JIGAWA JOURNAL OF
ENVIRONMENTAL AND EARTH SCIENCES
Federal University Dutse | Department of Environmental Sciences

Volume 1 • Issue 1 • November 2026 ISSN: 3093-8852 ISSN Online: 3093-8842

ORIGINAL RESEARCH ARTICLE

# Impact of polystyrene waste incorporation on the physicochemical properties and hydrological behavior of Sudan Savanna agricultural soils

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| RECEIVED | ACCEPTED | PUBLISHED |
|---|---|---|
| 19/08/2026 | 30/10/2026 | 02/11/2026 |

**How to cite:** Amoo Afeez Oladeji, Asaju Catherine Iyabode, Muhammad Ibrahim Kamilu, Adeleye Adeniyi Olarewaju, Umar Isah Ibrahim, Ismail Maryam, Ibraheem Saeed Saleem, Lawal Nabeela, Ijanu Emmanuel Madu, Haruna Aminu Ya'u, Bashir Suleiman Adamu, Isa Abass Muri, Ibrahim Mallam (2026). Impact of polystyrene waste incorporation on the physicochemical properties and hydrological behavior of Sudan Savanna agricultural soils. *Jigawa Journal of Environmental and Earth Sciences*, 1(1), 12–28.
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**ABSTRACT**

Expanded polystyrene (EPS) waste is an emerging concern for semi-arid agricultural soils, but its effects on soil properties are poorly documented. This pot experiment evaluated the effect of ground EPS (< 5 mm) on the emergence of cowpea in one homogenised composite sandy-loam topsoil from the teaching farm of the Federal University Dutse, Jigawa State, Nigeria at 0, 2 and 5 % (w/w, gravimetric, of the air-dry soil–EPS mixture). The experiment was conducted using a completely randomized design with three replicate pots per treatment (n = 3) and the soil was sampled at 0 WAT, 6 WAT, and 12 WAT; results from 12 WAT are reported. Treatments were compared by one-way ANOVA (df = 2, 6) with Tukey's HSD. Organic carbon (0.70, 0.02 and 0.12 %; $F = 134.80$, $p < 0.001$), available phosphorus (2.3, 18.9 and 2.53 mg/kg; $F = 67.44$, $p < 0.001$), aggregate stability (65.3, 48.7 and 32.5 %; $F = 49.51$, $p < 0.001$), available water capacity (13.8, 10.4 and 7.1 %; $F = 21.91$, $p = 0.002$) and water retained at 0.33 bar (22.4, 18.7 and 15.2 %; $F = 10.36$, $p = 0.011$) differed among treatments. Changes in pH ($p = 0.082$), sum of exchangeable bases ($p = 0.064$; CEC was not measured) and bulk density ($p = 0.126$) were not significant. No cowpea (Vigna unguiculata) emerged from either EPS treatment (0 seeds of 15) as compared to 15 of 15 in the control. The results indicate that the effect of EPS is highly detrimental to soil fertility, hydrological function and plant establishment, thus the need to have better plastic-waste management and remediation strategies to reduce the vulnerability of the agricultural systems of semi-arid regions to degradation.

**Keywords:** Expanded polystyrene (EPS); Secondary microplastics; Soil physicochemical properties; Soil hydrology; Cowpea emergence; Semi-arid agriculture

## Introduction

The presence of plastic wastes in the agricultural soil has emerged as a critical environmental concern in regions where waste management services are not readily

available and agricultural land is stressed (Aslam *et al.,* 2026; Raphael *et al.,* 2025). The production of plastics has also reached unprecedented levels, with over 450 million tonnes produced annually, of which much is transported to terrestrial environments through various pathways including agricultural mulching, wastewater irrigation, application of compost, and atmospheric deposition (Ayoub et al., 2026; Briassoulis, 2023; Garbounis *et al.,* 2026). One of the most common and problematic forms of plastic waste is plastic packaging, including expanded polystyrene (EPS), which are used for packaging, food containers and insulation materials (Lewanska & Barczynska, 2025; Rabelo *et al.,* 2025). EPS can persist in soils for an extended period and is believed to degrade into microplastic sized fragments (<5 mm) which can build up and impact soil ecosystems (Liu *et al.,* 2025; Mondol *et al.,* 2025). However, the supporting evidence is largely limited to micro plastics in general or other polymers; direct evidence for use of EPS in agricultural soils is limited, and the effects reported on other polymers do not necessarily match those of EPS.

The Sudan Savanna region of West Africa encompasses parts of Nigeria, Niger, Chad and Mali, characterized by semi-arid climate, low inherent organic matter and nutrient content in soils, and high susceptibility to degradation (Alhassan *et al.,* 2021; Chomba *et al.,* 2020; Nguru *et al.,* 2026). Likewise, Adeleye *et al.* (2021), Amoo *et al.* (2026), and Nkereuwem *et al.* (2022, 2024) have shown that organic amendments are effective for bioremediation of agricultural soils contaminated by other pollutants in Nigerian soils and could also be examined in the context of microplastic-contaminated soils. In this area, agricultural systems are already challenged by low soil fertility, water scarcity and increasing climate variability, and could be vulnerable to further stresses from plastic contamination. Chronic plastic contamination of these agro-ecosystems may worsen ongoing soil-degradation processes and thereby threaten the food security and livelihoods of smallholder farmers. A similar finding has been documented in other sub-Saharan African countries with municipal solid-waste compost containing between 49 000 and 62 000 microplastic pieces $kg^{-1}$ dry weight (Okori *et al.,* 2025). Soil-function indicators decreased with the increase of macroplastic content, even for low concentrations, in California, whereas no correlation with microplastic content was observed (Tiwari & Sistla, 2024).

The impacts of EPS and other plastic pollutants on soil properties are complex and still not well understood, especially in semi-arid environments (Liu *et al.,* 2025). Plastic particles' physical changes can affect soil structure by creating physical barriers, changing pore-size distribution, and affecting aggregate formation and stability (Sajjad *et al.,* 2022; de Souza Machado *et al.,* 2018). The physical changes can also influence water infiltration, water retention, and water movement in soil profile, which can significantly impact water availability for plant growth under water-limited conditions (Chen *et al.,* 2025). Surface characteristics, chemical composition and interactions between microplastics and soil components may change soil pH and electrical conductivity, alter soil organic matter cycling and nutrient turn-over (Mondol *et al.,* 2025). It has been recently demonstrated that microplastic presence affects the pH of soil, and the direction and intensity of the pH change varies depending on the polymer type and concentration (Aslam *et al.,* 2026; Perfanova *et al.,* 2026). In a recent review, Chen *et al.* (2025) discussed the evidence of soil pH changes caused by polystyrene microplastics, which depends on the type of polymer and concentration. Furthermore, micro-plastics can affect soil microbial communities and their

processes, thus affecting the key soil processes such as decomposition of organic matter and nutrient cycling (Liu *et al.,* 2025).

The addition of plastic to agricultural soils could alter the hydrological properties of these soils, particularly in semi-arid zones where water is the primary factor limiting crop production (Islam et al., 2025). Plastic particles can modify the infiltration rate and water holding capacity of soil and in certain environments can also lead to higher surface runoff that may reduce water availability for plants use (Sajjad *et al.,* 2022). Liu *et al.* (2025) found that microplastics can influence soil aggregation and porosity, which subsequently impacts hydraulic conductivity and runoff. The authors submitted further that, alterations to soil chemical characteristics and microbial processes could have additional effects on plant growth, nutrient uptake, and productivity.

Despite the growing focus on the contamination of terrestrial ecosystems by microplastic wastes, research on the specific impacts of EPS on the physical and chemical characteristics of soils and their hydrological behaviour in semi-arid agricultural systems is still limited (Tiwari & Sistla, 2024). As of now, research on plastic pollution has predominantly centered on aquatic environments, with limited studies examining the effects of plastic pollution on terrestrial habitats, especially in regions with poor waste management practices and stressed agricultural systems in developing areas (Bodor *et al.,* 2023; Ozlu *et al.,* 2026; Rathikannu *et al.,* 2025). The lack of waste management infrastructure, the growing use of plastics, and the high vulnerability of agricultural systems in the Sudan Savanna may all contribute to higher risks of plastic contamination in agricultural soils, making this a priority research gap. It has been noted by Essien *et al.* (2025) that microplastic accumulation in soils will have environmental and toxicological implications, while it is important to undertake region-specific risk assessment.

This study involved ground EPS packaging waste as the test material. It is therefore not a microplastic produced by environmental weathering but rather a secondary microplastic, created from a larger microplastic object in the laboratory, and the particle size is at the upper end of the microplastic spectrum (<5 mm). The loadings applied (2 % w/w and 5 % w/w) exceed concentrations for most agricultural soils (which were below approximately 4.5 % w/w, based on the majority of sites reviewed by Büks and Kaupenjohann, 2020, and above 0.03 % w/w measured in the soil in an industrial area in Sydney, as reported by Fuller & Gautam, (2016), at the upper end of the range. No data on the concentration of EPS in Nigerian agricultural soils was obtained.

This study addressed three research questions: (1) Does incorporating ground EPS at 2 % and 5 % w/w change the pH, electrical conductivity (EC), organic carbon, total nitrogen, available phosphorus and exchangeable bases of a sandy-loam topsoil? (2) Does it alter the particle-size distribution, water retention, bulk density or aggregate stability? (3) Does it affect cowpea emergence? We hypothesised that, relative to the control, EPS would ($H_1$) alter soil chemical properties, ($H_2$) reduce water retention and aggregate stability, and ($H_3$) reduce cowpea emergence, with effects increasing with EPS loading.

# Materials and methods

## Study area and soil collection

This study was conducted at the teaching farm (Figure 1) of the Federal University Dutse in the Sudan Savanna ecological zone of Jigawa state, Nigeria (11°42'N and 9°20'E). Climate is semi-arid tropical, with one rainy season (May–September) and long dry season, but no site-specific climate records were measured in this study. No profile description or soil-series classification was made; the soil is reported to be sandy-loam, of the Alfisol order (USDA classification; Soil Survey Staff, 2014; Adeleye *et al.,* 2021).

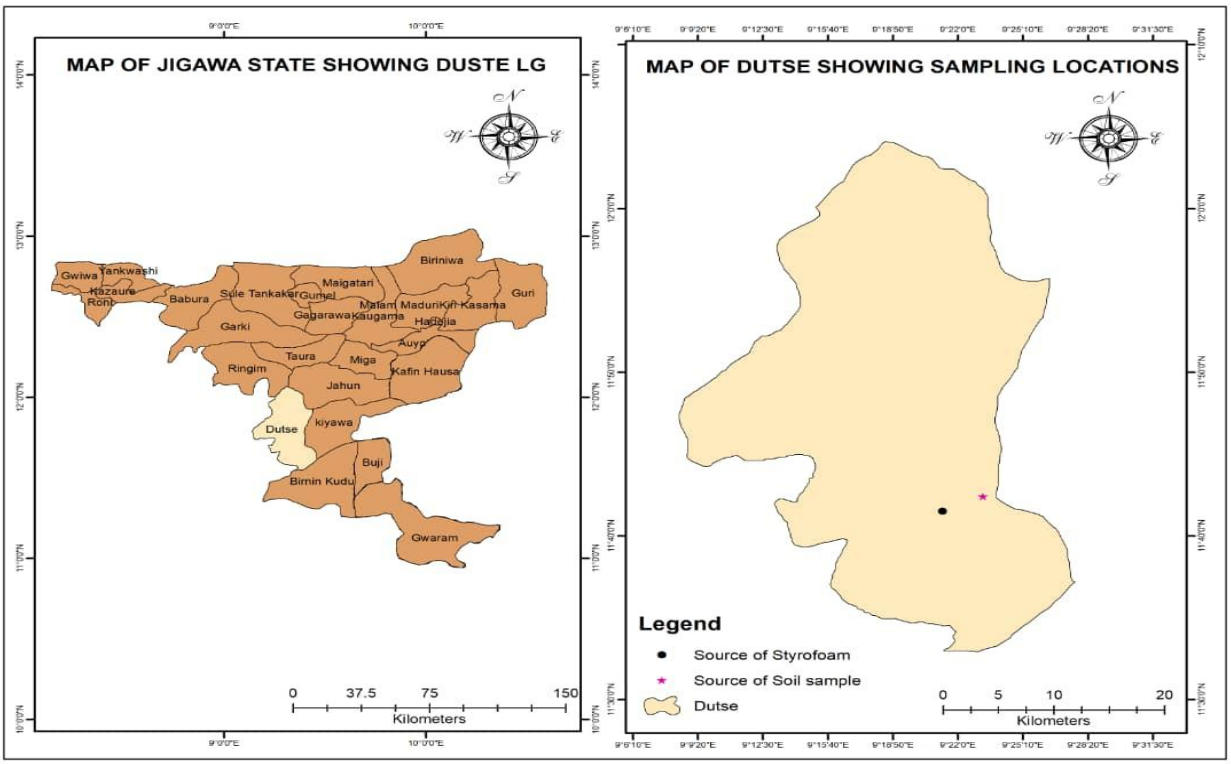



**Figure 1:** Map showing the sampling points from the study area

Soil samples were collected from the top 0–15 cm using the soil auger following standard soil sampling techniques (Edwards, 2010; Kabala *et al.,* 2021; Nkereuwem *et al.,* 2024). Samples were taken as a composite, air-dried at room temperature (25–28 °C), and sieved through a 2 mm mesh to remove larger particles and to homogenise the sample. A single composite soil sample was then split and inference is therefore limited to this batch of the composite soil and not to Savanna soils from Sudan in general. Baseline physicochemical properties of the composite were measured before the experimental treatments according to standard procedures (Gee & Or, 2002) and are given in Table 1.

**Table 1.** Baseline physicochemical properties of the composite soil from the study area.

| Property | Value |
|---|---|
| Moisture content (%) | 2.04 |
| pH (water) | 6.5 |
| EC (dS $m^{-1}$) | 0.92 |
| Available phosphorus (mg $kg^{-1}$) | 11.02 |
| Total nitrogen (%) | 0.06 |
| CEC (cmol $kg^{-1}$) | 3.51 |
| Clay + silt (g $kg^{-1}$) | 420 |
| Clay (g $kg^{-1}$) | 100 |
| Silt (g $kg^{-1}$) | 320 |
| Sand (g $kg^{-1}$) | 580 |
| Textural class | Sandy loam |

NB: EC, electrical conductivity; CEC, cation-exchange capacity. Values are single baseline determinations on the composite.

## Preparation of EPS-contaminated soil

The EPS waste used was typical plastic waste generated in urban areas from Dutse Ultra-Modern Market. The term "Styrofoam" is a trade name, and the product was not confirmed as this brand; hence the material is used as EPS throughout. The material was cleaned to remove surface contamination, air dried and mechanically ground to fragments of <5 mm to simulate the presence of microplastic. As explained in the Introduction, three loadings were chosen to represent high exposure scenarios based on reported soil concentrations (Büks & Kaupenjohann, 2020; Fuller & Gautam, 2016; Okiri *et al.,* 2025):

a) Control (0 % w/w): 500 g soil (no EPS addition).

b) 2 % loading (2 % w/w): 10 g EPS + 490 g soil.

c) 5 % loading (5 % w/w): 25 g EPS + 475 g soil.

The masses above are based on air-dried soil, and percentages are gravimetric (w/w) shares of air-dry soil–EPS mixture. The fragments of EPS were mixed well with the soil to get uniformity. The treated soils were stored in plastic containers for 14 days for equilibration at ambient temperature (25-28 °C) prior to analysis and planting.

Since EPS has a very low density (around 10-50 kg $m^{-3}$), mass fractions are similar to large volume fractions. In case of EPS bulk density of 0.020 g $cm^{-3}$, and soil bulk density of 1.42 g $cm^{-3}$ (as control), 10g of EPS occupies 500$cm^3$ and 25g of EPS occupies 1 250cm3 while 345$cm^3$ and 335$cm^3$ respectively of soil. EPS would then make up roughly 59 % and 79 % of the combined volume (about 49–66 % and 71–83 % for assumed bulk densities of 0.030–0.015 g $cm^{-3}$). These are approximate figures since bulk volume per pot was not measured. Volume fractions of this magnitude are well beyond the realm of field conditions and are a significant confounder of the physical and germination results.

## Experimental design

The experiment was designed in a completely randomised design (CRD) consisting of three blocks each (Festing, 2020). Three treatments and three replicates were used, with an experimental unit being a pot. All pots were subjected to the same environmental and watering parameters and soil moisture was maintained at around 60 % field capacity.

Because field capacity differed among treatments, a common fraction of field capacity implies different absolute water contents among treatments, and moisture was not independently verified. Soil samples were collected at 0, 6 and 12 weeks of incubation period for analysis. Since only nine pots were set up, the three-times samplings were also all obtained from the same pots, which means that the analysis of the whole time series would have to be conducted in a treatment × time repeated measures model. It is only the 12-week values reported and analysed here as a one-time comparison.

## Soil physicochemical analysis

The particle-size distribution was calculated by the hydrometer method (Beverwijk, 1967; Mir, 2021). The soil pH was determined by measuring the pH of a 1:2.5 soil–water suspension using a calibrated digital pH meter (Elberling & Matthiesen, 2007; Schirrmann *et al.,* 2011). Electrical conductivity (EC) was determined using a conductivity meter according to Slavich and Lugg (1993) who compared EC with suspensions of soil and water at a ratio of 1:5. Walkley & Black (1934); Nelson & Sommers (1996) Procedure was used to determine the amount of organic carbon, and organic matter was computed as organic carbon ×1.724 (Nelson & Sommers, 1996). Total nitrogen was determined using the Kjeldahl digestion method (Bremner & Mulvaney, 1982), and available phosphorus was determined using Bray-1 extraction method (Bray & Kurtz, 1945) (other extractants can produce different extractable phosphorus values for acid soils, (Maghanga *et al.,* 2012).

The exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$) were extracted by 1 M ammonium acetate at pH 7 (Thomas, 1982) and then determined by atomic-absorption spectrophotometry (Ca, Mg) and flame photometry (K, Na) (Zhang *et al.,* 2012). The value reported as "CEC" in the original submission was the sum of exchangeable bases (SEB = $Ca^{+}$, $Mg^{+}$, $K^{+}$, Na, cmol $kg^{-1}$; based on Antonangelo *et al.,* 2024). No exchangeable acidity was measured, nor was CEC determined without relying upon the cobaltihexamine method of Aran *et al.* (2008) cited originally.

## Soil hydrological and structural assessment

Water contents are reported on a gravimetric basis (gravimetric water content as a percentage of the soil mass, g). Soil water retention was measured using a pressure-plate apparatus at 0.33 bar, which was operationally defined as field capacity (FC) (Cassel & Nielsen, 1986) and at 15 bar (PWP) (Elbeltagi *et al.,* 2023; Dane & Hopmans, 2002). However, this is a coarse-textured soil, and the 0.33 bar is often too high for coarse-textured soils, so it should not be interpreted to represent the field capacity in this sandy-loam soil; the same suction was applied to all treatments, and thus, in principle, does not affect comparisons among treatments. Available water capacity was defined as the difference between the field capacity and permanent wilting point. The bulk density was determined using the core method described by Blake & Hartge (1986) and the aggregate stability using the wet-sieving method described by Kemper & Rosenau (1986) and Malgwi & Abu (2011). Observations were also taken in a qualitative manner, including crusting and structural integrity.

## Plant growth assessment

Cowpea (*Vigna unguiculata L.*) was selected as the test crop due to its significance in the agricultural production of the Sudan Savanna (Iseki *et al.,* 2021; Kim *et al.,* 2025) and its

sensitivity to soil conditions (Iseki *et al.,* 2021; Kim *et al.,* 2025). Five seeds were sown in each pot at a depth of 2 cm; after emergence seedlings were thinned to three per pot. The plant-growth parameters (germination rate, plant height, and visual appearance) were measured weekly for five weeks, and emergence was scored as the shoot emerging above the soil surface. During the experiment no fertiliser was applied to prevent masking of treatment effects. None of these pots were treated in any way except the untreated pots, which were sown and watered in the same manner, and no seed-viability test was made.

### Statistical analysis

Data were analysed with IBM SPSS Statistics (version 27). The pot (n = 3 per treatment) was the experimental unit. One-way analyses of variance (df = 2, 6) were followed by Tukey's (1949) Honestly Significant Difference (HSD) test at the 0.05 level of significance only when the omnibus test was significant. Effect size is reported as $\eta^2$ (SS between ÷ SS total). This model assumes normality (Shapiro & Wilk, 1965) and homogeneity of variance (Levene, 1960); the test of these assumptions is not very powerful for three pots per treatment. The F statistics, exact p values, $\eta^2$, and Tukey groupings reported here were calculated from the treatment means and standard deviations (n = 3). Germination (0/15 versus 15/15) exhibits complete separation and is reported descriptively; even in complete separation an exact two-sided Mann–Whitney p of only 0.10 is obtained with only three pots per treatment, and Fisher's exact test on the pooled seeds would assume independence among seeds within a pot, which is not true. All data are expressed as mean ± SD (n = 3). There was no correlation analysed between the three ordered treatment levels as this is not sufficient as evidence of mechanism.

## Results

### Baseline and control soil

Significant differences between the baseline composite (Table 1) and the 12-week control (Tables 2-7) were observed in some of the properties: pH 6.5 versus 5.69, EC 0.92 versus 0.38 dS $m^{-1}$, available phosphorus 11.02 versus 2.3 mg $kg^{-1}$, and total nitrogen 0.06 versus 0.0093 %. Baseline silt (32 %) was different from the control (7.9 %), and a different procedure was used to measure the baseline CEC (3.51 cmol $kg^{-1}$). These changes in untreated soil suggest significant change in either incubation or in sampling and analysis and must be explained before the results of treatments can be interpreted.

### Particle-size distribution

The soil texture was sandy loam in all treatments (Table 2). Sand content ranged from 73.7 % to 76.3 %, silt from 7.5 % to 8.2 %, and clay from 16.2 % to 18.1 %. No statistically significant differences in particle-size distribution were detected (clay: $F(2, 6) = 0.75$, $p = 0.512$, $\eta^2 = 0.20$; silt: $F(2, 6) = 0.22$, $p = 0.812$, $\eta^2 = 0.07$; sand: $F(2, 6) = 0.52$, $p = 0.620$, $\eta^2 = 0.15$). Higher compaction and lower aggregate stability was observed in the 5 % EPS treatment with qualitative notes, which were quantified in Table 7.

**Table 2.** Particle-size distribution and soil texture across treatments (12-week sampling).

| Treatment | Clay (%) | Silt (%) | Sand (%) | Textural class |
|---|---|---|---|---|
| Control (0 %) | 16.7 ± 2.1 | 7.9 ± 1.3 | 75.4 ± 3.2 | Sandy loam |
| 2 % EPS | 16.2 ± 1.8 | 7.5 ± 1.1 | 76.3 ± 2.8 | Sandy loam |
| 5 % EPS | 18.1 ± 2.0 | 8.2 ± 1.5 | 73.7 ± 3.5 | Sandy loam |

NB: Values are means ± SD ($n$ = 3). No significant differences among treatments ($p > 0.05$).

## Soil pH and electrical conductivity

Mean pH was 5.69 ± 0.15 in the control, 5.80 ± 0.12 at 2 % and 6.03 ± 0.18 at 5 % EPS (Table 3). The difference between the extremes (0.34 pH units) was not statistically significant ($F(2, 6) = 3.91$, $p = 0.082$, $\eta^2 = 0.57$; control versus 5 %, Tukey $p = 0.075$). EC (0.35–0.42 dS/m) also did not differ among treatments ($F(2, 6) = 1.44$, $p = 0.308$, $\eta^2 = 0.32$).

**Table 3.** Soil pH and electrical conductivity across treatments (12-week sampling).

| Treatment | pH | Electrical conductivity (dS/m) |
|---|---|---|
| Control (0 %) | 5.69 ± 0.15 a | 0.38 ± 0.05 a |
| 2 % EPS | 5.80 ± 0.12 a | 0.42 ± 0.06 a |
| 5 % EPS | 6.03 ± 0.18 a | 0.35 ± 0.04 a |

Values are means ± SD ($n$ = 3). The same letter indicates no significant difference (Tukey's HSD, $p \geq 0.05$).

## Organic carbon and organic matter

The decline of organic carbon and organic matter was significant but not concentration dependent (Table 4). Control soil contained 0.70 ± 0.08 % organic carbon and 1.20 ± 0.14 % organic matter. At 2 % EPS these values fell to 0.02 ± 0.01 % and 0.034 ± 0.017 %, respectively (a 97 % decrease); at 5 % they recovered only partially to 0.12 ± 0.05 % and 0.20 ± 0.08 %. Treatment effects were large (organic carbon: $F(2, 6) = 134.80$, $p < 0.001$, $\eta^2 = 0.98$; organic matter: $F(2, 6) = 136.20$, $p < 0.001$, $\eta^2 = 0.98$). The treatment with both EPSs were significantly different from the control (Tukey $p < 0.001$) but not from each other (Tukey $p = 0.143$ for organic carbon). A 97 % decrease at 2 % EPS is not explainable by dilution, since only 2 % of the soil mass was replaced by EPS, and a near total loss at 2 % EPS followed by partial recovery at 5 % does not seem likely as a single dose–response. The two variables were not independent, since organic matter was calculated as organic carbon × 1.724.

**Table 4.** Organic carbon and organic matter content across treatments (12-week sampling).

| Treatment | Organic carbon (%) | Organic matter (%) |
|---|---|---|
| Control (0 %) | 0.70 ± 0.08 a | 1.20 ± 0.14 a |
| 2 % EPS | 0.02 ± 0.01 b | 0.034 ± 0.017 b |
| 5 % EPS | 0.12 ± 0.05 b | 0.20 ± 0.08 b |

Values are means ± SD ($n$ = 3). Different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Organic matter = organic carbon × 1.724.

## Available phosphorus and total nitrogen

Total nitrogen and available phosphorus showed non-linear response (Table 5). Phosphorus rose from 2.3 ± 0.8 mg/kg in the control to 18.9 ± 3.2 mg/kg at 2 % (about eightfold), then fell to 2.53 ± 1.1 mg/kg at 5 % ($F(2, 6) = 67.44$, $p < 0.001$, $\eta^2 = 0.96$; the 2 % treatment differed from both other treatments, $p < 0.001$, and the control and 5 % did not differ, $p = 0.989$). Total nitrogen followed a similar pattern (0.0093 ± 0.0012 % → 0.011 ± 0.0014 % → 0.0073 ± 0.0009

%; F (2, 6) = 7.33, p = 0.024, $\eta^2$ = 0.71) and differed significantly only between the 2 % and 5 % treatments (p = 0.020). Both N values are extremely low.

**Table 5.** Available phosphorus and total nitrogen across treatments (12-week sampling).

| Treatment | Available phosphorus (mg/kg) | Total nitrogen (%) |
|---|---|---|
| Control (0 %) | 2.3 ± 0.8 a | 0.0093 ± 0.0012 ab |
| 2 % EPS | 18.9 ± 3.2 b | 0.011 ± 0.0014 a |
| 5 % EPS | 2.53 ± 1.1 a | 0.0073 ± 0.0009 b |

Values are means ± SD ($n$ = 3). Different letters indicate significant differences at $p < 0.05$ (Tukey's HSD).

## Exchangeable bases and their sum

The sum of exchangeable bases (SEB) was 2.65 ± 0.35 cmol/kg in the control, 2.76 ± 0.28 cmol/kg at 2 % and 3.45 ± 0.42 cmol/kg at 5 % EPS (Table 6), a difference that was not significant (F(2, 6) = 4.49, p = 0.064, $\eta^2$ = 0.60). The tabulated value is equal to $Ca^+$, $Mg^+$, $K^+$, Na in each treatment and is therefore not a measured CEC. Exchangeable Ca and Mg did not differ among treatments (Ca: F (2, 6) = 1.00, p = 0.422, $\eta^2$ = 0.25; Mg: F (2, 6) = 2.90, p = 0.131, $\eta^2$ = 0.49). Exchangeable K was higher at 5 % EPS than in the other treatments (F (2, 6) = 8.23, p = 0.019, $\eta^2$ = 0.73), and Na was 0.20, 0.18 and 0.46 cmol/kg at 0, 2 and 5 %, more than twice as high at 5 % as in the control (F (2, 6) = 40.67, p < 0.001, $\eta^2$ = 0.93; Tukey p < 0.001).

**Table 6.** Sum of exchangeable bases (SEB) and exchangeable bases across treatments (12-week sampling).

| Treatment | SEB (cmol/kg) | Ca (cmol/kg) | Mg (cmol/kg) | K (cmol/kg) | Na (cmol/kg) |
|---|---|---|---|---|---|
| Control (0 %) | 2.65 ± 0.35 a | 1.42 ± 0.18 a | 0.68 ± 0.09 a | 0.35 ± 0.05 a | 0.20 ± 0.03 a |
| 2 % EPS | 2.76 ± 0.28 a | 1.48 ± 0.15 a | 0.72 ± 0.08 a | 0.38 ± 0.04 a | 0.18 ± 0.03 a |
| 5 % EPS | 3.45 ± 0.42 a | 1.62 ± 0.20 a | 0.85 ± 0.10 a | 0.52 ± 0.07 b | 0.46 ± 0.06 b |

Values are means ± SD ($n$ = 3). Different letters within a column indicate significant differences at $p < 0.05$ (Tukey's HSD). SEB = $Ca^+$, $Mg^+$, $K^+$, Na; cmol/kg notation is used throughout.

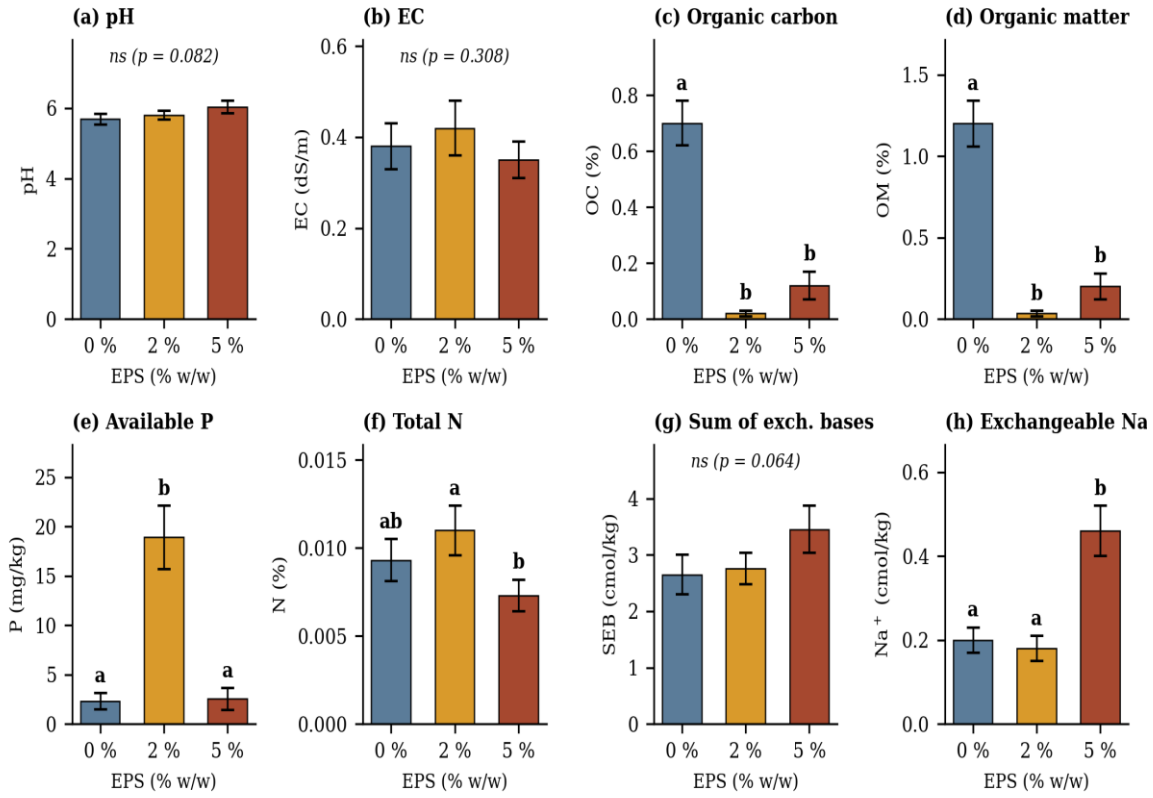



**Figure 1.** Soil chemical properties under 0, 2 and 5 % (w/w) EPS (12-week sampling): (a) pH, (b) electrical conductivity (EC), (c) organic carbon (OC), (d) organic matter (OM), (e) available phosphorus, (f) total nitrogen, (g) sum of exchangeable bases (SEB) and (h) exchangeable $Na^+$. Bars are means and error bars are SD ($n$ = 3); different letters indicate significant differences (Tukey's HSD, $p < 0.05$) and ns indicates a non-significant ANOVA.

## Hydrological and structural properties

Water retained at 0.33 bar (field capacity) declined from 22.4 % in the control to 18.7 % at 2 % and 15.2 % at 5 % EPS (Table 7; F (2, 6) = 10.36, p = 0.011, $\eta^2$ = 0.78; only the control and 5 % EPS differed, p = 0.009). Available water capacity fell from 13.8 % to 10.4 % and 7.1 % (F(2, 6) = 21.91, p = 0.002, $\eta^2$ = 0.88; all pairwise comparisons p < 0.05), whereas permanent wilting point differed little among treatments (8.1–8.6 %; F(2, 6) = 0.29, p = 0.756, $\eta^2$ = 0.09). Bulk density increased numerically from 1.42 to 1.49 and 1.58 g $cm^{-3}$ but the difference was not significant (F(2, 6) = 2.98, p = 0.126, $\eta^2$ = 0.50). Aggregate stability fell from 65.3 % to 48.7 % and 32.5 % (F(2, 6) = 49.51, p < 0.001, $\eta^2$ = 0.94; all pairwise comparisons p < 0.05). The higher the bulk density, the less it makes sense because EPS is much less dense than mineral soil; the treatment of EPS mass and volume in the calculation, its packing and core volume should be checked.

**Table 7.** Soil hydrological properties across treatments (12-week sampling; water contents on a gravimetric basis).

| Property | Control (0 %) | 2 % EPS | 5 % EPS |
|---|---|---|---|
| Field capacity (%) | 22.4 ± 2.1 a | 18.7 ± 1.8 ab | 15.2 ± 1.9 b |
| Permanent wilting point (%) | 8.6 ± 0.9 a | 8.3 ± 0.8 a | 8.1 ± 0.7 a |
| Available water capacity (%) | 13.8 ± 1.4 a | 10.4 ± 1.2 b | 7.1 ± 1.1 c |
| Bulk density (g $cm^{-3}$) | 1.42 ± 0.08 a | 1.49 ± 0.07 a | 1.58 ± 0.09 a |
| Aggregate stability (%) | 65.3 ± 4.2 a | 48.7 ± 3.8 b | 32.5 ± 4.1 c |

Values are means ± SD ($n$ = 3). Different letters indicate significant differences at $p < 0.05$ (Tukey's HSD). Field capacity is water retained at 0.33 bar.

## Cowpea emergence and growth

The control had 15/15 seeds germinate, reaching 100 % germination at 7 days (week 1), with plants reaching an average height of 25.4 ± 2.8 cm at week 5 (Table 8). However, in both the 2 % and the 5 % EPS treatments, germination was 0 % during the five-week observation period (0 of 15 seeds in each, three pots × five seeds). From a visual inspection, it was suggested that EPS fragments may have been present around the seeds, but this was not quantified, and no quantitative examination was conducted for ungerminated seeds (imbibition, decay or radicle protrusion) and the cause of non-emergence is unknown.

**Table 8.** Plant-growth parameters across treatments.

| Treatment | Seeds emerged (of 15) | Germination rate (%) | Week 1 height (cm) | Week 3 height (cm) | Week 5 height (cm) |
|---|---|---|---|---|---|
| Control (0 %) | 15 | 100 | 5.2 ± 0.8 | 15.8 ± 1.6 | 25.4 ± 2.8 |
| 2 % EPS | 0 | 0 | 0 | 0 | 0 |
| 5 % EPS | 0 | 0 | 0 | 0 | 0 |

Values are means ± SD ($n$ = 3).

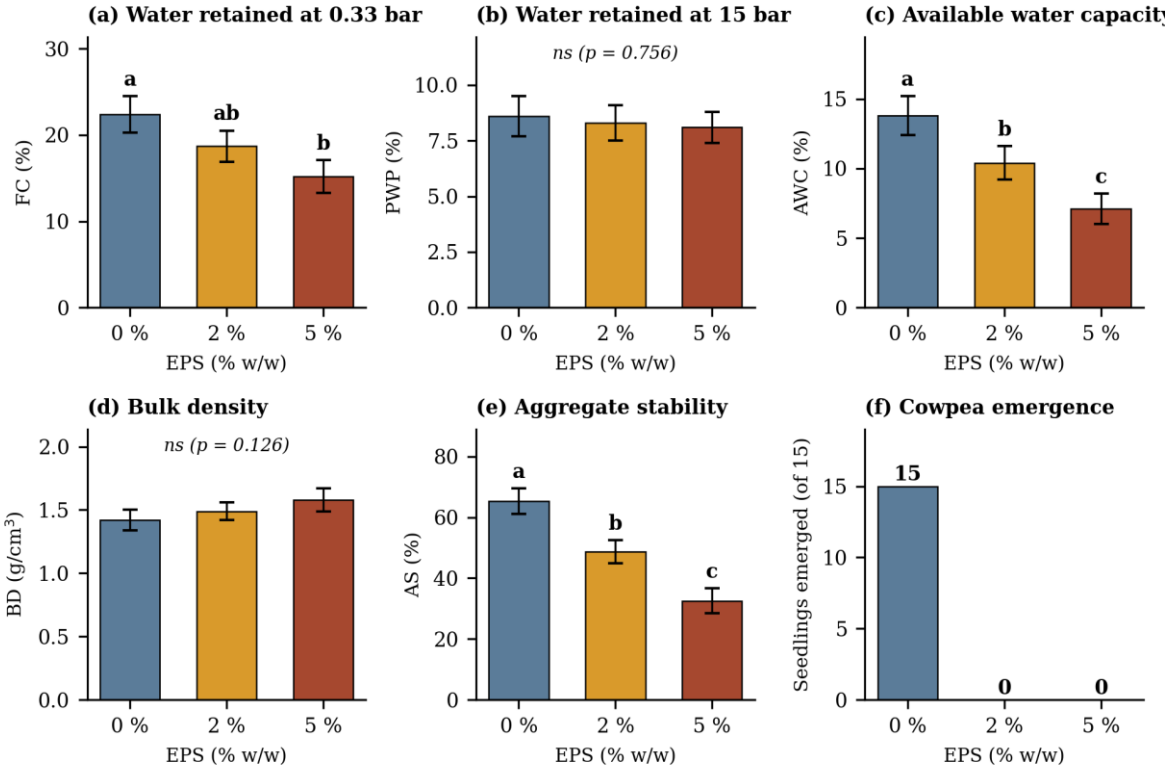



**Figure 2.** Hydrological and structural properties and cowpea emergence under 0, 2 and 5 % (w/w) EPS: (a) water retained at 0.33 bar (field capacity), (b) water retained at 15 bar, (c) available water capacity, (d) bulk density, (e) aggregate stability and (f) number of cowpea seedlings emerged out of 15 seeds sown. Bars are means and error bars are SD ($n$ = 3); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

## Summary of omnibus tests

**Table 9.** One-way ANOVA (df = 2, 6) and Tukey HSD summary for all variables (12-week sampling).

| Variable | $F$ | $p$ | $\eta^2$ | Pairs differing (Tukey, $p < 0.05$) |
|---|---|---|---|---|
| Clay (%) | 0.75 | 0.512 | 0.20 | none |
| Silt (%) | 0.22 | 0.812 | 0.07 | none |
| Sand (%) | 0.52 | 0.620 | 0.15 | none |
| pH | 3.91 | 0.082 | 0.57 | none |

| Variable | *F* | *p* | $\eta^2$ | Pairs differing (Tukey, $p < 0.05$) |
|---|---|---|---|---|
| EC (dS/m) | 1.44 | 0.308 | 0.32 | none |
| Organic carbon (%) | 134.80 | <0.001 | 0.98 | 0 vs 2 %; 0 vs 5 % |
| Organic matter (%) | 136.20 | <0.001 | 0.98 | 0 vs 2 %; 0 vs 5 % |
| Available P (mg/kg) | 67.44 | <0.001 | 0.96 | 0 vs 2 %; 2 vs 5 % |
| Total N (%) | 7.33 | 0.024 | 0.71 | 2 vs 5 % |
| Sum of exchangeable bases (cmol/kg) | 4.49 | 0.064 | 0.60 | none |
| Ca (cmol/kg) | 1.00 | 0.422 | 0.25 | none |
| Mg (cmol/kg) | 2.90 | 0.131 | 0.49 | none |
| K (cmol/kg) | 8.23 | 0.019 | 0.73 | 0 vs 5 %; 2 vs 5 % |
| Na (cmol/kg) | 40.67 | <0.001 | 0.93 | 0 vs 5 %; 2 vs 5 % |
| Water retained at 0.33 bar (%) | 10.36 | 0.011 | 0.78 | 0 vs 5 % |
| Water retained at 15 bar (%) | 0.29 | 0.756 | 0.09 | none |
| Available water capacity (%) | 21.91 | 0.002 | 0.88 | 0 vs 2 %; 0 vs 5 %; 2 vs 5 % |
| Bulk density ($g/cm^3$) | 2.98 | 0.126 | 0.50 | none |
| Aggregate stability (%) | 49.51 | <0.001 | 0.94 | 0 vs 2 %; 0 vs 5 %; 2 vs 5 % |

$\eta^2$ = SS between ÷ SS total. Calculated from treatment means and SD ($n$ = 3).

# Discussion

## Soil chemical responses

A similar shape- and polymer-dependent increase in pH due to microplastic exposure was reported by Zhao *et al.* (2021) and also described in the reviews mentioned above (Guo *et al.,* 2024; Chen *et al.,* 2025). The pH increase in the present data was small and not statistically significant, thus no pH effect of EPS is demonstrated. The 97 % decrease in organic carbon at 2 % EPS followed by partial recovery at 5 % is not consistent with a concentration dependent mechanism and the explanations provided in the original submission (physical obstruction of turnover pathways, microbial disruption, “new equilibrium”) are not suitable as they would have to be verified by measurements. The results also indicate plant uptake and activity in the roots of the control pots and the lack of plant uptake activity in the EPS pots, which will affect nitrogen, phosphorus and organic carbon; the cowpea plants were present in the control pots for the 6- and 12-week samplings.

There are reports of non-linear nutrient response to polystyrene microplastics (Liu *et al.,* 2025; Oladele *et al.,* 2023; Zhao *et al.,* 2021); direction and size is dependent on soil, polymer and conditions. The following two untested hypotheses have been considered in the present pattern: (1) temporary release of previously bound nutrients at 2 % and (2) adsorption or precipitation at 5 %. The eightfold phosphorus boost at 2% is too great and requires verification to be interpreted. The sum of exchangeable bases should not be considered as an estimate of improved fertility or as a measure of CEC and did not change significantly between the treatments. Explanations for the increase in $K^+$ and $Na^+$ at 5 % could be, but are not necessarily, that the cations are carried by the EPS, cleaning residues or irrigation water, particularly the increase in Na (from 0.20 to 0.46 cmol/kg) suggests a possible contamination source and should be investigated.

### Hydrological and structural responses

The lower field capacity, available water capacity and aggregate stability at 5 % EPS are in line with the reports of changes in water-holding capacity, bulk density and aggregation caused by microplastics (de Souza Machado *et al.,* 2018; Sajjad *et al.,* 2022; Chen *et al.,* 2025; Zucchini *et al.,* 2025). A simple hypothesis is that if EPS fills the majority of the treated volume as suggested by the illustrative calculation, a hydrophobic, non-porous, low-density phase takes the place of water-holding soil. The higher bulk density, which was not significant, cannot be explained by this reasoning and requires verification. In semi-arid agriculture, water scarcity is a common limitation, and infiltration, runoff, root penetration and erosion were not determined, so no impacts on these are asserted.

### Cowpea emergence

The 0 % emergence for both EPS treatments is unusual and must be confirmed with viable seed tested and with proper controls. The control pots, which were sown and watered in the same way, had 15 of 15 plants emerge, suggesting that it was not a pot failure, water failure or handling failure, but does not rule out that it was due to the seed-lot problem specific to the EPS pots, or that it was a change in the water, or aeration or moisture. The salinity (EC 0.35-0.42 dS/m) and pH (5.69-6.03) were moderate and thus salinity or extreme pH cannot be ruled out based on these data. This is rare in the polystyrene microplastic literature (e.g., Oladele et al., 2023) and warrants caution. Seeding viability test should be used in repeat, inert-material control and treatments to differentiate toxicity from physical effects should be used.

### Limitations

In this study one type of composite soil was used, together with three pots for each treatment, a short duration and very high EPS loading, by mass, which corresponds to a large volume of foam. The reporting of temporal data was incomplete, as soil samples were taken at 0, 6 and 12 weeks, but only 12-week data is reported. No mechanistic measurements were done and no characterisation of the polymer and its additives. No control pots were available, moisture targets were different among treatments and a single procedural control was not available. Certain procedural information (such as pot sizes and packing, seed cultivar and lot, pressure-plate equilibration time, core size and size of the sieves) and analytical quality-control data (calibration, blanks, duplicates, reference materials and recoveries) is not reported here, reducing the degree of reproducibility. There are some values which are out of the ordinary (organic carbon, phosphorus, bulk density and emergence) and the statistics have been based on summary data. Generalisations must not be made from the data from one soil composite and nine pots to regional scale agricultural risk.

## Conclusions

Incorporation of ground EPS at 2 % and 5 % w/w resulted in significantly lower organic carbon and organic matter (unverifiable) and higher available phosphorus at 2 % (unverifiable) and lower available water capacity and aggregation stability, and lower water retained at 0.33 bar at 5 % EPS within the limits of this controlled pot experiment (three pots per treatment).

Changes in pH, the sum of exchangeable bases and bulk density were not statistically significant. The emergence of neither cowpea was obtained in any of the EPS treatments and is yet to be established and attributed to any cause. These loadings are much higher than those found in agricultural soils, and are not based on field exposure risk. It is recommended that confirmation should be done using polymer and additive characterisation, seed viability tests and procedural controls, and field-relevant dose–response experiments with much lower loadings. This experiment cannot provide any regulatory or remediation recommendations but the results do support field surveys of EPS in Sudan Savanna soils.

## Declarations

**Author contributions (CRediT):** *Not applicable*

**Funding:** *Not applicable*

**Conflict of Interest:** The authors declare that they have no conflict of interest.

**Author's Declaration of Competing Interest:** The author has no competing financial interests to declare.

**Ethics Statement:** *Not applicable*

**Data availability:** *Not applicable*

**Use of AI tools (where applicable):** *Not applicable*

**Acknowledgement:** The author thanks the Department of Environmental Sciences, Soil Science, and Chemistry, both of the Federal University Dutse for their laboratory facilities used during the analysis.

**Supplementary Materials:** None.

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