a basal spacing of 12.1 \AA in the air-dried state,

implying a single layer of adsorbed water within the interlayer, coupled with exchangeable monovalent cations. WAS is a natural resource extracted from a lateritic palaeosol enriched with kaolinitic sands [37,38]. The naturally occurring trace elements present in the clays displayed relatively low concentrations, except for As, which reached up to 36 mg kg^{-1} .

CBS exhibited a neutral to slightly alkaline reaction ($\text{pH} = 7.5$) and a low to moderate electrical conductivity (3.2 mS cm^{-1}). Notably, CBS is a rich source of organic matter, accounting for 54% of the total dry weight, providing a valuable reservoir for plant nutrients. Essential nutrients like phosphorous (4.2%), nitrogen (2.6%), and potassium (1.21%) were present in significant concentrations, along with Ca and Mg (Table 1). Moreover, CBS contains noteworthy concentrations of trace elements crucial for plant growth in small quantities, such as Mn (642 mg kg^{-1}), Zn (458 mg kg^{-1}), and Cu (161 mg kg^{-1}).

3.2. Geotechnical Properties

Effective landfill topsoil covers require a balance of key properties: mechanical strength, long-term stability, minimal infiltration, and the ability to facilitate lateral drainage. While WFS and WAS individually might not fully meet all these requirements, their strategic combination can achieve the desired particle size distribution, leading to the necessary geotechnical properties. The results of the evaluated geotechnical parameters are presented in Table 2.

Table 2. Geotechnical parameter values of the tested samples, including percent finer, Atterberg limits, optimum moisture content, maximum dry density, relative density, void ratio, swelling potential, California bearing ratio (CBR), permeability coefficient, and shear strength parameters.

Geotechnical Parameter	Waste Foundry Sands (WFS)	Washing Aggreg. Sludge (WAS)	Mixture 90:10 (WFS/WAS)	Mixture 80:20 (WFS/WAS)	Mixture 70:30 (WFS/WAS)
Fine-grained fraction ¹ (%)	17.5	89.4	20.6	26.4	34.8
Liquid limit (LL)	26	60	28	27	33
Plastic limit (PL)	no plastic	29	no plastic	no plastic	no plastic
Plasticity index (PI)	0	31	0	0	0
USCS classification ²	ML	CH	ML	ML	ML
Optimum moisture content (%)	13.40	26.95	13.57	15.36	15.45
Maximum dry density (g/cm^3)	1.74	1.50	1.77	1.75	1.74
Relative density of particles (G)	2.50	2.58	2.47	2.50	2.50
Void ratio	0.44	0.72	0.40	0.46	0.46
Free swelling (%)	0	0.25	0	0	0
Swelling pressure (kPa)	0	0	0	0	0
CBR index	-	-	23.2	8.4	-
CBR swelling (%)	-	-	0.58	0.76	-
Permeability coefficient (cm/s)	-	-	1.48×10^{-6}	1.00×10^{-6}	-
Cohesion (kPa)	-	-	40	-	-
Friction angle (ϕ , degree)	-	-	30	-	-

¹ Material passing through the #200 sieve size (0.075 mm); ² USCS classification (ML: silty sands with slight plasticity; CH: inorganic clays of high plasticity).

Grain size distribution significantly impacts water retention and permeability, which in turn influence compaction, drainage, and cover soil stability [39]. The waste materials used in the formulation of the protective layer showed distinct grain size compositions (Figure 3). WFS was coarse-grained, retaining over 80% of particles by weight on the #200 sieve (0.075 mm), while WAS consisted of fine-grained particles, with almost 90% of fine particles by weight. The fine-grained fraction varied among mixtures, ranging from 20% to 35%.

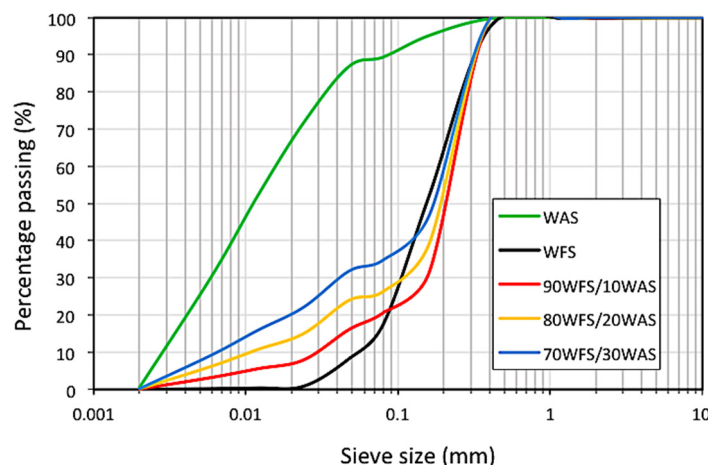


Figure 3. Granulometric curves of the tested samples obtained by combining sieving and laser diffraction results.

The blend 90WFS/10WAS maintained a moderate fine-grained fraction, balancing coarse and fine particles, which could enhance both compaction and permeability. WFS is known for its ability to granulometrically stabilize clayey soils, making it a suitable protective cover material in landfill settings [40]. Selecting a moderately fine-grained blend like 90WFS/10WAS could improve compaction and alleviate settlement concerns. However, mixtures with higher fine-grained fractions, such as 80WFS/20WAS and 70WFS/30WAS, may require additional consideration to ensure effective compaction and proper drainage. This strategic choice aligns with sustainable landfill cover design principles by promoting long-term stability [41] and minimizing maintenance requirements.

High-plasticity materials in landfill top covers can lead to significant volumetric changes due to moisture fluctuations, often resulting in shrinkage and cracking. Materials with high liquid limits and plasticity indices exhibit increased settlement potential and volume changes. Among the tested materials, WAS displayed the highest liquid limit (LL = 60), indicating substantial plasticity and susceptibility to volume change during wetting and drying cycles. The plasticity index of 29 further emphasizes the plastic nature of WAS. Design considerations should prioritize mixtures with liquid limits below 30 to minimize the risk of shrinkage and cracking. For instance, the blend 70WFS/30WAS, with its high liquid limit (LL = 33), may lead to prolonged settlement and instability issues, while mixtures with lower liquid limits, such as 90WFS/10WAS and 80WFS/20WAS, can enhance the durability and sustainability of the landfill top cover. Based on the Unified Soil Classification System (Figure 4), WAS is classified as an inorganic clay with high plasticity (CH), while WFS and mixtures of WAS with WFS (90WFS/10WAS, 80WFS/20WAS, and 70WFS/30WAS) are categorized as silty sands with slight plasticity (ML).

Optimum moisture content results provide valuable insights into compaction behavior of mixtures, guiding sustainable landfill cover construction. The moisture content values for maximum compaction varied among samples, reflecting the influence of WFS and WAS on compaction (Table 2). WAS, with its finer texture and elevated plasticity, required a comparatively higher water content (26.95%) for maximum compaction. Conversely, WFS and WFS-containing mixtures (13.4–15.5%) exhibited lower optimum moisture content, attributed to their coarse-grained, non-plastic nature, allowing optimal compaction with reduced water content. Adding WAS into the mixture resulted in a slight increase in moisture demand for achieving optimal compaction. Mixtures with lower optimum moisture content have the potential to improve compaction efficiency by requiring less water consumption, leading to cost savings and a reduced environmental footprint.

Achieving maximum dry density through compaction is essential for ensuring the stability and load-bearing capacity of landfill covers. As evident from the moisture-density (Proctor) curves (Figure 5), the blend 90WFS/10WAS reached the highest maximum dry

density value of 1.77 g cm^{-3} , indicating its superior compaction potential. This elevated maximum dry density value reflects a greater ability of the material to pack tightly, resulting in a denser structure with fewer voids, thereby enhancing stability. This translates to improved load-bearing capacity, reduced settlement potential, and greater resistance to erosion, which are crucial aspects of a sustainable landfill cover design. Conversely, WAS exhibited poor compaction behavior, yielding a lower maximum dry density value (1.50 g cm^{-3}), thereby compromising its compaction efficiency.

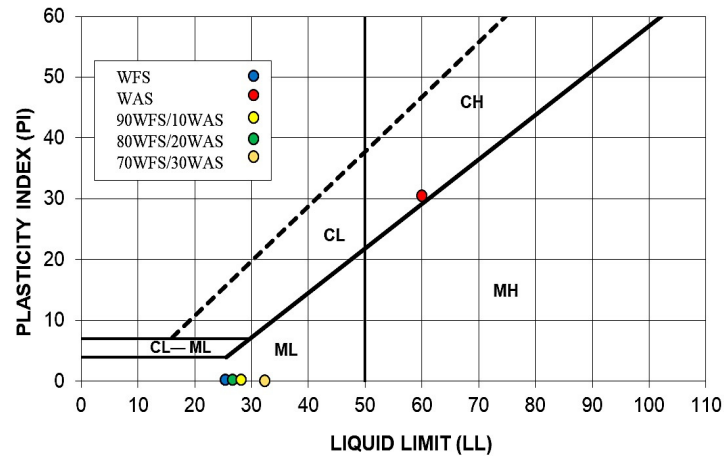


Figure 4. Sample classification based on liquid limit (LL) and plasticity index (PI) values. Plasticity chart as per Unified Soil Classification System (USCS).

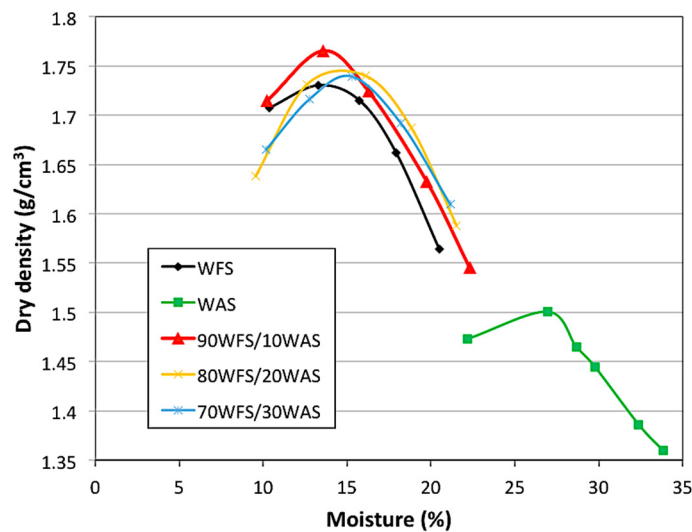


Figure 5. Standard Proctor compaction test results of the tested samples.

Analysis of void ratio variations among mixtures highlights the influence of WFS and WAS content. WAS, with its fine-grained and plastic nature, exhibited a remarkably high void ratio (0.72), suggesting an increased susceptibility to deformation. In contrast, WFS-bearing mixtures consistently displayed lower void ratio values (0.40–0.46). This suggests that WFS-based mixtures hold promise for efficient compaction and enhanced stability. Notably, increasing WAS proportions did not substantially affect the overall void content, indicating that WFS effectively counteracts the void-creating tendencies of WAS.

Swelling and stability are paramount factors in the design of landfill top covers. Materials with minimal swelling and collapse potential are essential for maintaining long-term stability and preventing deformations caused by moisture variations. WAS exhibited a free swelling value of 0.25%, indicating slight expansion or shrinkage during wetting and

drying cycles. This low swelling potential is primarily due to the mineralogical composition of WAS, which is dominated by kaolinite, a non-swelling clay mineral. WFS and the mixture 90WFS/10WAS showed negligible swelling behavior, evidenced by their zero free swelling values. While smectite is present in WFS, the low proportion of this expandable mineral compared to quartz minimizes its influence on the overall material behavior. Consequently, both WFS and the blend 90WFS/10WAS maintain stability, experiencing minimal pressure or volumetric fluctuations with moisture exposure.

Among the formulations showing the most favorable compaction conditions, the mixtures 90WFS/10WAS and 80WFS/20WAS underwent CBR testing to assess their strength properties (Figure 6a). The blend 90WFS/10WAS had the highest CBR index (23.2), demonstrating outstanding resistance to deformation under load. This feature holds significant importance in the design of landfill covers, as materials with high CBR values can reliably support loads without excessive settlement. Moreover, the CBR swelling value for the blend 90WFS/10WAS was relatively low (0.58%), indicating minimal susceptibility to expansion upon soaking. The mixture 80WFS/20WAS displayed a moderately higher CBR swelling value (0.76%), suggesting a slightly increased potential for expansion upon soaking compared to the blend 90WFS/10WAS. Therefore, selecting the formulation 90WFS/10WAS could contribute to the development of a resilient and sustainable landfill cover capable of withstanding external forces and minimizing deformations.

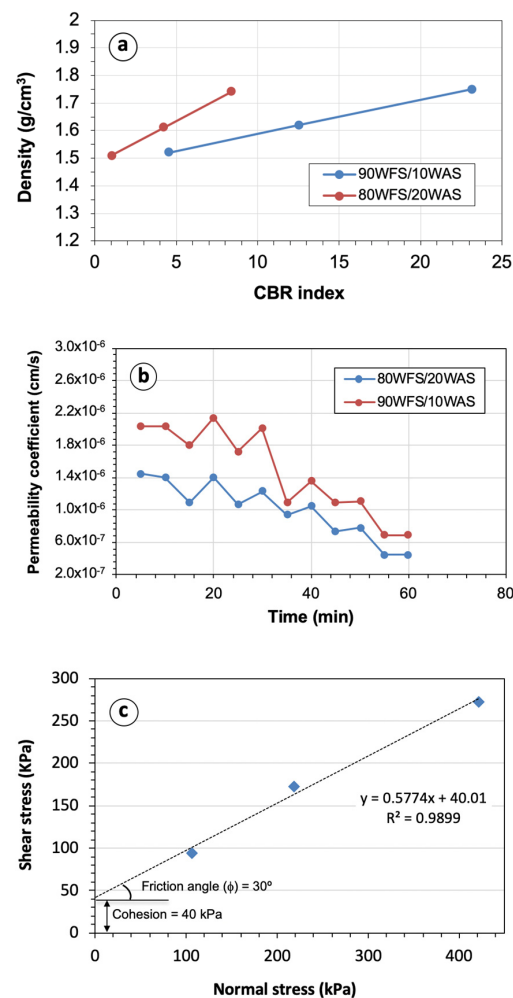


Figure 6. Plots of geotechnical results of the tested mixtures: (a) California bearing ratio (CBR) index against density; (b) water permeability coefficient plotted as a function of time; and (c) linear relationship between shear stress and normal stress data derived from a direct shear test on the blend 90WFS/10WAS.

The hydraulic conductivity of landfill top cover materials is a critical factor influencing their drainage and overall hydrological performance. WFS has been recognized as a reliable hydraulic barrier material through laboratory and field studies [42,43]. The blends 90WFS/10WAS ($k = 1.48 \times 10^{-6} \text{ cm s}^{-1}$) and 80WFS/20WAS ($k = 1.00 \times 10^{-6} \text{ cm s}^{-1}$) exhibited relatively low permeability coefficients (Figure 6b), allowing for controlled fluid flow and minimizing the risk of excessive water infiltration that can lead to the bathtub effect. The slightly higher permeability coefficient of the blend 90WFS/10WAS offers an additional benefit. It could further enhance drainage efficiency and reduce the likelihood of ponding on the landfill cover surface.

Shear strength parameters are important for understanding the Technosol's response to shear stresses and assessing its suitability as a sustainable material to maintain the stability of the landfill top cover, especially in sloped sections. Direct shear testing on the mixture 90WFS/10WAS, compacted at its optimal moisture content, revealed a cohesion value of 40 kPa and a friction angle (ϕ) of 30° (Figure 6c). These parameters indicate a moderate degree of shear resistance, which is generally desirable for landfill cap stability. The cohesiveness of this Technosol can minimize erosion from wind or water runoff, thereby enhancing the impermeability of the cover system.

The findings emphasize the significant influence of Technosol compositions on their geotechnical properties. Based on the results described above and summarized in Table 2, it is evident that the formulations 90WFS/10WAS and 80WFS/20WAS demonstrated superior qualities in terms of strength, deformability, and permeability. The high plasticity, swelling potential, and poor compaction characteristics observed in WAS present significant construction challenges. In contrast, mixtures with higher WFS proportions offer improved compaction and stability. The CBR index and permeability coefficient further elucidate the noteworthy differences in strength and permeability among the mixtures. The blend 90WFS/10WAS achieved the highest CBR index compared to other formulations, indicating its superior strength and load-bearing capacity. Overall, this blend effectively balances critical geotechnical properties, including load-bearing capacity, volume changes, stability, pore index, and maximum compaction density.

3.3. Vegetative Landfill Cap

Following a thorough assessment of geotechnical properties, the blend 90WFS/10WAS has demonstrated compliance with requirements for compaction, bearing capacity, permeability, and shear strength, presenting a promising option for Technosol-based landfill capping applications.

To promote a thriving vegetative layer conducive for plant growth on the landfill surface, the blend 90WFS/10WAS was enhanced with the addition of CBS at a ratio of 81WFS/9WAS/10CBS. This amended formulation, comprising 81% waste foundry sand, 9% waste aggregate sludge, and 10% composted biosolids containing 54% organic matter (dry weight basis), was specifically tailored to attain a minimum of 5% organic matter content in the final product. The CBS was thoroughly integrated into the existing mixture to ensure uniformity, mimicking the homogenizing effects of plowing or tilling.

Notably, the blend 81WFS/9WAS/10CBS was crafted utilizing waste materials with physical–chemical parameters (pH, Eh, and electrical conductivity) closely resembling natural soils. Consequently, it can be expected that this uppermost layer of the Technosol not only facilitates plant growth but also mitigates environmental risks associated with potential trace element leaching due to their low concentrations within the formulation.

In fact, subsequent pot experiments using the formulation 81WFS/9WAS/10CBS and planting *B. juncea* yielded promising results. Within a week of planting, the plants displayed a remarkable ability to thrive within the Technosol, with shoots emerging as an indicator of the favorable conditions (Figure 7a). Over a 120-day period, four out of the five plants in each pot remained viable (Figure 7b), demonstrating the Technosol's capacity to support healthy vegetation growth, potentially leading to increased evapotranspiration, reduced

water infiltration and leachate generation, and improved erosion control by stabilizing the landfill cover surface.

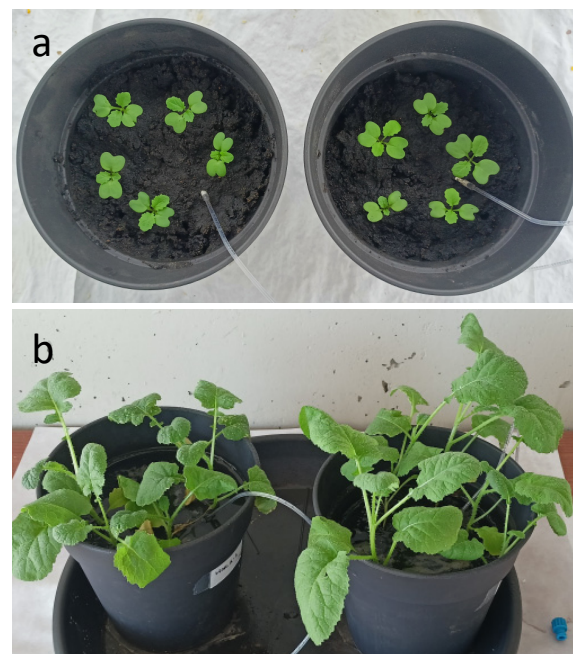


Figure 7. Representative growth stages of *Brassica juncea* within the vegetative layer (81WFS/9WAS/10CBS) of the Technosol: (a) early seedling stage; and (b) pre-flowering stage.

The results of the leaching test conducted to assess the potential release of trace elements from the blend 81WFS/9WAS/10CBS are presented graphically in Figure 8, along with pH, Eh, and electrical conductivity measurements. The recovered solutions showed a mildly alkaline pH (7.92), an oxidizing redox potential (Eh = 416 mV), and relatively low electrical conductivity (0.62 mS cm^{-1}), suggesting limited concentration of water-soluble salts within the Technosol.

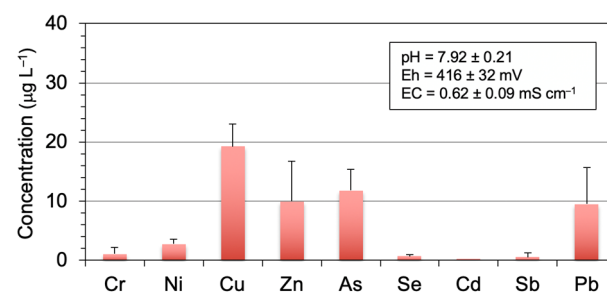


Figure 8. Trace element concentrations and physical–chemical parameters measured in the solution leached from the vegetative layer (81WFS/9WAS/10CBS) of the Technosol.

The waste materials integrated into the blend 81WFS/9WAS/10CBS contain significant amounts of acid-neutralizing components, such as calcite in WFS, and adsorbent phases, like iron oxy-hydroxides in WAS and organic matter in CBS. These components play a crucial role in limiting the mobility of potentially toxic trace elements, thereby, reducing the risk of environmental contamination [44,45]. Indeed, the pool of trace elements available for plant uptake and leaching through percolation was found to be negligible. The most prevalent trace elements in the leachates, ranked in descending order of concentration, were Cu, As, Zn, and Pb, with mean values as low as (in $\mu\text{g L}^{-1}$) 19.29 Cu, 11.85 As, 10.01 Zn, 9.56 Pb, and 2.76 Ni. Other trace elements of concern, such as Cr, Se, Sb, and Cd, were detected at levels around or below $1.0 \mu\text{g L}^{-1}$.

When compared to international water quality guidelines, the levels of trace elements released from the Technosol generally fell below safe drinking water standards. The exception was As, which slightly exceeded the highest permissible value of $10 \mu\text{g L}^{-1}$ set by the EU Directive 98/83/CE and the World Health Organization for drinking water quality [46].

4. Conclusions and Future Work

This study has highlighted the promising potential of non-hazardous waste materials in the construction of sustainable landfill capping systems and has stressed the importance of integrating circular economy principles into landfill closure strategies. Specifically, it explored the feasibility of tailor-made Technosols, composed of waste mixtures, as environmentally friendly alternatives for topsoil cover construction.

Currently, the tested waste materials are landfilled, representing a missed opportunity for their sustainable reuse. Our Technosol formulation provides a more sustainable and cost-effective solution by reusing these materials for landfill capping directly at the disposal site. This approach enhances sustainability and delivers multiple environmental benefits, such as, (a) reduced landfill waste diversion, minimizing the need for virgin materials and maximizing landfill capacity; (b) lower energy consumption and greenhouse gas emissions by eliminating transportation of natural cover materials; and (c) establishment of a vegetative cover on the landfill, which may contribute to methane capture through plant–microbe interactions.

The formulated Technosols were assessed for their geotechnical properties, aiming to achieve an optimal balance between compaction, stability, and permeability. Among the tested mixtures, the composition 90WFS/10WAS emerged as the most favorable, exhibiting a compelling set of geotechnical attributes, including optimal compaction potential, low deformability and permeability, and stable volume changes, aligning with sustainable landfill cover design principles.

Further enhancement of the mixture 90WFS/10WAS with 10% composted biosolids supported successful plant growth with negligible environmental risks, indicating its potential for establishing and sustaining vegetation on landfill surfaces. These findings underscore the importance of material selection and formulation in landfill design, showcasing the engineered Technosol's potential to offer innovative solutions to waste management challenges.

This study has established a foundation for Technosol's potential applications, but further research is needed to ensure its successful transition to real-world implementation. Future studies should include field-scale trials to thoroughly evaluate its performance under real-world conditions and weathering tests to simulate the effects of environmental exposure on Technosol behavior. Furthermore, compatibility of Technosol with existing landfill infrastructure should be investigated, including any potential modifications required at landfills to accommodate Technosol placement while minimizing disruption to current operational practices.

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