Evaluating Sludge from Landfill Leachate Treatment as a Soil Conditioner Using the Analytic Hierarchy Process: Balancing Soil Health, Toxicity, and Cost

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Research Article

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Abstract

This study evaluates the potential of raw sludge (RS) and pyrolyzed sludge (PS), derived from landfill leachate treatment, as sustainable soil conditioners by examining their impacts on soil health, toxicity, and cost-effectiveness. Soil health indicators—including pH, EC, organic carbon, and nutrient levels—were monitored over incubation, while toxicity was assessed through cytotoxicity tests on HepG2 cells and phytotoxicity assays using maize germination. Cost analysis incorporated amendment dosages and energy requirements for pyrolysis. RS demonstrated higher nutrient content and greater improvements in soil fertility, whereas PS exhibited reduced cytotoxicity and enhanced phytotoxicity performance, reflecting the detoxifying effect of pyrolysis. However, PS incurred significantly higher production costs. To integrate these multifaceted criteria, the Analytic Hierarchy Process (AHP) was employed. Toxicity emerged as the most critical criterion, followed by soil health and cost. AHP results identified 5 g kg^{-1} RS as the most practical and balanced option due to its favorable nutrient profile, low toxicity at this dosage, and cost-efficiency. These findings underscore the environmental and economic benefits of valorizing landfill leachate sludge in agriculture, promoting resource recovery, circular economy strategies, and reduced dependence on synthetic fertilizers.

Highlights

- Raw and pyrolyzed sludges were assessed as soil conditioners.
- AHP approach balanced soil health, toxicity, and economic factors.
- Pyrolysis reduced toxicity but increased production cost.
- Raw sludge at 5 g/kg was identified as the optimal and practical soil amendment.

1. Introduction

Global waste generation has escalated significantly over recent decades, increasing from 635 million tons in 1965 to 1,999 million tons in 2015, with projections indicating a rise to 3,539 million tons by 2050 (Chen et al., 2020a). Among various waste management strategies, landfilling remains the predominant method due to its relatively low cost compared to alternatives such as incineration (Gautam and Kumar, 2021; Nanda and Berruti, 2021; Gani et al., 2022). However, one of the major drawbacks of landfilling is the production of leachate—a highly complex effluent containing a mixture of organic and inorganic pollutants, including heavy metals, dissolved organic compounds, and xenobiotics (Gao et al., 2015). If not properly treated, landfill leachate poses substantial risks to both environmental and human health.

To address these challenges, a circular economy model is increasingly being adopted in waste management, emphasizing resource recovery, reuse, and sustainability (Hoornweg and Bhada-Tata, 2012). Within the context of landfill leachate treatment, this approach promotes the valorization of by-products—such as nutrient-rich sludge—for use in agricultural systems, while also harnessing biogas as a renewable energy source (Lieder and Rashid, 2016; Nabavi-Pelesaraei et al., 2017). This transition from a linear to a circular system not only reduces environmental burdens but also contributes to long-term sustainability goals.

Among various valorization techniques, pyrolysis has emerged as a promising method for transforming sludge derived from leachate treatment into beneficial soil amendments. Pyrolysis thermochemically converts the organic fraction of sludge under limited oxygen conditions, resulting in a carbon-rich material known as biochar. This process not only reduces sludge volume and eliminates pathogens but also enhances the physicochemical properties of the resulting material (Jin et al., 2016). Biochar produced from wastewater sludge has been shown to improve soil fertility, supply essential nutrients, and reduce the mobility and bioavailability of toxic elements (Goldan et al., 2022; Racek et al., 2020; Gopinath et al., 2021).

Although pyrolysis is traditionally applied to biomass with high organic content, it can also be effectively utilized for mineral-rich substrates such as zeolitic sludge. In such materials, pyrolysis facilitates the carbonization of residual organics and induces structural changes in the mineral matrix, potentially enhancing properties such as porosity, thermal stability, and sorption capacity (Psaltou et al., 2020). This expanded application underscores the versatility of pyrolysis as a treatment method for a broader range of waste materials.

Nevertheless, the application of raw or pyrolyzed landfill leachate sludge as a soil conditioner raises several concerns. The presence of toxic substances may disrupt soil microbial communities, impair plant growth, or pose risks to human health via bioaccumulation in the food chain. Cytotoxicity testing is therefore essential to evaluate the potential for cellular damage (de Lemos and Erdtmann, 2000; Fenech et al., 2003), while phytotoxicity assays help determine impacts on plant germination and development (Bożym, 2020). In addition to toxicity, the long-term effects on soil structure, nutrient dynamics, and biological activity must be assessed, given the soil’s central role in agricultural productivity and ecological function (Spanner and Napolitano, 2015). Finally, the economic feasibility of such amendments is a critical factor influencing their adoption by farmers and land managers.

This study aims to assess the suitability of raw and pyrolyzed landfill leachate sludge as soil conditioners by evaluating their effects on soil health, toxicity (cytotoxicity and phytotoxicity), and cost-effectiveness. The Analytic Hierarchy Process (AHP) is employed to integrate and prioritize multiple criteria, offering a comprehensive evaluation framework to guide decision-making in sustainable agricultural applications.

2. Materials and methods

2.1. Sludge preparation and characterization

Landfill leachate samples were collected from the Saravan landfill site (37°04'17" N, 49°37'52" E), located within a 20-kilometer radius of Rasht City, Guilan Province, Iran. Raw sludge (RS) was obtained through an integrated leachate treatment process involving adsorption using natural zeolite, coagulation with polyferric sulfate, and struvite precipitation. The resulting sludge was oven-dried at 60°C and subsequently sieved (Alirezazad et al., 2025).

The dried RS was subjected to pyrolysis under limited oxygen conditions, with a controlled heating rate of 22°C min^{-1}. Upon reaching 300°C, the material was maintained at this temperature for 2 hours to produce pyrolyzed sludge (PS), following the protocol described by Hossain et al. (2011). Physicochemical properties of both RS and PS were evaluated, including total nitrogen (TN), total phosphorus (TP), total potassium (TK), total coliform bacteria (TCB), electrical conductivity (EC), and pH, by standard methods for organic fertilizer analysis (Singh et al., 2017). Elemental composition (carbon, hydrogen, nitrogen, and sulfur) was determined using a CHNS analyzer (Elemental Analyzer, CE Instruments Flash EA 1112 Series). Further structural characterization of the soil conditioners was conducted using Fourier Transform Infrared (FT-IR) spectroscopy (Thermo Nicolet 380, Waltham, MA, USA) in the range of 400–4000 cm^{-1}.

2.2. Incubation and Soil Health Assessment

An incubation experiment was conducted using nutrient-deficient surface soil (0–20 cm depth) collected from Luleman (37°14'35.9" N, 49°48'1.6" E) in Guilan Province, Iran. The soil was air-dried, passed through a 2 mm sieve, and stored at 4°C before use. Baseline soil properties were determined using standard procedures as outlined by Carter and Gregorich (2007), with the results presented in Table 1.

Soil conditioners were applied at rates of 5, 10, and 15 g kg^{-1}, and the treated soils were incubated for 90 days at 25 ± 2°C. Soil moisture content was maintained at approximately 70% of field capacity by replenishing with deionized water every three days or as needed. Following incubation, key soil health parameters were assessed, including electrical conductivity (EC), pH, total nitrogen (TN), organic carbon (OC), available phosphorus (AP), available potassium (AK), mean weight diameter (MWD) of soil aggregates, and microbial biomass carbon (MBC), in accordance with the methods described by Carter and Gregorich (2007).

Table 1
Physical and chemical properties of the soil before incubation.

Properties	Unit	Value
pH	(1:10 soil-to-water ratio)	7.55
Electrical conductivity (EC)	$\mu S\ cm^{-1}$ (1:10 soil-to-water ratio)	199.65
Organic carbon (OC)	$g\ kg^{-1}$	4.5
Total nitrogen (TN)	$mg\ kg^{-1}$	200
Available phosphorus (AP)	$mg\ kg^{-1}$	8.22
Available potassium (AK)	$mg\ kg^{-1}$	134.33
Soil textural class	-	Loamy sand
Saturation percentage (SP)	%	36
Mean weight diameter (MWD)	mm	0.35

2.3. Toxicity Assessment

Toxicity was evaluated through both cytotoxicity and phytotoxicity assays, aimed at determining the adverse effects of the soil conditioners on human cell viability and plant growth, respectively. These complementary approaches provide essential information on potential health and environmental hazards, thereby facilitating a comprehensive assessment of the toxicological risks associated with the application of soil conditioners.

2.3.1. Cytotoxicity Assay

The cytotoxic effects of soil conditioners were evaluated using the HepG2 human liver carcinoma cell line. Cells were cultured in 25 cm^2 disposable flasks at 37°C in a humidified atmosphere containing 5% CO_2. The culture medium consisted of 5 mL Dulbecco's Modified Eagle's Medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and 0.1% antibiotic-antimycotic solution.

Cytotoxicity was assessed via cell viability using the MTT (3-[4,5-dimethylthiazol-2-yl]-2,5 diphenyl tetrazolium bromide) assay, following the method described by Mosmann (1983). HepG2 cells were seeded in 96-well plates at a density of 2×10^4 cells per well and allowed to stabilize for 24 h under standard incubation conditions (37°C, 5% CO_2). After stabilization, the cells were treated with soil conditioners at concentrations of 0, 27.78, 55.56, and 83.34 $g\ L^{-1}$, corresponding to soil application rates of 5, 10, and 15 $g\ kg^{-1}$ (based on 50% field capacity).

Following a 24 h exposure period, 20 µL of MTT solution was added to each well, and the plate was incubated for an additional 4 h. After incubation, the MTT solution was removed, and 100 µL of dimethyl sulfoxide (DMSO) was added to solubilize the formazan crystals. Absorbance was measured at 540 nm using a microplate spectrophotometer (Multiskan FC, Thermo Scientific). All treatments were conducted in triplicate to ensure reproducibility.

2.3.2. Phytotoxicity Assay

To evaluate the effect of soil conditioners on phytotoxicity, the germination test was conducted using maize seeds (Zea mays L.) in solutions with concentrations of 0, 27.78, 55.56, and 83.34 g L^{-1} RS or PS. For effective sterilization, the seeds were first washed with 90% ethanol and thoroughly rinsed with distilled water. To ensure surface sterilization, mercuric chloride (0.1%) was applied for 30 s, followed by three rinses with autoclaved distilled water (Oyebanji et al., 2009). The amount of solution required to maintain humidity for the seeds, with a thousand kernel weight (TKW) equal to 166 g, was calculated through the following equation:

TKW × number of seeds /10^5 = 1% of the proposed water amount (1)

Subsequently, the calculated solution volumes were added to sterile 9-cm Petri dishes lined with single sterile filter papers. The seeds were sown on the filter paper in each Petri dish, which was then covered with lids, sealed with parafilm, and incubated in the dark at 25°C for 10 days (Khaeim et al., 2022). After 10 days, the number of germinated seeds in each Petri dish was recorded, and root lengths were measured. The Germination index (GI) was calculated through the following equation (Paradelo et al., 2010):

$$GI = \left(\frac{G}{G_C}\right) \times \left(\frac{L}{L_C}\right) \times 100$$

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Where G and L are the total number of germinated seeds and root length average of the samples, respectively, and G_C and L_C are the total number of germinated seeds and root length average of the control, respectively.

2.4. Cost Assessment

A linear cost function was utilized to model and analyze the production costs of the soil conditioners, offering a straightforward yet effective approach for estimating total production expenditures. The total cost (C) was determined using the following equation:

$C = a + bX$ (3)

In this equation, *C* denotes the total production cost, *a* represents the fixed costs—those that remain constant regardless of production volume, such as equipment, infrastructure, and baseline labor—and *bX* accounts for the variable costs, which fluctuate with the quantity of soil conditioner produced. Here, *b* indicates the cost per unit mass or volume of soil conditioner, including expenses related to energy consumption, chemical inputs, and sludge handling labor, while *X* refers to the total quantity produced. This cost estimation framework aligns with established economic modeling approaches in production analysis (Samuelson et al., 2021).

2.5. Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) was utilized to determine the most suitable soil conditioner and its optimal application rate for agricultural purposes. This decision-making framework involves structuring the problem into a hierarchical model consisting of the overall goal, evaluation criteria, and a set of alternatives. Pairwise comparisons were carried out based on expert judgment to assess the relative importance of each criterion, resulting in a comparison matrix. The priority weights for each criterion were then calculated using the normalized matrix, following the methodology outlined by Saaty (2008) and further applied in similar contexts by Wang et al. (2019).

In this study, the selection process was guided by three primary criteria: (1) toxicity, (2) soil health, and (3) cost efficiency (Fig. 1). The soil health criterion was further subdivided into eight sub-criteria: organic carbon (OC), mean weight diameter (MWD), total nitrogen (TN), microbial biomass carbon (MBC), available phosphorus (AP), pH, electrical conductivity (EC), and available potassium (AK). The toxicity criterion included two sub-criteria: cytotoxicity and phytotoxicity. The prioritization of these criteria and sub-criteria was informed by expert and academic opinions, as well as insights from previous studies (Seyedmohammadi et al., 2018; Xue et al., 2019b).

Six treatment alternatives were evaluated: RS1, RS2, RS3, PS1, PS2, and PS3, corresponding to application rates of 5, 10, and 15 g kg^{-1} for RS and PS amendments, respectively. Pairwise comparisons were conducted among these alternatives under the defined criteria, enabling the identification of the most effective soil conditioner and its optimal dosage.

2.6. Data Analysis

A one-way ANOVA was conducted to analyze the effects of soil conditioners on soil properties, cytotoxicity, and phytotoxicity. Tukey's post hoc test ($p < 0.05$) was applied to identify significant differences. Data analysis and visualization were performed using SPSS 16.0 (SPSS Inc., Chicago, IL, USA) and OriginPro 9.8, while AHP analysis was conducted using Expert Choice 11 software.

3. Results and Discussion

3.1. Characterization of Raw and Pyrolyzed Sludge

The physicochemical properties of RS and PS are summarized in Table 2. Both materials exhibited near-neutral pH values, with PS showing a slightly higher pH than RS. This increase in alkalinity is likely attributable to the retention of alkali metals during pyrolysis, which remain in the solid fraction post-treatment (Yang et al., 2018). The EC of PS was lower than that of RS, reflecting a reduced solubility of salts and other compounds following thermal transformation.

The elemental ratios also shifted as a result of pyrolysis. Specifically, the C/N and C/H ratios in PS were 0.98 and 1.29, respectively—both higher than the corresponding ratios in RS (0.94), indicating a slight reduction in carbon content and a more pronounced volatilization of nitrogen and hydrogen during the pyrolysis process (Kong et al., 2019). RS was rich in macronutrients such as TN, TP, and TK. Upon pyrolysis, TN content decreased, likely due to nitrogen volatilization and sublimation of ammonium compounds (El-Naggar et al., 2019; Leng et al., 2020). In contrast, the concentrations of TP and TK showed a modest increase, which may be attributed to the reduction in sludge mass and the subsequent concentration of mineral elements (Cao and Harris, 2010; Liang et al., 2014). TCB was not detected in either RS or PS. This absence is likely due to the high total dissolved solids (TDS) content in the initial leachate matrix, which creates a hostile environment for microbial survival (Naveen et al., 2017; Alirezazad et al., 2025).

Table 2
Characteristics of soil conditioners.

Sample ID	Yield	TCB	$pH_{1:10}$	$EC_{1:10}$	C	H	N	S	P	K
Unit	%	CFU g_{dm}^{-1}	-	dS m^{-1}	g kg^{-1}					
RS	8.64	ND	7.64	1.75	15.52	16.51	16.44	ND	14.61	46.35
PS	7.61	ND	7.81	1.21	12.63	9.81	12.92	ND	15.23	47.82

RS: Raw sludge, PS: Pyrolyzed sludge, EC: Electrical conductivity, TCB: Total coliform bacteria, and ND: Not detected.

The FT-IR spectra of the two materials are presented in Fig. 2. No significant changes in functional groups were observed post-pyrolysis. The characteristic absorption bands at 602 cm^{-1} and 792 cm^{-1} are attributed to Si–O–Si and K–O vibrations, respectively, indicating inorganic surface interactions on the zeolite component of the sludge (Guo and Chen, 2014; Kukobat et al., 2022). The band at 1027 cm^{-1} corresponds to antisymmetric stretching vibrations (v_3) of phosphate (PO_4^{3-}) groups, while the peak at 1440 cm^{-1} indicates NH_4^+ antisymmetric bending (v_4), confirming the presence of struvite crystals (Atalay et al., 2022; Zhang et al., 2020). The peak at 1630 cm^{-1} reflects C = C stretching, characteristic of sp^2-hybridized carbon structures, which further supports effective coagulation and partial carbonization during treatment (Hossain et al., 2021). A broad band at 3252 cm^{-1}, associated with O–H stretching, suggests the presence of hydroxyl functional groups (Ren et al., 2018).

3.2. Impact of applied conditioners on soil health

The effects of RS and PS applications on key soil health parameters over a 90-day incubation period are presented in Fig. 3. A slight decrease in soil pH was observed with increasing application rates of both

RS and PS (Fig. 3A). The decline was more pronounced in RS-treated soils, likely due to the production of weak organic acids and CO_2 from the decomposition of labile organic matter (Skowrońska et al., 2020). In contrast, the limited degradable organic matter content in PS, a result of thermal degradation during pyrolysis (Zhang et al., 2016), contributed to the relatively smaller pH reduction in PS treatments.

Soil EC increased with the application of both conditioners (Fig. 3B), but more so with RS. The highest EC value recorded was 1377 μS cm^{-1} for RS and 1233 μS cm^{-1} for PS at a concentration of 15 g kg^{-1}. This difference is attributed to the greater presence of water-soluble salts in RS compared to PS (Igalavithana et al., 2017; Li et al., 2018a), as pyrolysis can immobilize some ionic species and reduce solubility.

The OC content showed a gradual increase with increasing application rates (Fig. 3C), in agreement with previous findings (Dhanker et al., 2021). The OC content in RS treatments (6.2 g kg^{-1}) was slightly higher than in PS treatments (5.8 g kg^{-1}), reflecting the higher initial organic matter content in RS. The effects of various application rates of RS and PS soil conditioners on TN, AP, and AK are presented in Figs. 3D, 3E, and 3F, respectively. All three macronutrients exhibited significant increases with increasing treatment levels. Notably, the enhancements in TN and AP concentrations were more pronounced in the RS treatments compared to the PS treatments. At the highest application rate, TN and AP levels reached 422 mg kg^{-1} and 124 mg kg^{-1} in the RS-treated soils, respectively, while the corresponding values for PS-treated soils were 340 mg kg^{-1} and 99 mg kg^{-1}.

The comparatively lower nutrient release in PS-amended soils may be attributed to the physicochemical changes induced by pyrolysis. Although pyrolyzed materials are characterized by high cation and anion exchange capacities and a porous structure capable of retaining ions and molecules (Schofield et al., 2019), their hydrophobic surfaces and reduced wettability may hinder water-mediated nutrient transport and subsequent release. This is consistent with previous studies suggesting that pyrolyzed materials often function as slow-release fertilizers (Hossain et al., 2020; Zhang et al., 2017). Additionally, the porous architecture of PS facilitates the adsorption of ammonium (NH_4^+), potentially lowering the diffusion rate of mineral nitrogen in the soil matrix (Shi et al., 2020).

In the case of phosphorus, its availability may be further constrained in PS due to the formation of insoluble complexes with iron, magnesium, and calcium during pyrolysis. Compounds such as $(CaMg)_3(PO_4)_2$ and $Fe_4(PO_4)_2O$ are less soluble under neutral to alkaline conditions and are typically more available in acidic environments (Schneider and Haderlein, 2016; Xiao et al., 2018). Conversely, the AK content showed a greater increase in PS-treated soils compared to RS. This may be attributed to the higher TK concentration observed in PS (Table 2) and the relatively weaker chemical bonding of potassium in both organic and mineral matrices when subjected to thermal treatment, as compared to nitrogen and phosphorus (Liu et al., 2020).

The results of ANOVA indicated that the application of both RS and PS had no statistically significant effect on the MWD of soil aggregates, with values ranging from 0.34 to 0.37 mm. MWD is a key indicator of soil aggregate stability, which is governed by multiple factors including organic matter content, clay content, mineralogy, the presence of multivalent cations, and iron oxide concentrations (Zhao et al., 2017). The absence of significant changes in MWD may be attributed to the inherently low organic matter content of the applied soil conditioners (Table 2) and the low clay content of the experimental soil (Table 1). Moreover, soil aggregate stability is a structural attribute that typically requires prolonged periods—often spanning several years—to exhibit measurable changes (Chrenková et al., 2014). Although iron oxides are known to play a role in aggregate formation (Krause et al., 2020; Xue et al., 2019a), their ineffectiveness in this context may be due to pH conditions unfavorable to iron-mediated aggregation processes, given that iron oxide flocculation is more effective below its isoelectric point (Goldberg, 1989).

The MBC also showed no significant variation after 90 days of incubation. MBC represents the labile fraction of the soil organic matter pool and typically comprises 2–5% of total soil carbon and nitrogen (Dhanker et al., 2021). While the addition of organic matter generally stimulates microbial activity, previous studies have reported that MBC often peaks within the first 20 days of incubation before declining due to the depletion of readily available carbon sources (Fernandes et al., 2005; Li et al., 2018b). In this study, the extended incubation period combined with the low organic matter input from RS and PS likely contributed to the lack of significant changes in MBC.

3.3. Toxicity assessment of soil conditioners

3.3.1. Cytotoxicity

The cytotoxic potential of RS and PS was evaluated using the HepG2 human liver cell line, and the results are depicted in Fig. 4. Both soil conditioners exhibited dose-dependent inhibitory effects on cell viability, with statistically significant reductions compared to the untreated control ($p < 0.05$). The observed cytotoxicity likely results from residual toxic compounds within the sludge materials that impair cellular metabolism, particularly mitochondrial activity, consistent with findings by Pulido and Parrish (2003).

However, a distinct contrast was observed between RS and PS treatments. At the highest applied concentration (83.34 g L^{-1}), PS-treated cells retained significantly higher viability than those exposed to RS ($p < 0.05$). This reduction in cytotoxicity after pyrolysis is attributed to the thermal degradation of organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), persistent organic compounds, and microbial toxins, which are often present in untreated sludges (Chen et al., 2020b). The results support the notion that pyrolysis can serve as an effective detoxification strategy to enhance the environmental safety of sludge-derived materials used as soil amendments.

These findings are aligned with the broader literature indicating that pyrolysis mitigates sludge toxicity by decomposing hazardous organic constituents and immobilizing heavy metals, thus reducing their bioavailability and cellular uptake (Morozesk et al., 2016).

3.3.2. Phytotoxicity

Phytotoxicity was assessed using the GI, a sensitive indicator that combines seed germination and root elongation to detect toxic effects on plants. As shown in Fig. 5, none of the RS or PS treatments induced phytotoxic effects, with all GI values exceeding 80%, indicating non-toxicity according to established thresholds (Paradelo et al., 2010).

Interestingly, GI values increased progressively with higher application levels of both RS and PS. The enhancement in GI, particularly in PS treatments ($p < 0.05$), suggests not only the absence of phytotoxicity but also a potential stimulatory effect on seed germination and early seedling development. This is likely due to the improvement in nutrient availability and reduced phytotoxic compounds after pyrolysis.

The superior performance of PS treatments supports earlier studies showing that pyrolysis stabilizes organic matter, degrades toxic intermediates, and reduces the mobility of heavy metals—factors that collectively lower the environmental risks of raw sludge (Kong et al., 2019; Ahmad et al., 2022). Moreover, since root elongation is more sensitive to contaminants than germination itself, the higher GI in PS treatments may reflect improved root zone conditions due to lower chemical stress and improved soil conditioner properties.

3.4. Cost effectiveness of soil conditioners

The economic feasibility of RS and PS as soil conditioners at varying dosages is illustrated in Fig. 6. The analysis indicates that PS incurs consistently higher costs across all application levels compared to RS. This difference is largely due to the additional energy and infrastructure demands associated with the pyrolysis process. In the management of landfill leachate sludge—a complex byproduct of municipal waste treatment—costs are typically divided into fixed and variable categories. Fixed costs, such as labor for monitoring and operation, remain constant regardless of treatment volume. In contrast, variable costs fluctuate with the volume of sludge treated and are influenced by energy consumption, chemical additives, and operational parameters. For PS, variable costs are notably elevated due to the energy-intensive nature of pyrolysis, as well as the potential need for specialized reactors and emission controls.

Despite its environmental advantages, the economic burden of producing PS raises questions about its scalability and practicality, particularly in regions where energy costs are high or where centralized pyrolysis facilities are lacking. Although pyrolysis improves the stability, safety, and agronomic value of the final product, these benefits must be weighed against the financial feasibility of its production and deployment.

From a cost-benefit perspective, RS remains a more economical option, especially for large-scale or short-term soil amendment applications. However, this must be carefully balanced with environmental and health considerations, as RS may pose higher risks of cytotoxicity and less stability in terms of nutrient release.

Overall, while PS offers superior environmental performance and lower toxicity, its higher production costs currently limit its wide-scale adoption. Future research into low-energy pyrolysis technologies, use of renewable energy sources, and economic incentives (e.g., carbon credits or waste valorization subsidies) may enhance the financial viability of PS and support its integration into sustainable waste management and soil health programs.

3.5. AHP-based Prioritization of Sludge Applications

The weights and rankings of the main criteria and their associated sub-criteria, as derived from the Analytic Hierarchy Process (AHP), are illustrated in Fig. 7. Among the three primary criteria, toxicity was identified as the most influential, with a weight of 0.49. Within the soil health category, OC emerged as the most important sub-criterion (weight = 0.33), while cytotoxicity held the highest weight (0.67) within the toxicity criterion.

The comparative performance of RS and PS across the three evaluation criteria, toxicity, soil health, and cost efficiency, is presented in Fig. 8. Based on the overall comparison, RS applied at 5 g kg^{-1} was identified as the most favorable alternative, with a weight of 0.21. For individual criteria, the most preferred alternatives were as follows: 5 g kg^{-1} PS for toxicity (weight = 0.23), 15 g kg^{-1} RS for soil health (weight = 0.24), and 5 g kg^{-1} RS for cost efficiency (weight = 0.38).

Despite the superior performance of PS treatments in reducing toxicity—particularly at the 5 g kg^{-1} level—and the prominence of toxicity as the highest-weighted criterion in the AHP analysis, PS was ultimately deemed less favorable. This was primarily due to its higher production costs, greater energy requirements, and the comparatively better performance of RS treatments in enhancing soil health. Furthermore, the toxicity levels of RS and PS at the 5 g kg^{-1} application rate did not differ significantly, suggesting that RS could offer similar benefits without the additional processing burden. Taken together, findings indicated that 5 g kg^{-1} RS represents the most stable, efficient, and economically viable option for soil amendment among the alternatives evaluated.

The AHP analysis highlights the complexity of selecting sustainable soil conditioners, where trade-offs between toxicity mitigation, soil quality enhancement, and cost-efficiency must be carefully balanced. While PS demonstrated promising results in toxicity reduction, its practical application is hindered by the economic and energetic demands of the pyrolysis process. This aligns with previous studies suggesting that the benefits of biochar derived from low-organic or mineral-rich waste materials may not always outweigh their production costs, particularly when the toxicity benefits are marginal.

Importantly, the dominance of toxicity in the overall weighting reflects the increasing emphasis on environmental and health safety in agricultural waste reuse strategies. Cytotoxicity, as the most critical sub-criterion, reinforces the need for rigorous safety assessments before field application of waste-derived soil amendments. Nonetheless, the high performance of RS at low application rates—especially in terms of soil health improvement and cost-effectiveness—demonstrates its potential as a low-input, circular economy solution.

The results also suggest that minimal yet targeted doses (i.e., 5 g kg^{-1}) of RS may be sufficient to improve soil quality without imposing significant risks or costs, thereby supporting sustainable land management practices in resource-limited settings. Further long-term field trials and life-cycle assessments are recommended to validate these findings and to explore the scalability of RS-based amendments in different agroecosystems.

4. Conclusion

This study evaluated the agronomic, toxicological, and economic performance of raw sludge (RS) and pyrolyzed sludge (PS) derived from landfill leachate treatment to identify the most sustainable and practical soil amendment option. The findings demonstrate that while both RS and PS have potential as soil conditioners, their effects on soil health, toxicity, and cost vary significantly. RS exhibited a greater capacity to improve key soil health parameters, including organic carbon (OC), total nitrogen (TN), available phosphorus (AP), and available potassium (AK), owing to its higher nutrient content. However, RS also induced higher levels of cytotoxicity, particularly at elevated application rates. PS, by contrast, showed reduced cytotoxicity and improved phytotoxicity profiles due to the thermal decomposition of hazardous organic compounds and stabilization of heavy metals during pyrolysis. Nevertheless, the nutrient release from PS was slightly less effective, likely due to its altered pore structure and lower initial organic matter content. The cost analysis revealed that PS is significantly more expensive to produce than RS, mainly due to the energy and infrastructure requirements of the pyrolysis process. Although PS offers environmental and toxicological advantages, these benefits come at a higher economic cost. The multi-criteria decision-making process using the Analytic Hierarchy Process (AHP) confirmed that 5 g kg^{-1} RS was the most favorable treatment when considering toxicity, soil health, and cost-effectiveness holistically. Despite the superior toxicity profile of PS, the marginal difference in performance between RS and PS at the 5 g kg^{-1} level, combined with the substantially lower cost and better nutrient enhancement from RS, supports its selection as the most stable and practical amendment. Overall, this research highlights the trade-offs between health, environmental safety, and economic feasibility in the application of sludge-derived soil conditioners. RS, particularly at lower dosages, emerges as a viable and scalable option for improving soil fertility, especially in resource-constrained settings. However, future improvements in pyrolysis technology, along with environmental policy incentives, could enhance the competitiveness and applicability of PS in sustainable waste valorization and soil management programs.

Declarations

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Authors’ Contribution

All authors contributed to the conception and design of the study. Data collection, analysis, and visualization were conducted by Paniz Alirezazad, with revisions provided by all authors. Mahmood Fazeli Sangani contributed to the conceptualization, project administration, investigation, editing, and supervision. Maryam Khalili Rad and Mohammad Bagher Farhangi contributed to the methodology, validation, editing and supervision. The first draft of the manuscript was written by Paniz Alirezazad, and all authors reviewed, provided feedback, and approved the final version of the manuscript.

Ethical Approval

This is not applicable.

Consent to Participate

This is not applicable.

Consent to Publish

This is not applicable.

Competing Interests

The authors declare no competing interests.

Data Availability Statement

The data supporting the findings of this study are available within the paper. Further information generated during the study are available from the corresponding author on reasonable request.

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Figures

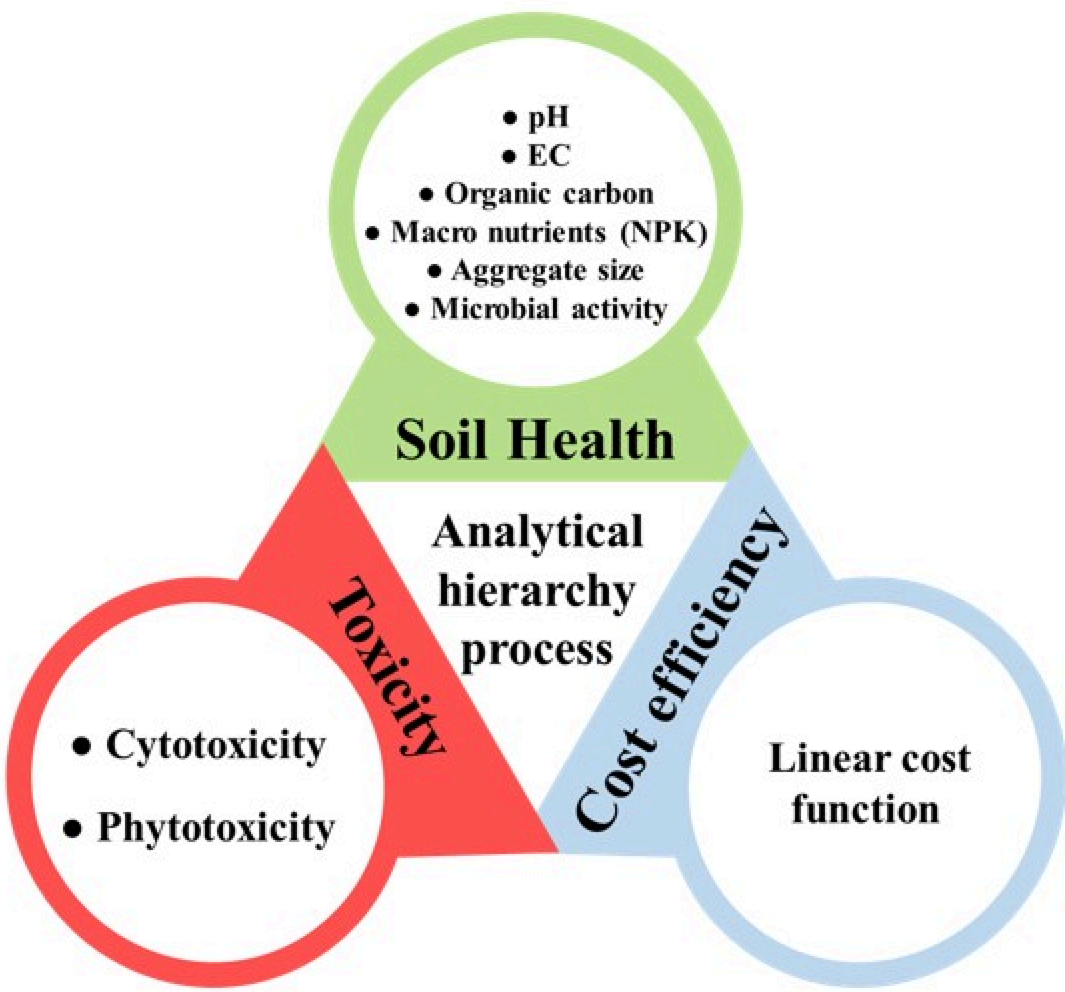

Figure 1

Integrated framework of criteria used in AHP for assessing of the optimal soil conditioner and its application rate.

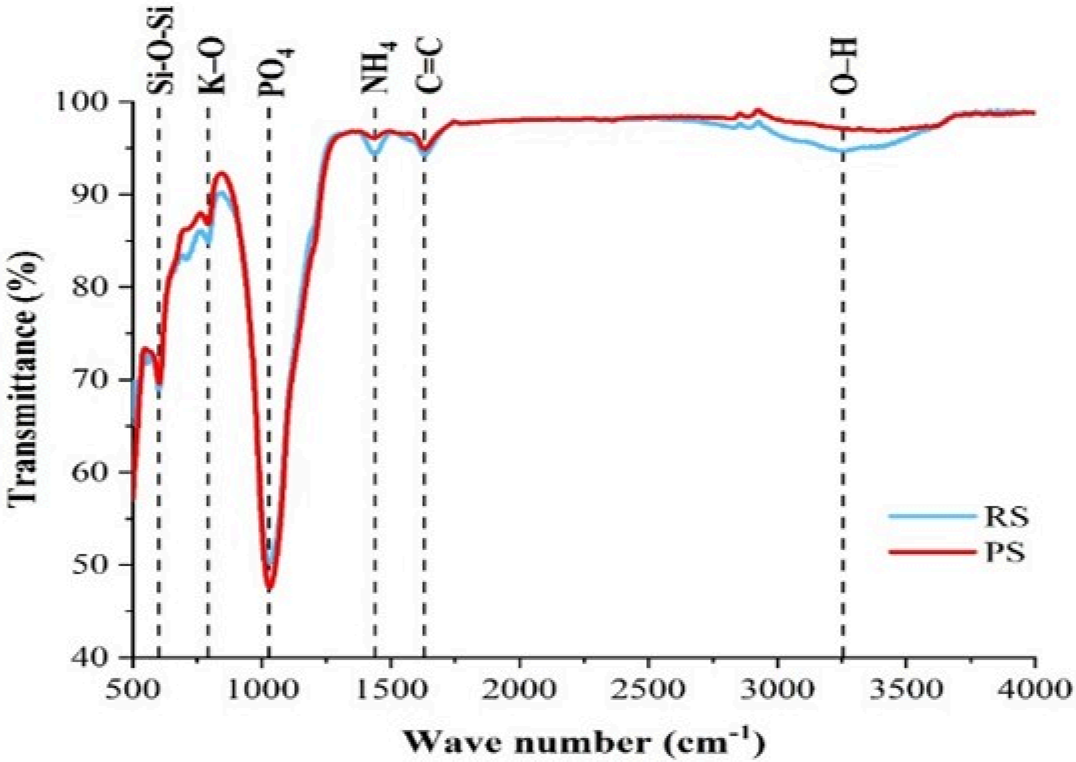

Figure 2

FT-IR spectra of soil conditioners. RS: Raw sludge and PS: Pyrolyzed sludge.

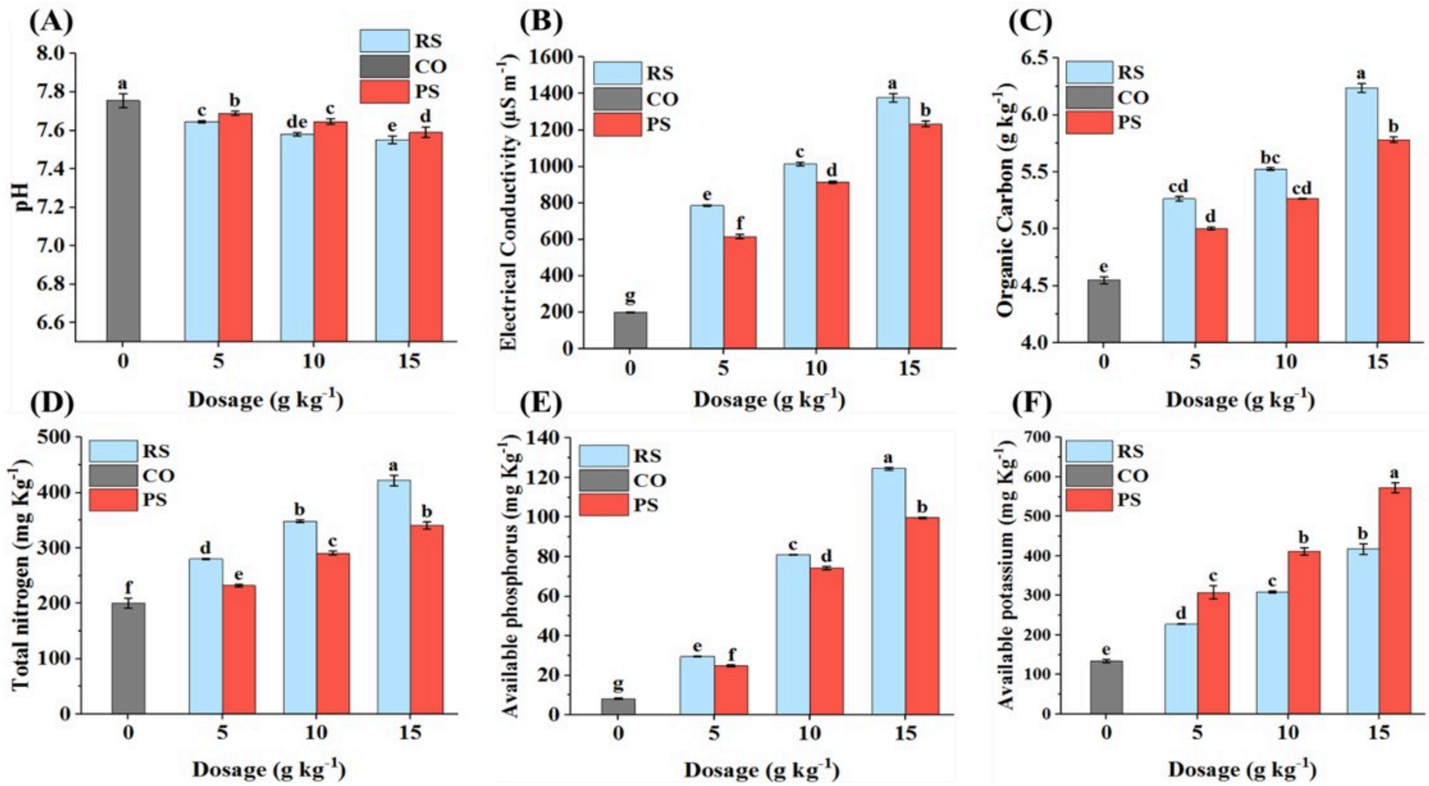

Figure 3

Changes in soil properties at the end of the incubation period. RS: Raw sludge and PS: Pyrolyzed sludge. The bars labeled with different lowercase letters are significantly different ($p < 0.05$). Data are mean values with standard errors ($n = 3$).

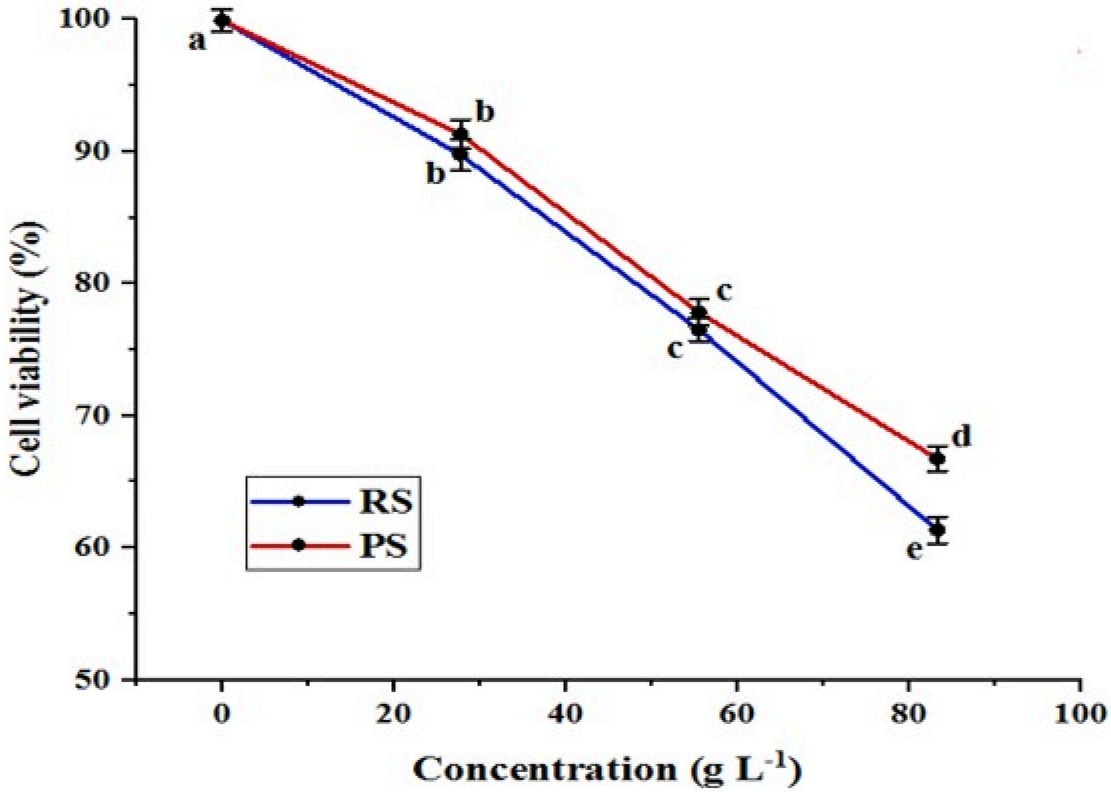

Figure 4

Cell viability in HepG2 cell culture after exposure to Raw sludge (RS) and Pyrolyzed sludge (PS) at varying concentrations. Different lowercase letters indicate statistically significant differences ($p < 0.05$). Data are mean values with standard errors ($n = 3$).

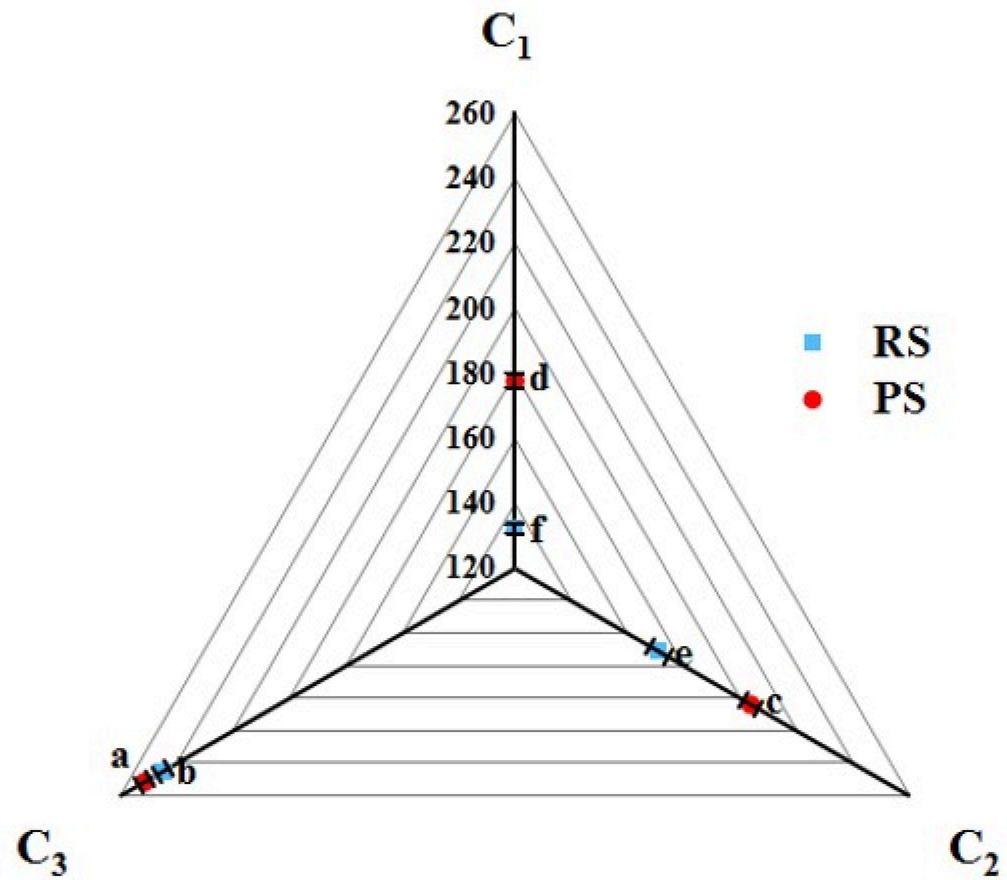

Figure 5

The effect of Raw sludge (RS) and Pyrolyzed sludge (PS) at concentrations of 27.78 (C_1), 55.56 (C_2), and 83.34 (C_3) g L^{-1} on maize seed germination index (%). Different lowercase letters indicate statistically significant differences ($p < 0.05$). Data are mean values with standard errors (n = 3).

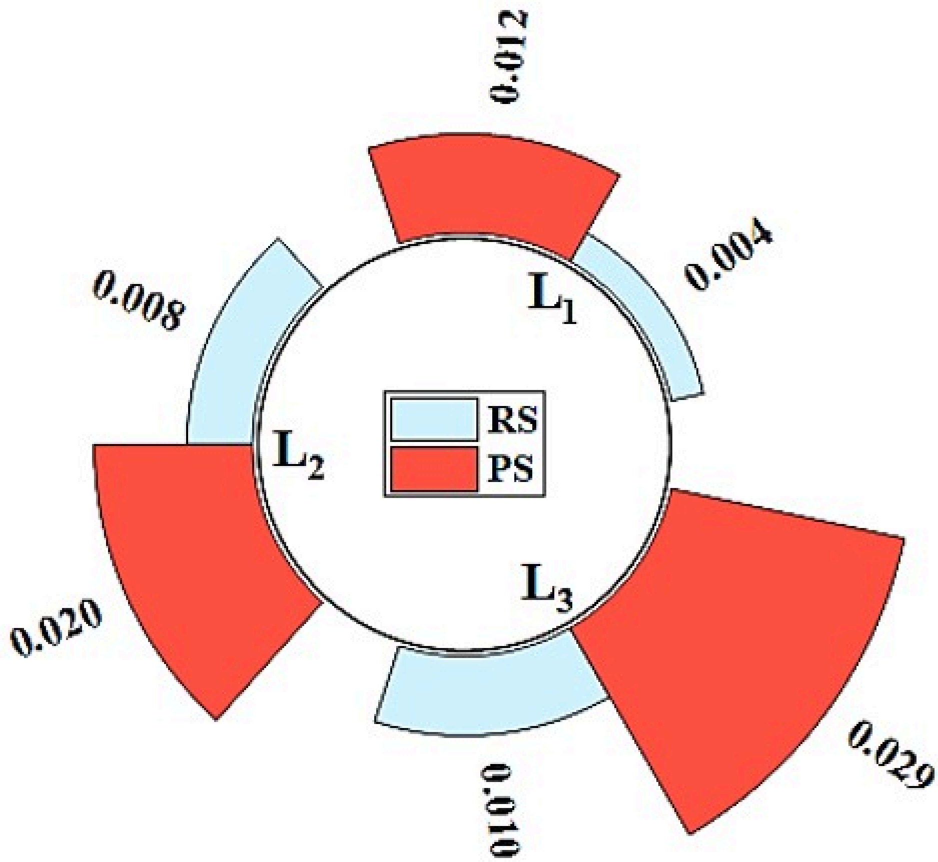

Figure 6

Cost ($) of soil conditioners at varying dosages: L_1, L_2, and L_3 correspond to applications of 5, 10, and 15 g kg^{-1} of soil conditioner to the soil, respectively.

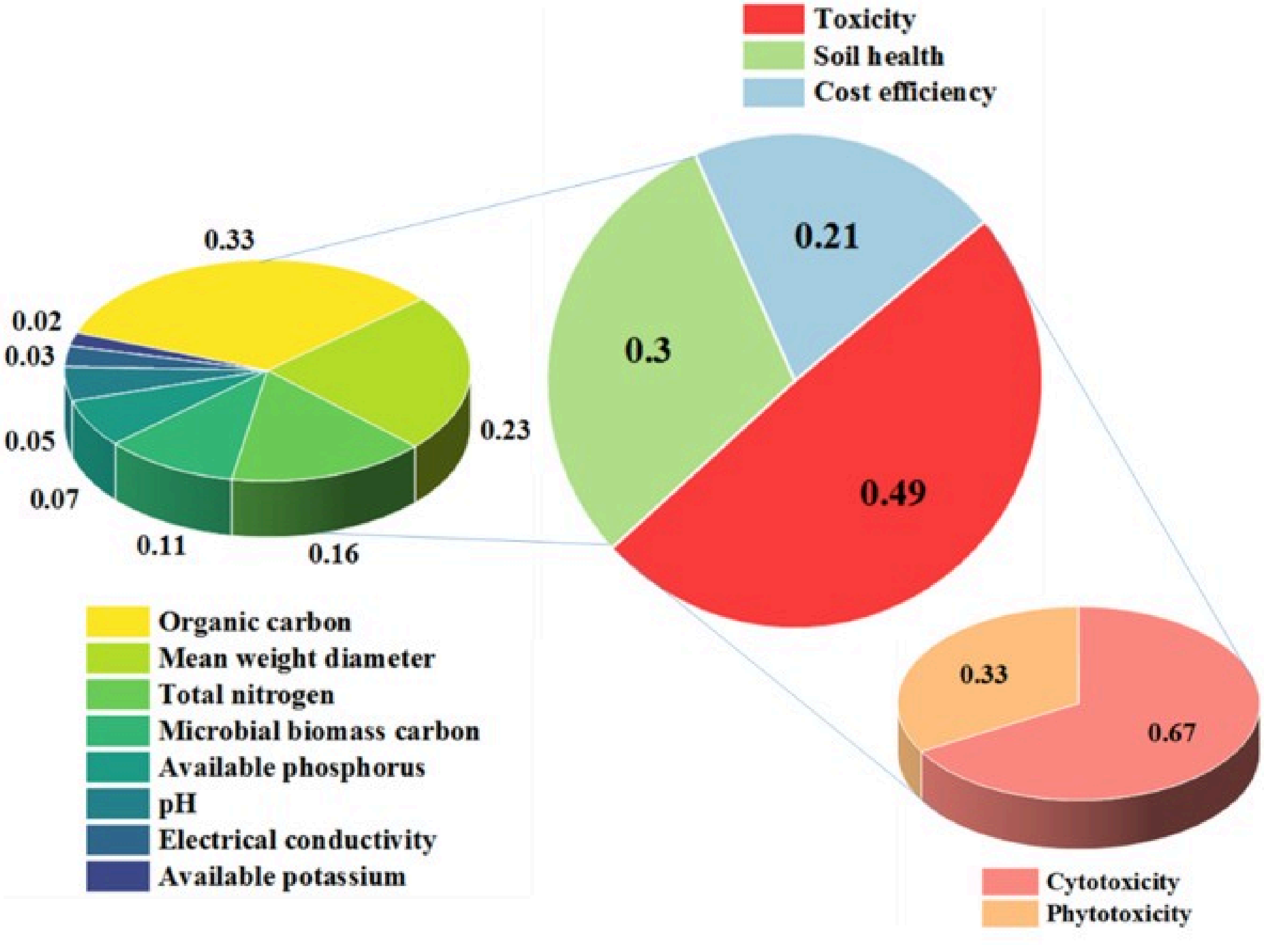

Figure 7

Weights assigned to overall criteria and sub-criteria using the AHP.

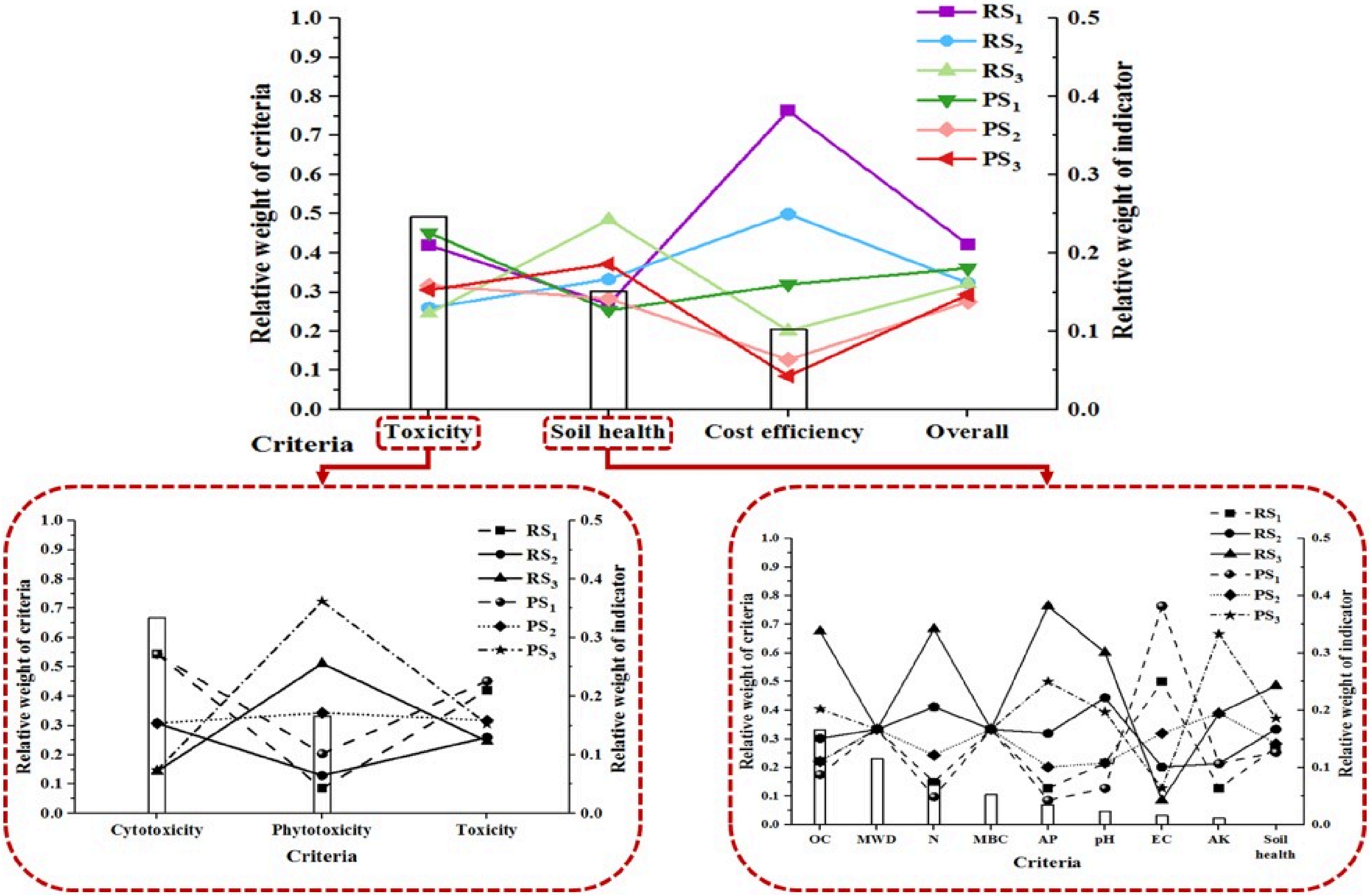

Figure 8

Implementation of analytic hierarchy process (AHP) for selecting the optimal soil conditioner and its dosage. TN: total nitrogen, AP: available phosphorus, AK: available potassium, MWD: mean weight diameter, OC: organic carbon, EC: electrical conductivity, MBC: microbial biomass carbon, RS_1, RS_2, RS_3 and PS_1, PS_2 and PS_3 represent 5, 10, and 15 g kg^{-1} raw sludge (RS) and pyrolyzed sludge (PS) applied to soil, respectively.

Supplementary Files

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