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ASSESSMENT OF TREATED WASTEWATER SLUDGE AS A SOIL AMENDMENT FOR ENHANCING LOAD-BEARING CAPACITY AND MINIMIZING EROSION

NasarAli.R[1], Dr.Eswara Veera Raghava Rao[2], Dr. Zunaithur Rahman[3]

[1] Research scholar, Department of civil Engineering, Kalinga University, Naya Raipur, Chattisgarh
[2] Professor & Head, Department of civil Engineering, Kalinga University, Naya Raipur, Chatttisgarh
[3] Associate Professor, Department of civil Engineering, AMS college of Engineering, Chennai, Tamil Nadu.

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ABSTRACT

The increasing generation of wastewater sludge poses both environmental challenges and opportunities for resource recovery. This study investigated the physicochemical, mechanical, and heavy metal characteristics of sewage sludge and five natural soils (Soil-A, Soil-B, Soil-C, Soil-D, and Soil-E) to assess their potential for environmental and geotechnical applications. Key physicochemical parameters, including pH, electrical conductivity (EC), and concentrations of Cu, Zn, Pb, Ni, Cr, and Cd, were analyzed to evaluate soil quality and environmental safety. Sewage sludge exhibited slightly alkaline pH (7.9–8.2) and higher EC (2.45 mS/cm) compared to natural soils (pH 6.4–7.2, EC 0.35–1.15 mS/cm), reflecting elevated organic matter and soluble ions. Mechanical properties were assessed through unconfined compressive strength (UCS), shear strength, bulk density, and moisture retention. UCS values ranged from 55 kPa (sludge) to 360 kPa (Soil-E), while shear strength varied from 28 kPa to 138 kPa. Partial sludge addition (5–10%) improved UCS and cohesion due to enhanced particle bonding, but proportions beyond 15% reduced mechanical stability because of higher moisture and organic content. Bulk density increased with mineral-rich soils (1.05–1.75 g/cm^3), whereas sludge addition reduced density due to air entrainment. Moisture retention was highest in sludge (~52.8%) and lowest in Soil-E (~25.8%), reflecting the water-holding capacity of organic matter. Overall, the study demonstrated that treated sewage sludge can serve as a sustainable soil amendment or engineering fill material when optimally incorporated, balancing mechanical stability with environmental and hydrological benefits.

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Keywords: Wastewater sludge, Soil amendment, Heavy metal bioavailability, Geotechnical properties, and Unconfined compressive strength.

1. INTRODUCTION

Sludge generation is an inevitable consequence of wastewater treatment processes worldwide. With the rapid expansion of urban centers, industrial activities, and modernized sewerage networks, the volume of sludge produced annually has increased substantially. Globally, it is estimated that about 20×10^{12} kg of sludge (equivalent to 30 million tons) is generated each year, with roughly 70% of this material being disposed of on land [1]. Wastewater sludge, commonly referred to as biosolids, is an organic-rich byproduct that typically contains more than 50% organic matter, along with considerable amounts of nitrogen (2–7%) and phosphorus (1–5%, equivalent to 2–10% P_2O_5). These characteristics render sludge a potentially valuable resource for agricultural applications, including soil fertility enhancement and micronutrient supplementation [2]. However, the practical use of sludge in agriculture is constrained by its content of heavy metals and other potentially toxic elements, which may pose risks to both environmental and human health. The chemical composition of wastewater sludge is highly variable, depending on the source of the wastewater, treatment methods employed, and operational conditions at treatment plants [3]. Metals such as copper (Cu), cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb), and zinc (Zn) are frequently reported in sludge, arising from domestic, industrial, and stormwater inputs. These metals can accumulate in soils following sludge application, where their mobility and bioavailability depend on physicochemical interactions with soil constituents, organic matter, and mineral phases [4]. Studies have consistently highlighted that the environmental risks associated with sludge application are largely determined by metal speciation rather than total metal content, underscoring the need for a mechanistic understanding of metal behavior in sludge-amended soils [5], [6]. Agricultural application remains one of the most common sludge disposal strategies worldwide. In Europe, countries such as Denmark, France, and Sweden report that more than 30% of total sludge produced is applied to farmland, while the United Kingdom applies nearly 40% of its sludge to arable and pasture lands annually [7]. Similar trends are observed in North America, where land application represents a major sludge management approach. With the discontinuation of ocean disposal and increasingly stringent environmental regulations, the proportion of sludge applied to land is expected to grow, making it essential to assess its potential benefits and

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environmental risks comprehensively. Regulatory frameworks exist to limit the introduction of potentially harmful metals into soils, yet no universally enforceable limits for trace metals in sludge have been established. Consequently, evaluating sludge quality before land application is critical for ensuring environmental safety [8]. The use of sludge as a bio-fertilizer has gained traction due to its capacity to improve soil fertility, enhance water retention, and supply essential nutrients. Sludge can be applied directly to land or processed into value-added products, including compost, fertilizer pellets, or liming agents, often in combination with amendments such as cement kiln dust [9]. By converting sludge into stabilized products, nutrient availability can be enhanced while reducing the potential for pathogen proliferation and odor generation. However, the long-term impact of sludge application on soil metal accumulation remains a topic of ongoing concern. The bioavailability of heavy metals in soil is primarily determined by the fraction present in water-soluble and exchangeable forms, which are most readily assimilated by plants. While total metal concentrations provide a useful indication of contamination, they are not always predictive of plant uptake due to variations in soil properties, environmental conditions, and plant physiology [10]. Empirical evidence demonstrates that metals can remain bioavailable for several years following sludge application, potentially leading to elevated concentrations in plant tissues and subsequent entry into the food chain [11]. A detailed understanding of metal speciation in both sludge and sludge-amended soils is therefore essential for evaluating potential environmental risks and informing sustainable management strategies. Metals within sludge are partitioned into different chemical forms during treatment, influenced by both biological and physicochemical processes. These forms, or fractions, include exchangeable metals, metals bound to organic matter (oxidizable), metals associated with carbonates (acid-soluble), metals linked to oxides and hydroxides (reducible), and metals integrated into silicate and detrital phases (residual). The chemical behavior and mobility of these fractions differ markedly, which directly affects the bioavailability of metals once sludge is applied to soils [12]. Understanding these associations is critical not only for environmental risk assessment but also for optimizing the beneficial reuse of sludge as a soil amendment. The increasing production of municipal sludge globally underscores the need for sustainable management practices. Urbanization, industrial expansion, and improvements in wastewater treatment efficiency have collectively contributed to rising sludge volumes. Observations from several countries indicate that, under controlled conditions, metal concentrations in sludge are generally below regulatory limits. Singh et al. (2023) [13]

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demonstrated that enforcement of industrial discharge standards and wastewater treatment controls can significantly reduce the concentrations of metals in sludge, rendering it safer for land application. Nonetheless, continuous monitoring and evaluation remain essential to ensure environmental compliance and to prevent the accumulation of potentially toxic metals in soils over time. The present study, therefore, addresses two critical aspects of sludge management: the mechanical enhancement of soils and the environmental implications of metal accumulation. By examining the dual objectives of improving soil load-bearing capacity and mitigating erosion while evaluating heavy metal bioavailability and mobility, this research contributes to the sustainable and safe utilization of wastewater sludge. The findings are expected to inform both agricultural management practices and regulatory frameworks, providing a basis for optimizing the reuse of sludge in a manner that maximizes benefits while minimizing environmental hazards. In conclusion, wastewater sludge represents a valuable, yet complex, resource for soil management. Its high organic and nutrient content can enhance soil fertility and structural performance, but the presence of heavy metals necessitates careful assessment of environmental risks. Understanding metal speciation, mobility, and bioavailability is essential to ensuring the safe application of sludge to soils. This study aims to contribute to this knowledge base by evaluating the suitability of treated wastewater sludge as a sustainable soil amendment capable of enhancing soil strength, reducing erosion, and maintaining environmental safety.

2. MATERIALS AND METHODS

2.1 Sampling location and collection

The Sewage Treatment Plant (STP) located within the premises of Sathyabama University, Chennai, Tamil Nadu, treats both domestic and institutional wastewater generated from hostels, academic buildings, and nearby residential areas. The treated effluent is discharged through a designated channel into the Pallikaranai Marshland system, while the sludge generated from the treatment process undergoes anaerobic digestion followed by sun drying. The resulting dried sludge is commonly used as organic manure for agricultural and horticultural purposes in nearby areas. Representative soil samples were collected from the following locations:

- Soil A – Semmancheri Village
- Soil B – Navalur area (adjacent to Old Mahabalipuram Road)
- Soil C – Sholinganallur agricultural field

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- Soil D – Perumbakkam area near Pallikaranai wetland
- Soil E – Thoraipakkam village, along the southern corridor of Chennai

Bulk samples of wastewater sludge were directly obtained from the Sewage Treatment Plant (STP) located within Sathyabama University, Chennai, Tamil Nadu. This plant treats domestic and institutional wastewater generated from the university campus and nearby residential areas. Soil samples from sludge-amended agricultural fields were collected from predetermined sites where the application of treated sludge as organic manure is routinely carried out. The sampling procedure followed the IUPAC standard method [14]. Each site was divided into 20 grid units of approximately equal size, and about 250 g of soil was collected from the central portion of each grid. These subsamples were thoroughly mixed to obtain a composite soil sample weighing approximately 5 kg for each site. The twenty subsamples were initially collected in clean polythene bags and subsequently combined into a larger bag to represent the composite field-moist soil sample for each location. Each sample was properly labeled with an identification code corresponding to its site location. A schematic representation of the sampling procedure is provided in Figure 1. From each site, surface soil (0–20 cm) and sub-soil samples (20–40 cm and 40–60 cm) were collected from the same profile using a stainless-steel auger to avoid contamination. The soils were air-dried and exposed to open air for three months to allow for natural compaction, during which moisture was maintained through periodic sprinkling of water to simulate field conditions. All soil samples from the representative sites were transferred into a large plastic tray and thoroughly mixed. The bulk soil was homogenized by tapping with a wooden pestle and remixed several times. The standardized bulking procedure was carried out using the coning and quartering method, repeated until the desired sample size was obtained. The samples were subsequently oven-dried at 60°C overnight to ensure that all experimental results were expressed on an oven-dry mass basis. This drying process also minimized potential chemical and microbial alterations.

2.2 Physico-Chemical Properties

Selected physicochemical parameters were determined using air-dried samples, except moisture content (%) and water-holding capacity (%), which were measured in field-moist samples. The pH and electrical conductivity (EC) were determined in a 1:10 (w/v) soil-to-water suspension using a digital pH meter and a conductivity meter, respectively. Soil organic matter

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content was assessed by the loss-on-ignition method. All physicochemical analyses were conducted following standard analytical procedures as described by Laoufi et al, 2025 [15].

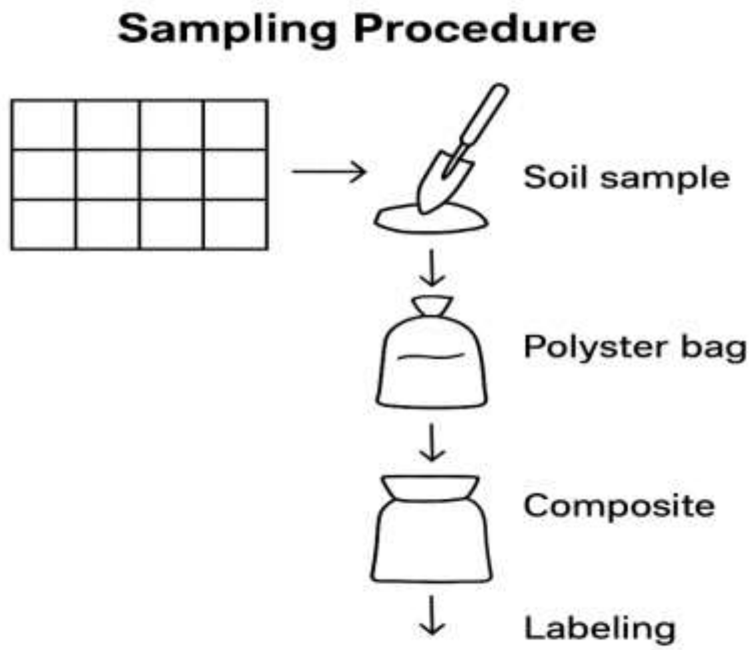

Figure 1 - Sampling procedure for analysis

2.3 Metal and Sequential Extraction

Laboratory glassware and polyethylene bottles were pre-cleaned with HCl and rinsed thoroughly with double-distilled water following the procedure outlined by Larrea et al, 2025 [16]. All metal extractions were carried out in triplicate using 5% HNO_3 acid-washed polycarbonate labware. Analytical reagent-grade chemicals were used for all procedures. Metal analysis included both total metal determination and sequential extraction for fractionated metals. The total metal content in sludge and sludge-amended soils was determined by aqua regia digestion, and concentrations were quantified using an atomic absorption spectrophotometer. One gram of the sample was mixed with 15 mL of aqua regia (3:1 concentrated HCl to concentrated HNO_3) in a reflux flask and heated under reflux at slightly below the boiling point for two hours. The digest was cooled to room temperature, diluted to a final volume of 50 mL with double-distilled water, centrifuged, and filtered. The clear filtrate was stored in polyethylene bottles for further analysis. In this study, two extraction approaches were undertaken to differentiate metals according to their binding forms. The sequential extraction procedure was designed to separate metals into

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operationally defined fractions, including exchangeable, oxidizable (associated with organic matter), acid-soluble (bound to carbonates), reducible (associated with Fe and Mn oxides or hydroxides), and residual (bound to silicate or detrital matrices). Triplicate one-gram sub-samples of wastewater sludge and sludge-amended soils were individually processed using a sequential extraction technique. Each extraction step was followed by centrifugation at 4500 rpm for 15 minutes. The supernatant was removed using a pipette and passed through a Whatman No. 42 filter paper. The residue was subsequently washed with a small amount of deionized water, shaken manually, and centrifuged again for 15 minutes before proceeding to the next stage of extraction.

2.4 Mechanical Performance Analysis

The mechanical behavior of sludge-amended soils was evaluated using standard laboratory tests: Unconfined Compressive Strength (UCS)- Cylindrical specimens (50 mm diameter × 100 mm height) of each sludge-soil mixture were prepared, compacted, and cured for 7, 14, and 28 days. UCS tests were performed using a universal testing machine at a constant strain rate, and peak stress values were recorded to assess load-bearing capacity. Direct shear tests were conducted on square specimens (60 mm × 60 mm × 20 mm) using a standard shear box apparatus. Normal stresses of 50, 100, and 150 kPa were applied, and the corresponding shear stress at failure was measured to determine cohesion (c) and internal friction angle (φ) of the sludge-amended soils. Bulk density (ρ_b) was measured by oven-drying known-volume soil specimens at 105°C until constant weight. Changes in bulk density due to sludge addition were analyzed to understand compaction behavior. Moisture retention characteristics were determined using the gravimetric method. Soil samples were saturated and allowed to drain under controlled conditions, and the moisture content at field capacity and wilting point was recorded to assess water-holding capacity. Figure 2 shows the complete experimental analysis of this research study.

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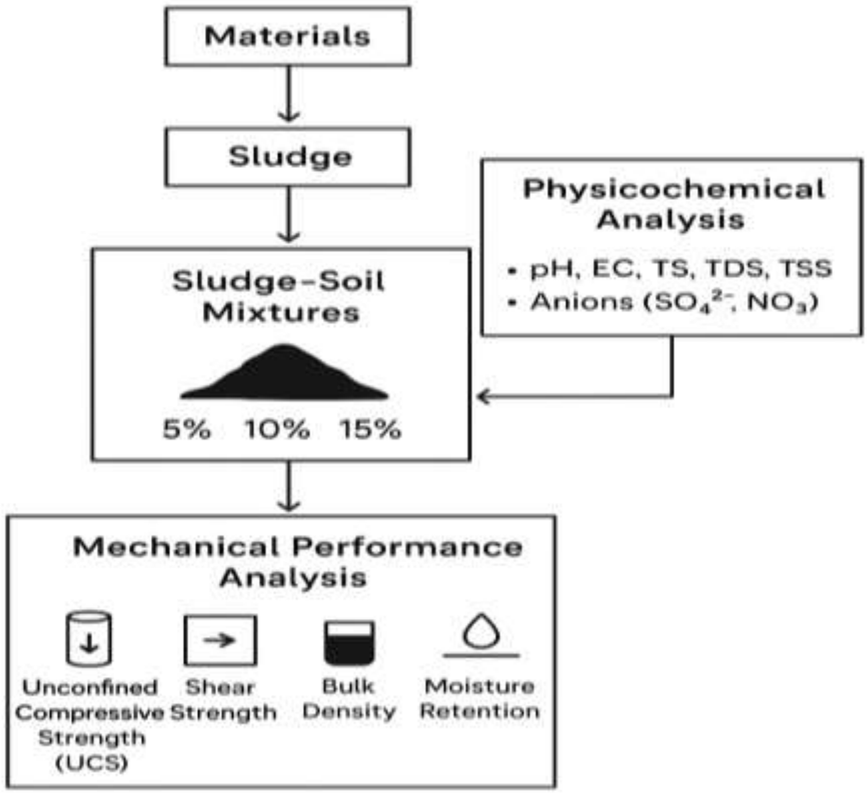

Figure 2 – Experimental study of mechanical performance analysis

3. RESULTS AND DISCUSSION

3.1 Physico-chemical properties

To assess physicochemical characteristics, representative wastewater sludge and soil samples were collected from different sites. Data presented in Figure 3 show that the sludge had an alkaline character, with an average pH of 9.1. The pH of soils amended with sludge varied between 6.8 and 8.6, suggesting slightly acidic to alkaline conditions. Organic matter content in the sludge reached 36.2%, which is 3–6 times higher than in sludge-treated soils. These results indicate that wastewater sludge is rich in organic material. Consequently, short-term modifications in soil properties after sludge application are likely due to organic enrichment and microbial humification processes. Over time, as these organic compounds degrade, their effects tend to subside. The electrical conductivity (EC) of wastewater sludge was measured at 0.56 mS/cm, whereas the soil samples exhibited EC values ranging from 0.34 to 0.87 mS/cm. The relatively higher conductivity observed in the sludge-amended soils may result from the recent application of sludge containing dissolved salts. The moisture content (MC) and water-holding capacity (WHC) of the wastewater

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sludge were 32% and 51%, respectively. In sludge-amended soils, these parameters varied from 24–42% for MC and 54–73% for WHC. The MC data suggest that fine-textured soils, which possess a high proportion of fine pores and moderate to high available water-holding capacity, maintain considerable permeability even under compacted conditions. The trends in the variation of physical properties are presented in Figure 3. Both WHC and MC exhibited noticeable variation across soil samples, likely influenced by environmental factors and biological processes. The physicochemical parameters were also found to depend on soil type and structure. As noted by Campillo-Cora et al, 2021 [17], characterization of these properties provides valuable insight for predicting the distribution of metals among different soil fractions.

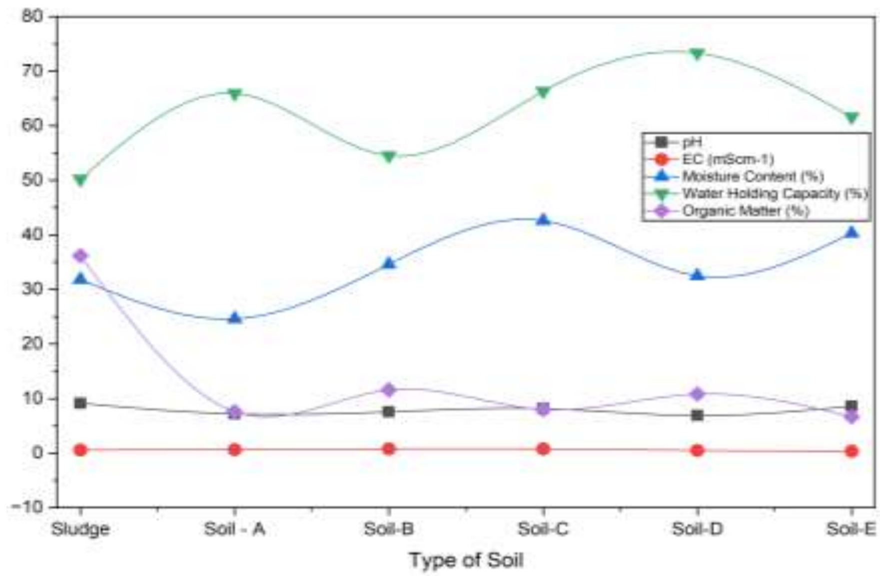

Figure 3 - Variations of physical-chemical characteristics for different types of soil

3.2 Total Metal Content

The acid digestion results showed that wastewater sludge contained more metals than the soils treated with sludge. The total metal concentrations in the sludge were 321.3 mg/kg for Cu, 408.5 mg/kg for Zn, 109.3 mg/kg for Pb, 127.2 mg/kg for Ni, 161.5 mg/kg for Cr, and 15.3 mg/kg for Cd. The metals appeared in the following order: Zn > Cu > Cr > Ni > Pb > Cd. The pattern of metal occurrence differed in the sludge-amended soils, and variations were evident among all five soil samples analyzed. The total concentrations of metals in the soils were within the ranges of 120.5–211.8 mg/kg for Cu, 149.2–337 mg/kg for Zn, 27.7–71 mg/kg for Pb, 46.5–136.2 mg/kg for Ni, 105.5–169.3 mg/kg for Cr, and 5.5–11.8 mg/kg for Cd, as presented in Figure 4. Among the

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analyzed soils, all except one exhibited the highest Zn concentration, while Cu reached its maximum level in Soil E (211.8 mg/kg). The total Zn concentration across the soils ranged from 149.2 to 337 mg/kg. A distinguishing feature was the consistently low Cd content in all samples. The patterns of Cu, Zn, and Cd were generally uniform across the sites, whereas Ni, Cr, and Pb displayed noticeable variation.

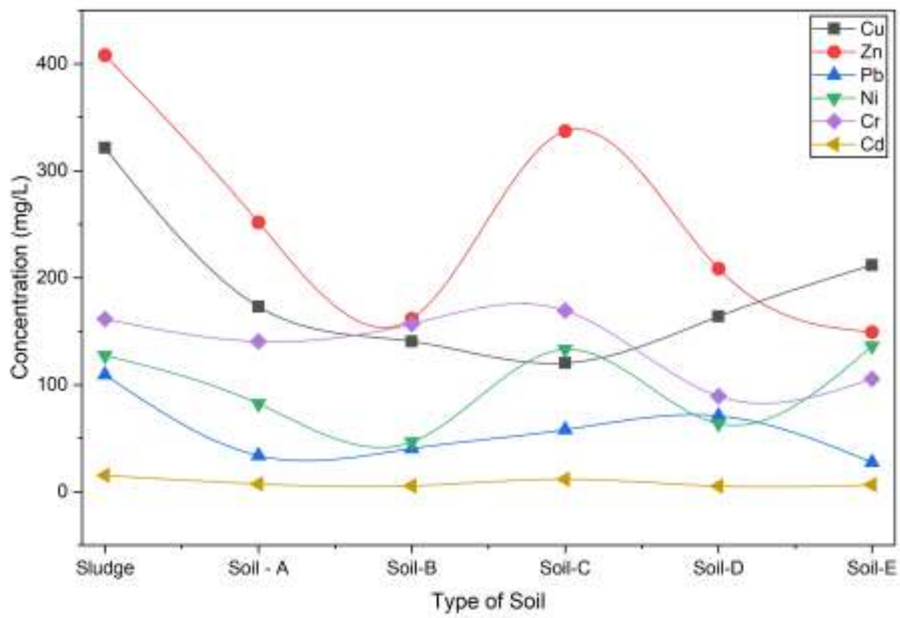

Figure 4 - Variations of metal ion concentrations for different types of soil

3.3 Sequential Extraction Scheme-A Versus Scheme-B

During the sequential extraction process, special care was taken in selecting reagents and leaching conditions to achieve the best possible selectivity for each step. The adopted procedures were based on established soil analysis methods and recent research on metal distribution in sludge and sludge-treated soils [18]. However, it is important to note that extractants used in such schemes are not perfectly selective; metals can seldom be extracted exclusively from the specific phase intended for attack by the chosen reagent. The outcomes of the two sequential extraction schemes are reported in Table 1, where the mean concentrations and corresponding standard deviations of three replicate analyses are expressed in mg/kg. The fractionation scheme developed here is suitable for identifying the chemical forms of metals in sludge, both native and introduced through soil amendment. The sequential extraction procedure thus provides a practical means to infer the relative mobility and bioavailability of metals in soils amended with wastewater sludge [19]. The results indicated that the fractionation schemes provided satisfactory metal recoveries. The sum of

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the fractions compared well with total metal concentrations obtained by soil digestion, yielding sum-to-total ratios of 1.02, 1.04, 1.07, 0.94, 1.06, and 1.12 for Cu, Zn, Pb, Ni, Cr, and Cd, respectively, under Scheme A, while Scheme B produced an average ratio of 1.00. In sludge-amended soils, Scheme A yielded higher ratios (1.08–1.24), whereas Scheme B again averaged 1.00. These findings suggest that Scheme A results in slightly higher recoveries than aqua regia digestion, reinforcing the interpretation that aqua regia provides only a pseudo–total measure of metal content [20]. The recovery efficiency of metals from the sequential extraction method was calculated by comparing the total amount of extracted metals with the independently measured total metal contents. For wastewater sludge, Scheme A gave recovery rates of 102%, 104%, 107%, 94%, 106%, and 112% for Cu, Zn, Pb, Ni, Cr, and Cd. Scheme B showed 100% recovery, as the residual part was taken as the total metal content minus the non-residual fractions. In sludge-treated soils, Scheme A recoveries were 108 ± 6%, 102 ± 5%, 115 ± 8%, 111 ± 4%, 104 ± 7%, and 124 ± 28%. While there were slight differences between samples, the metal fractionation pattern remained mostly consistent. A comparison of metal extractability (non-residual vs. residual fractions) between the two sequential extraction schemes was performed for both wastewater sludge and sludge-amended soils (Figures 5 - 6). Results demonstrate that Scheme A provides more reliable data for the non-residual fractions, which are environmentally relevant since these metals are potentially mobile under changing soil conditions. The non-residual fractions obtained through Scheme A in wastewater sludge were 39%, 49.7%, 27.2%, 38.6%, 20.9%, and 34.3% for Cu, Zn, Pb, Ni, Cr, and Cd, respectively. Scheme B yielded slightly lower values of 29.1%, 38.3%, 29.8%, 25.9%, 20.3%, and 28.8%. In sludge-amended soils, the proportion of non-residual copper varied across the samples, ranging from 16.4% to 30.6% under Scheme A and from 10.9% to 22.1% under Scheme B. This consistent difference indicates that Scheme A provides a more effective and representative estimation of the non-residual fraction than Scheme B. Thus, a higher concentration of metals can be extracted using Scheme A across different phases or fractions. This approach enables a more accurate estimation of the actual metal fractions present in the soil system, thereby improving the assessment of metal mobility and bioavailability under natural environmental conditions. Variations were observed in the mass balance, defined as the sum of metals in all fractions relative to the total content. These discrepancies are attributed mainly to soil heterogeneity caused by differences in particle size [21]. Therefore, metal partitioning was calculated using the total metal values obtained from each sequential extraction method instead of

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the totals shown in Figure 7. As shown in Table 1, Scheme A produced notably higher non-residual fraction values compared with Scheme B. This difference primarily reflects the variation in leaching agents used in the two procedures. For the exchangeable fraction, two distinct reagents were utilized, which caused slight metal-specific differences in extraction results. The exchangeable fraction holds particular environmental importance, as it represents the most mobile and easily available metal form within the soil matrix [22]. Results indicated that the residual fraction of metals generally increased with total metal concentration. This trend is unexpected, as the residual fraction reflects the natural metal composition of the soil matrix and would not typically vary in direct proportion to the total metal concentration in soils treated with sludge. The rise in residual metal concentration may be linked to the physico-chemical characteristics of the original contamination, with certain components remaining strongly bound in the soil and resistant to extraction by all but total dissolution methods [23]. Consequently, the sequential extraction technique provides significant information on both the magnitude and the relative rate of heavy metal release from soils under increasingly intensive chemical conditions.

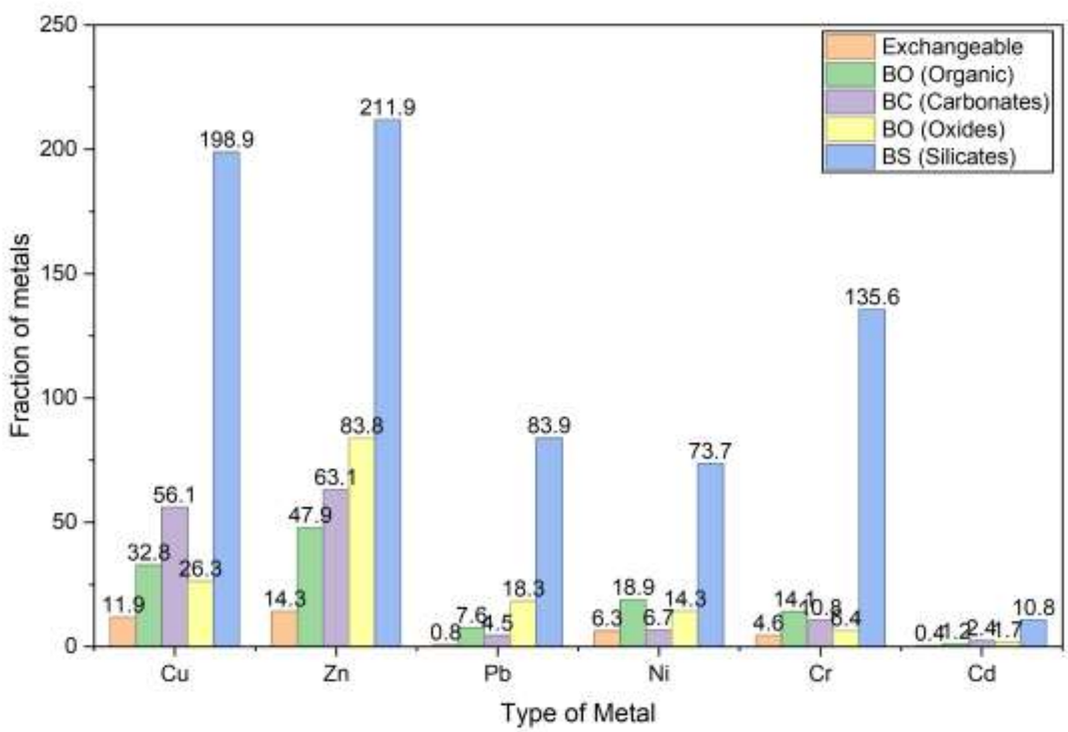

Figure 5 - Chemical fraction of metals – Scheme A

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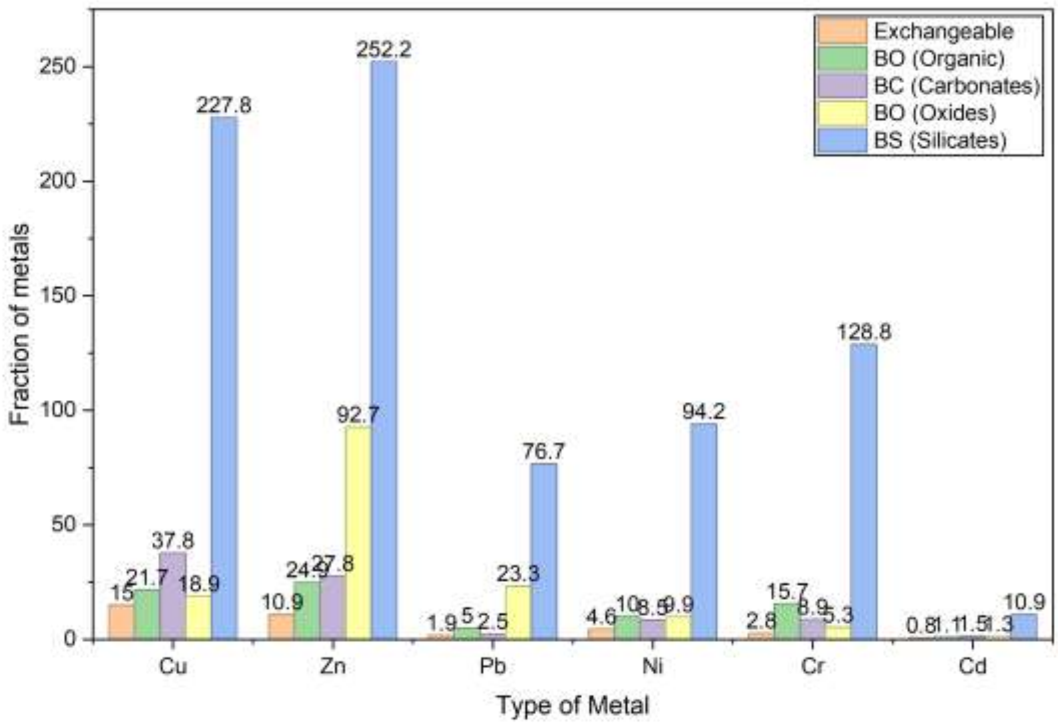

Figure 6 - Chemical fraction of metals – Scheme B

Table 1 - Distribution of Metals among the five fractions in Sludge and Sludge-amended Soils

Fractions	**SCHEME-A**						**SCHEME-B**					
	Sludge	**Soil-A**	**Soil-B**	**Soil-C**	**Soil-D**	**Soil-E**	**Sludge**	**Soil-A**	**Soil-B**	**Soil-C**	**Soil-D**	**Soil-E**
EXCH Cu	3.6	1.7	1.2	1.4	3.2	0.2	4.7	2.6	2.4	1.9	4.7	0.9
Zn	3.4	2.6	1.2	2.9	2.4	1.6	2.7	1.4	0.6	1.5	1.2	1.1
Pb	0.8		1.2	2.8	3.3		1.7		1.1	3.6	2.6	
Ni	5.3	4.7	6.2	2.4	3.7	3.9	3.6	6.2	9.4	3.1	1.9	2.7
Cr	2.7	1.9	2.8	3.4	0.6	0.4	1.7	1	2.1	1.5	1.3	0.6
Cd	2.4	4.1		8.2		7.5	3.9	13.7		24		12.4
OXID Cu	10.1	7.5	8.3	11.8	8.6	7.6	6.8	4.3	4.5	10.7	3.2	2.2

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Zn	11.4	15.9	6.1	7.4	4.7	4.7	6.1	9.5	3.7	5.4	3.2	2.5
Pb	6.6	7	6.6	6.9	6.8	2.8	4.6	2.2	6.3	1.3	4.1	1.7
Ni	15.8	7.5	4.2	4.3	5	6.4	7.9	6	4.2	3.9	2.2	5
Cr	8.2	11	9	10.8	13.1	7.9	9.7	8.7	6.4	8.5	10.2	7.3
Cd	7.3			16.8		14.9	7			10.3		11.3
ACID Cu	17.2	5.4	5.9	10.3	5.7	5.1	11.8	3.9	3.8	4	2.3	1.6
Zn	15	3.9	9.2	5.1	8.2	9.2	6.8	2	5.3	1.8	5.4	4.4
Pb	3.9	8.7	11.9	10.8	10.2	10.9	2.3	6.5	8.8	4.8	5.3	10.1
Ni	5.6	4.4	3.2	10	13.7	10	6.7	2	1.1	2.1	6.1	7.2
Cr	6.3	5	7.7	3.6	5.6	4.8	5.5	3.3	4.3	1.9	3.4	3.6
Cd	14.4	8.9	20.2	9.5	11.1		9.6	26.5	31.7	20.6	28.8	
RED Cu	8.1	4.2	4.6	7.2	3.6	3.5	5.9	3.3	2.2	5.5	2.7	6.2
Zn	19.9	6.2	15.9	6.7	15.4	16	22.7	4.8	19	3.7	12.1	21.3
Pb	15.9	32.5	22.7	17.1	15.7	29.1	21.3	26.7	17.2	28.8	15	19.7
Ni	11.9	15.1	21.1	14.1	20.1	15.5	7.8	24.4	34	18	27.6	20
Cr	3.7	6	5.9	7	2.9	3.2	3.3	8	4.9	7.9	6.1	2.3
Cd	10.1	11.6	6.7	5.9		18	8.3	17.4	9.8	4		26.8
RESD Cu	61	81	80	69.4	78.9	83.6	70.9	85.8	87.1	77.9	87.1	89.1
Zn	50.3	71.5	67.7	77.9	69.2	68.5	61.7	82.3	71.5	87.5	78.1	70.7
Pb	72.8	51.8	57.6	62.3	64	57.1	70.2	64.6	66.7	61.5	72.9	68.5
Ni	61.4	68.3	65.2	69.2	57.4	64.2	74.1	61.4	51.4	72.9	62.2	65.1
Cr	79.1	76.1	74.6	75.2	77.8	83.7	79.7	79	82.4	80.1	79	86.2
Cd	65.7	75.3	73.1	59.5	88.9	59.6	71.2	42.5	58.5	41.1	71.3	49.5

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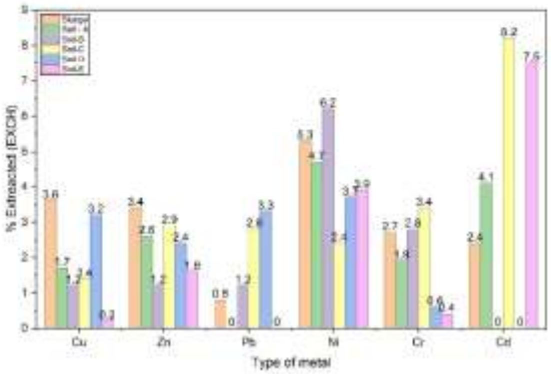

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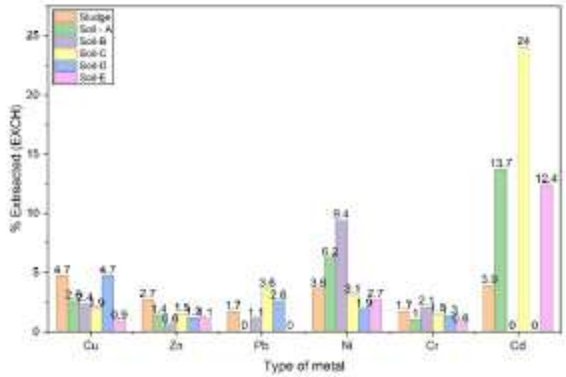

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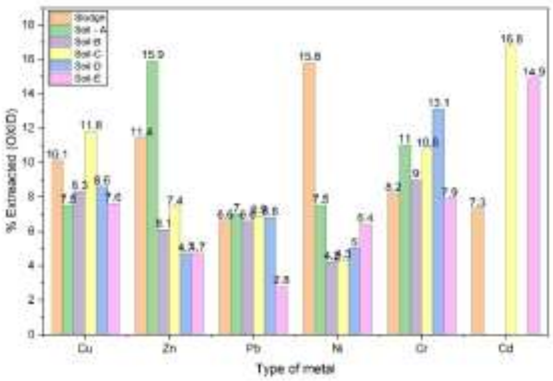

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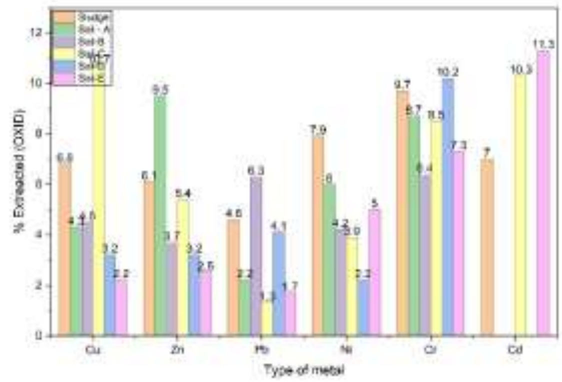

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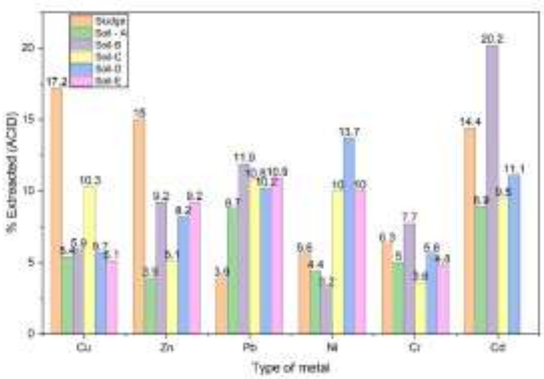

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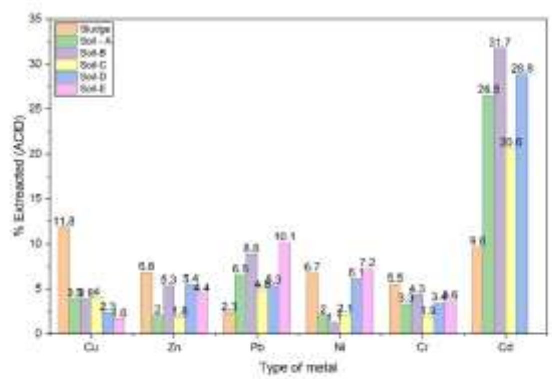

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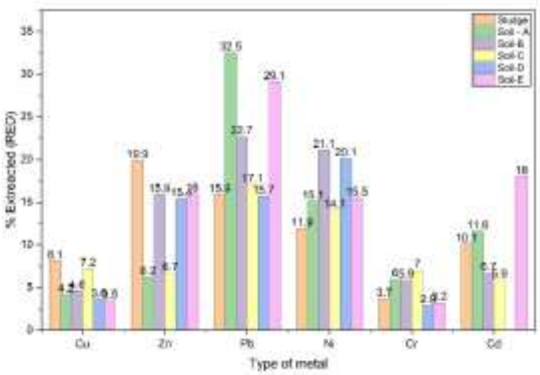

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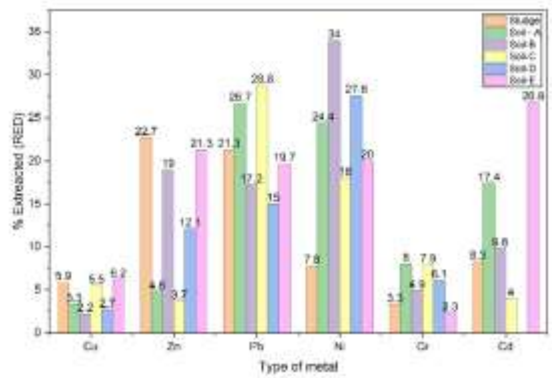

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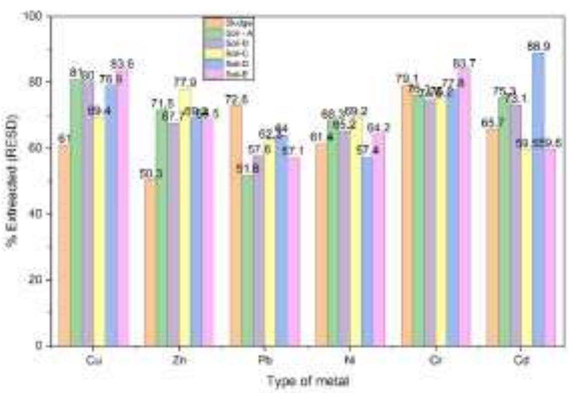

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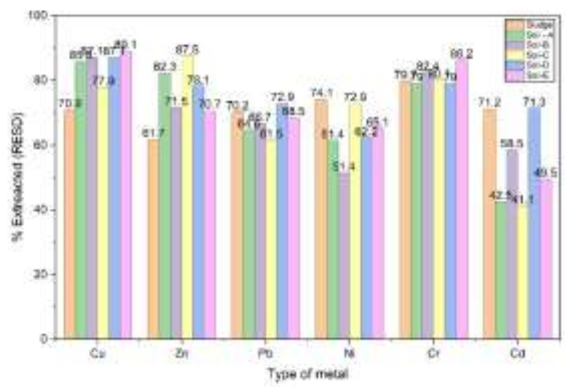

(j)

Figure 7 – Extraction of metals for Schemes A and B – (a) & (b) – Exchangeable, (c) & (d) – Oxidation, (e) & (f) Acid, (g) & (h) Reduction, and (i) & (j) Residual, respectively

3.4 Metals Mobility

Figure 8 shows the total metal counts for different types of soils. Before the lysimeter study, the average total concentrations of Cu, Zn, Pb, Ni, Cr, and Cd in the sludge-amended soil were 182.1, 273.5, 47.2, 71.2, 153.9, and 11.1 mg/kg in the top layer; 157.4, 295.7, 23.2, 53.1, 137.1, and 5.9 mg/kg in the middle layer; and 131.4, 153.1, 13.4, 27.9, 80.6, and 1.5 mg/kg at the bottom (Table 2). Metal levels generally decreased with depth, except for Zn, which was highest in the middle layer, indicating its higher mobility relative to other metals. In the initial stage of the experiment, water was used to elute the lysimeter, causing most soluble metals in the sludge-amended soil to be mobilized into the percolated leachate. Trace levels of Cd (0.02–0.04 mg/L), Cr (0.02–0.06 mg/L), and Pb (0.02–0.05 mg/L) were observed, whereas Zn (0.02–0.08 mg/L), Ni (0.02–0.07 mg/L), and Cu (0.02–0.09 mg/L) were leached at comparatively higher concentrations. The detection of metals in the leachate indicates that metals in sludge-amended soils are mobile.

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The leaching and downward movement of metals applied as sludge through soil layers have been a subject of study for several years, with many researchers concluding that such processes can lead to groundwater contamination. Direct measurements of metal concentrations in percolated water remain limited, and earlier studies Gerelt-Od et al, 2025 [24] often reported concentrations below the detection limits of instruments available at that time. When the mixed metal solution was introduced during the second experimental phase, the concentration of metals detected in the leachate increased only marginally. This demonstrates that the soil profile retained a substantial proportion of the applied metals. The recorded concentration ranges were Cu (0.22–0.44 mg/L), Zn (0.52–0.94 mg/L), Pb (0.06–0.18 mg/L), Ni (0.11–0.66 mg/L), Cr (0.31–0.48 mg/L), and Cd (0.02–0.14 mg/L). The slight increase in Cu, Zn, Ni, and Cr levels, relative to Pb and Cd, suggests that these metals were more mobile within the soil system. The leachate showed a significant increase in Cu, Zn, and Ni concentrations, with Cu concentrations approximately doubling. However, the overall leaching of metals was still negligible compared to the total amount introduced into the soil. The sludge solution generally promoted higher metal mobility in the sludge-amended soils. This behavior can be attributed to several interacting factors, such as increased background levels of metals and ions and a higher ionic strength of the soil solution following amendment. A comparable pattern was observed in soils treated with wastewater sludge, supporting the observations of Rahman et al, 2023 [25], who found that metal mobility rises when metal adsorption in the soil is reduced. During the final experimental phase, soil samples from the surface, middle, and bottom lysimeter layers were analyzed for total metal content using the same method as before the experiment. the concentrations of Cu, Zn, Pb, Ni, Cr, and Cd were 332.5, 375.1, 211.2, 153.5, 381.1, and 159.3 mg/kg in the surface layer; 207.7, 410.3, 54.6, 176.3, 173.7, and 59.2 mg/kg in the middle layer; and 147.1, 166.5, 22.9, 43.2, 109.1, and 20.0 mg/kg in the bottom layer. The results demonstrate that metal accumulation decreases progressively with soil depth.

3.5 Mechanical Performance Analysis

Mechanical testing (UCS, shear strength, bulk density, and moisture retention) provided insights into the engineering suitability of sludge and sludge-amended soils.

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Table 2 - Total Metals Content (mg/kg) in the Profile of the Sludge-amended soil before and after the Lysimeter Experiment. (Mean ± SD, n=3)

Metals	Before Experiment			After Experiment		
	Top Soil Layer	Middle Soil Layer	Bottom Soil Layer	Top Soil Layer	Middle Soil Layer	Bottom Soil Layer
Copper	182.1 ± 9.7	157.4 ± 9.0	131.4 ± 10.0	332.5 ± 9.7	207.7 ± 10.8	147.1 ± 8.6
Zinc	273.5 ± 7.7	295.7 ± 7.0	153.1 ± 9.0	375.1 ± 10.0	403.3 ± 16.9	166.5 ± 7.5
Lead	47.1 ± 8.6	23.2 ± 5.3	13.4 ± 4.9	211.1 ± 7.4	54.6 ± 8.8	22.9 ± 6.1
Nickel	71.2 ± 10.8	53.1 ± 8.9	27.9 ± 6.8	153.5 ± 8.3	176.3 ± 11.3	43.2 ± 4.9
Chromium	153.9 ± 10.0	137.1 ± 9.1	80.6 ± 11.1	381.1 ± 6.3	173.7 ± 12.1	109.1 ± 6.9
Cadmium	11.1 ± 3.4	5.9 ± 2.5	1.5 ± 0.7	159.3 ± 8.1	59.2 ± 8.0	20.0 ± 5.2

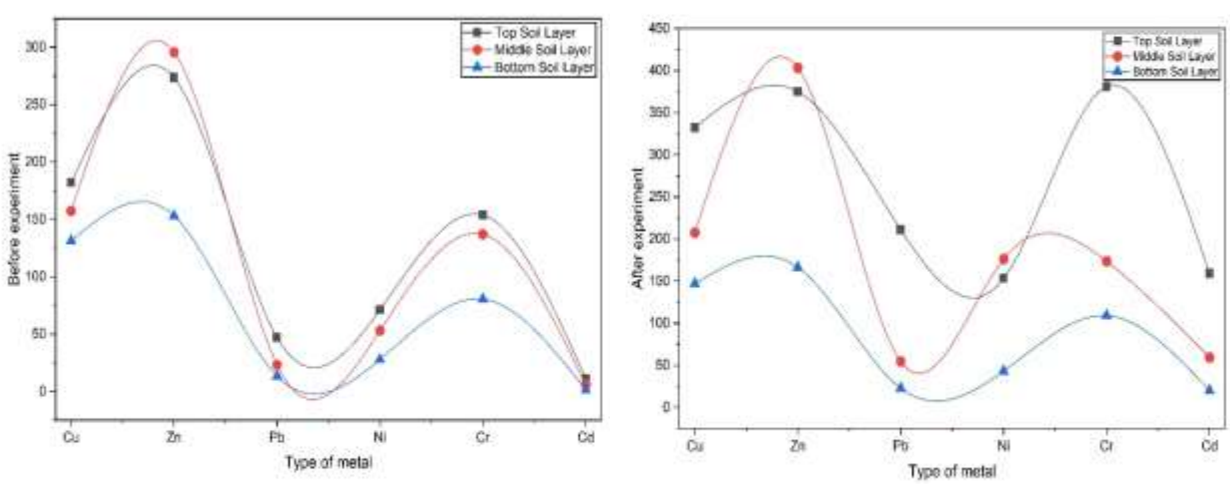

Figure 8 – Total metals count (mg/g) – before and after treatment process

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3.5.1 Unconfined Compressive Strength (UCS)

The unconfined compressive strength is a primary indicator of the load-bearing capacity and structural integrity of soils. The UCS of the pure sludge sample was found to be very low (≈55 kPa), which can be attributed to its high organic matter content, weak particle bonding, and elevated moisture level. The sludge's gelatinous nature and fine texture limited its ability to resist deformation under axial stress. Among the natural soils, Soil-E exhibited the highest UCS value (≈360 kPa), followed by Soil-D (315 kPa), Soil-C (265 kPa), Soil-B (195 kPa), and Soil-A (135 kPa). The progressive increase in UCS from Soil-A to Soil-E correlates with decreasing organic content, higher mineral (sand/silt) fractions, and denser packing of particles. When sludge was introduced into the soil matrix (in the range of 5–15% by weight), the UCS values initially improved up to 10% addition. This improvement is attributed to the cementitious bonding developed between organic colloids and fine soil particles, enhancing cohesion [26]. However, beyond this threshold, the UCS decreased due to excess moisture and the lubricating effect of organic compounds that hindered particle interlocking. Overall, the UCS results indicate that moderate sludge incorporation (≤10%) can slightly enhance the compressive strength of fine-grained soils (A and B), while excessive incorporation significantly reduces load-bearing performance.

3.5.2 Shear Strength

Shear strength represents the soil's resistance to failure along internal planes and is governed by cohesion (c) and the angle of internal friction (φ). The sludge sample exhibited the lowest shear strength (~28 kPa), cohesion (~10 kPa), and friction angle (~12°), reflecting its soft, plastic nature and lack of granular interlocking. For the natural soils, both c and φ values increased consistently from Soil-A to Soil-E. The highest shear strength (138 kPa) and friction angle (29°) were recorded for Soil-E, primarily due to its dense structure and higher sand content, which improved interparticle friction. Soils A and B, being finer and more plastic, relied more on cohesive bonding than frictional resistance, while Soils C, D, and E showed a combined effect of cohesion and friction. In sludge-amended mixtures, a similar pattern to UCS was observed — low sludge additions (5–10%) slightly increased cohesion due to the binding effects of organic colloids, but higher sludge contents (>10%) led to a sharp reduction in both cohesion and friction angle, weakening the soil structure. The reduction occurs as excess organics form a slippery film between particles, reducing effective stress transfer during shear [27].

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3.5.3 Bulk Density

Bulk density is a measure of soil compactness and mass per unit volume, reflecting the internal packing and void ratio. The results show that sludge possessed the lowest bulk density (1.05 g/cm³) due to its high organic content, high porosity, and water retention. Among the natural soils, bulk density increased progressively from Soil-A (1.35 g/cm³) to Soil-E (1.75 g/cm³). This increase is linked to higher mineral content, lower organic matter, and denser particle arrangement. When sludge was added, the overall bulk density of the soil decreased, particularly beyond 10% sludge addition. This reduction can be attributed to the replacement of heavier mineral particles with lighter organic sludge components and the resulting increase in void spaces [28]. While reduced density can improve aeration and root penetration for agricultural applications, it is generally unfavorable for load-bearing structures, as it corresponds to lower compressive strength. Table 3 and Figure 9 show the mechanical strength of various soils.

Table 3 – Mechanical Performance analysis results

Property	Sludge	Soil - A	Soil - B	Soil - C	Soil - D	Soil - E
UCS (Kpa)	55	135	195	265	315	360
Shear Strength (Kpa)	28	62	84	108	125	138
Bulk density (g/cm^3)	1.05	1.35	1.45	1.60	1.70	1.75
Moisture retention (%)	52.8	38.4	35.2	30.1	28.5	25.8
Cohesion (Kpa)	10	28	34	42	48	52
Friction angle (°)	12	18	22	25	27	29

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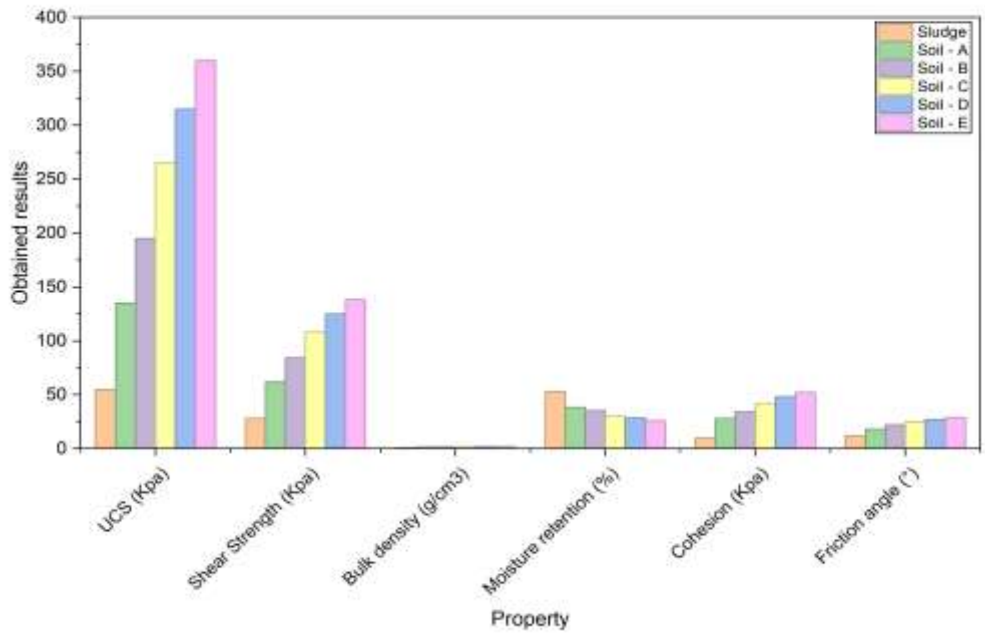

Figure 9 – Mechanical properties of different types of soils

4. CONCLUSION

This study demonstrated the dual potential of treated sewage sludge as both a soil amendment and an engineering fill material. Physicochemical analysis indicated that the sludge is slightly alkaline with high electrical conductivity and elevated concentrations of key metals, emphasizing the need for careful monitoring to mitigate environmental risks. Mechanically, sludge exhibited the lowest UCS and shear strength among the tested materials, while mineral-rich soils showed superior structural performance. Partial blending of sludge (5–10%) enhanced particle cohesion and marginally improved UCS, but higher sludge content (>15%) reduced soil stability due to increased moisture and organic matter. Bulk density and porosity analyses indicated that mineral-rich soils were more compact, whereas sludge addition reduced density and increased water retention, which can benefit agricultural applications but may limit geotechnical performance. Heavy metal content remained within environmentally acceptable limits, suggesting that treated sludge can be safely utilized under controlled conditions. Overall, the findings highlight that sewage sludge can contribute to sustainable soil management and erosion control, provided its incorporation is optimized to maintain mechanical stability while leveraging its nutrient and water-retention benefits.

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